The Metaverse and Space Informatics

Yung Kai-leung, Andrew Ip Wai-hung, Tang Yuk-ming

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Preface

In recent years, one of the most intriguing research fields has been space informatics. The use of AI, robots, IoT systems and theories in the design and development of spacecraft, operation of space systems, and their related technologies are known as space informatics. Many space exploration and exploitation missions are in part sustained by the growing informatics approach, in aspects that include design, prediction, planning, navigation and control of ground stations, satellites, spacecraft, and robotics. Space informatics requires hardware and software integration, as well as various computer architectures with sensors, networks, and apps, among other things, for simulation and optimisation, decision-support methods and algorithms. Furthermore, given the sophisticated, high cost, and high-risk characteristics of space missions and the systems associated with spacecraft, improved technologies in 3D modelling, computer simulation, workflow optimisation, and decision-support approaches are necessary to increase safety, reliability, efficiency, and effectiveness in deep space exploration and exploitation. The challenges involved have given us the motivation to write a book that relates to state-of-the-art space informatics with metaverse technologies and their integration. This book outlines the latest research and cutting-edge space exploration and metaverse technologies, with the goal of contributing to current and future space missions and spaceflight development.

Deep space exploration and exploitation refer to the integration of various disciplines including astronomy, astronautics, and space technology needed for exploring the distant regions from the Moon and beyond. Deep space exploration is challenging partly due to the large amount of resources and the complexity of the technologies involved. A more economic and efficient approach is to be based on computer simulations with mixed reality. Computer simulations enable outer space experiments to be conducted in the digital or metaverse environment to simulate the many complex situations and scenarios by modelling for evaluation. With the wider adoption of virtual reality (VR), the results from simulations can be visualised, modified, and interacted with. The metaverse offers a network of interconnected virtual worlds that enhance a single virtual space, usually provided by VR. Each digital context in the metaverse can be designed and managed independently and allows users to move freely from one virtual space environment to another. This book aims to provide researchers, engineers, designers, practitioners, and others with a wide range of methods and tools for control and collaboration when conducting deep space exploration experiments, verifying safety measurements, maintenance and settings in the spaceship, robots, man and machine, and astronauts and machines, that are important in deep space exploration.

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Chapter 1

Metaverse-Enabling Technologies in Deep Space Exploration Applications

Abstract

Deep space exploration and exploitation refers to astronomy, astronautics, and space technology that is involved with exploring the distant regions of outer space. However, deep space exploration is difficult due to the large amount of resources and the complexity of the technologies involved. A more economic and efficient approach is based on computer simulations. Computer simulations enable outer space experiments to be conducted in the digital environment, while many complex situations and scenarios can also be modelled for evaluation. With the wider adoption of virtual reality (VR), the results from the simulations can be visualised, modified, and interacted with. The metaverse offers a network of interconnected virtual worlds that enhances the single virtual space that is usually provided by VR. Each digital context in the metaverse can be designed and managed independently, and allows users to move freely from one virtual space environment to another.

This provides stakeholders with a wide range of control and collaboration opportunities for deep space exploration and other collaborative tasks such as conducting experiments, verifying safety measurements, maintenance and settings in the spaceship that are particularly important in many deep space activities. This chapter introduces the recent literature as well as the metaverse paradigm in deep space exploration.

Keywords: metaverse, deep space exploration, deep space mission

1 Introduction

The emerging metaverse paradigm promises to transform domains ranging from social connection to professional collaboration. This transformation is enabled by the metaverse's integration of extended reality, pervasive networking, blockchain architectures, and artificial intelligence. While early metaverse applications targeted entertainment and virtual economies, the potential to enhance specialised technical fields is gaining increasing attention.

One domain ripe for metaverse disruption is deep space science and exploration. Defined as the realm spanning from beyond low Earth orbit to the farthest reaches of the solar system, deep space represents humanity's next frontier. Realising ambitious initiatives in deep space will require advances across key capabilities including communication, autonomous operations, human-machine collaboration, and integrated modelling. The metaverse offers convergence potential to enhance these areas through immersion, persistent connectivity, intelligent automation, and unified data integration.

This literature review synthesises early research at the intersection of metaverse technologies and deep space applications. The objective is to extract insights from contributions across diverse disciplines, and to assess the potential benefits and challenges of applying the metaverse paradigm to space systems. Trends in the findings reveal a burgeoning research nexus between established aerospace engineering foundations and ascendant digital transformation trends. Strategic investment in this synergistic relationship promises to unlock deep space's next frontiers by leveraging metaverse technology capabilities to profoundly augment the human experience.

2 Literature Review

The metaverse, a term that has gained significant attention in recent years, represents a collective virtual shared space created by the convergence of physical and virtual reality. This space is not just a representation of the world as we know it, but is a world fully built and populated by the creativity of its inhabitants, enabled by a range of key technologies. Meanwhile, deep space exploration represents humanity's quest to learn more about our universe, expanding our knowledge and presence beyond the confines of our planet.

2.1 Defining the Metaverse

The metaverse is an expansive network of digital experiences and assets that are interoperable and accessible across different hardware platforms (Ritterbusch & Teichmann, 2023). It represents a collective virtual shared space that is created by the fusion of virtually enhanced physical reality and physically persistent virtual reality, converging in a shared online space that is persistent, spans the digital and physical worlds, incorporates a fully functioning economy, and is populated by "users and Ais" (Gao et al., 2023).

2.2 Key Technologies Enabling the Metaverse

Artificial Intelligence (AI) plays a crucial role in the metaverse, with subsets such as Machine Learning (ML), Natural Language Processing, and Computer Vision being integral components. AI enables personalised experiences, automates processes, and drives interactivity in the metaverse (Saritas & Topraklikoglu, 2022).

Technologies such as 5G/6G, the Internet of Things (IoT), Cloud Computing, and Edge Computing are vital to the functioning of the metaverse. They ensure the high-speed data transfer, ubiquitous connectivity, and real-time processing required for immersive and seamless metaverse experiences.

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Brain-Computer-Interface (BCI), is the foundation of the metaverse. These technologies enable the creation of immersive digital environments and interactions (Gao et al., 2023).

Blockchain, Smart Contracts, and Cryptocurrency underpin the economy of the metaverse, facilitating secure and transparent transactions of digital assets and services (Ritterbusch & Teichmann, 2023).

Digital Twins, Computational Simulation, Asset Twins, System Twins, and Avatars enable the creation of digital representations of physical entities and environments in the metaverse, facilitating interaction and experimentation (Saritas & Topraklikoglu, 2022).

2.3 Deep Space Exploration

Deep space exploration involves the investigation of cosmic bodies beyond the Earth's moon, including other planets, asteroids, and exoplanets (Wu et al., 2012). Activities in this field include the deployment of spacecraft, satellites, and astronauts for various missions aimed at better understanding the universe.

2.4 Research Questions

Given the expansive capabilities of the metaverse and the vast potential of deep space exploration, several key research questions arise:

1. What are the applications of the metaverse in the deep space industry?
2. What are the impacts of key enabling technologies in the metaverse on the deep space industry?
3. How is the metaverse's development challenge and future opportunity in the deep space industry?

Exploring these questions will provide valuable insights into how the metaverse can be leveraged for advancements in deep space exploration, potentially facilitating new discoveries, enhancing efficiency, and opening novel opportunities in the field.

3 Methodology

In the pursuit of a comprehensive and systematic review of the literature related to the metaverse's applications in deep space exploration, we employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology. PRISMA is a renowned approach for conducting systematic reviews and meta-analyses, and it offers a robust framework to ensure the transparency and completeness of the review.

Our sources for this study were three of the most respected academic databases: Web of Science, IEEE Xplore, and ScienceDirect. We used the PRISMA flow diagram to guide our methodology, offering, as it does, a clear visual representation of the process we undertook in the identification, screening, eligibility assessment, and final inclusion of studies in this review.

3.1 Identification

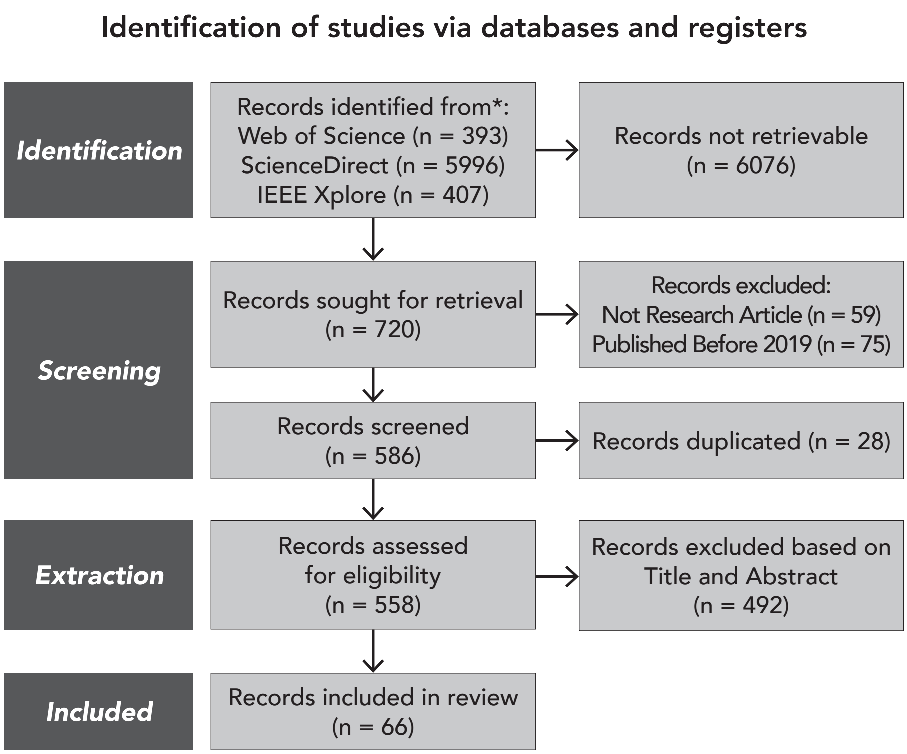

Figure 1. PRISMA Analysis Flowchart

Table 1. The Search Query Used in Three Databases Searching

Database	Search Query
Web of Science	(“Metaverse” OR “Metaverses” OR “Artificial Intelligence” OR “Machine Learning” OR “Natural Language Processing” OR “Computer Vision” OR “Networking” OR “5G” OR “6G” OR “Internet of Things” OR “Cloud Computing” OR “Edge Computing” OR “Extended Reality” OR “Virtual Reality” OR “Augmented Reality” OR “Mixed Reality” OR “Blockchain” OR “Smart Contracts” OR “Digital Twins” OR “Simulation” OR “Virtual Environment”) AND (“deep space” OR “deep space exploration” OR “deep space mission” OR “space exploration” OR “human space exploration” OR “space mission” OR “aerospace” OR “astronaut” OR “satellite” OR “asteroid” OR “space vehicle” OR “exoplanet” OR “spacecraft” OR “earth observation”), Open Access, Document Types: Article, Publication Years: 2019 or 2020 or 2021 or 2022 or 2023
Science Direct	(“Metaverse” OR “Metaverses” OR “Artificial Intelligence” OR “Machine Learning” OR “Natural Language Processing” OR “Computer Vision” OR “Networking” OR “5G” OR “6G” OR “Internet of Things” OR “Cloud Computing” OR “Edge Computing” OR “Extended Reality” OR “Virtual Reality” OR “Augmented Reality” OR “Mixed Reality” OR “Blockchain” OR “Smart Contracts” OR “Digital Twins” OR “Simulation” OR “Virtual Environment”) AND (“deep space” OR “deep space exploration” OR “deep space mission” OR “space exploration” OR “human space exploration” OR “space mission” OR “aerospace” OR “astronaut” OR “satellite” OR “asteroid” OR “space vehicle” OR “exoplanet” OR “spacecraft” OR “earth observation”)
IEEE Xplore	(“All Metadata”:“Metaverse” OR “All Metadata”: “Metaverses” OR “All Metadata”:”Artificial Intelligence” OR “All Metadata”:“Machine Learning” OR “All Metadata”:“Natural Language Processing” OR “All Metadata”:“Computer Vision” OR “All Metadata”:“Networking” OR “All Metadata”:“5G” OR “All Metadata”:“6G” OR “All Metadata”:”Internet of Things” OR “All Metadata”:“Cloud Computing” OR “All Metadata”:“Edge Computing” OR “All Metadata”:“Extended Reality” OR “All Metadata”:“Virtual Reality” OR “All Metadata”:“Augmented Reality” OR “All Metadata”:“Mixed Reality” OR “All Metadata”:“Blockchain” OR “All Metadata”:“Smart Contracts” OR “All Metadata”:“Digital Twins” OR “All Metadata”:“Simulation” OR “All Metadata”:“Virtual Environment”) AND (“All Metadata”:”deep space” OR “All Metadata”:“deep space exploration” OR “All Metadata”:“deep space mission” OR “All Metadata”:“space exploration” OR “All Metadata”:“human space exploration” OR “All Metadata”:“space mission” OR “All Metadata”:“aerospace” OR “All Metadata”:“astronaut” OR “All Metadata”:“satellite” OR “All Metadata”:“asteroid” OR “All Metadata”:“space vehicle” OR “All Metadata”:“exoplanet” OR “All Metadata”:“spacecraft” OR “All Metadata”:“earth observation”)

To start with the identification phase, we divided our search terms into two primary categories. The first category focused on the metaverse and its key technologies, including terms such as “Artificial Intelligence”, “Machine Learning”, “Natural Language Processing”, “Computer Vision”, “Networking”, “5G”, “6G”, “Internet of Things”, “Cloud Computing”, “Edge Computing”, “Extended Reality”, “Virtual Reality”, “Augmented Reality”, “Mixed Reality”, “Blockchain”, “Smart Contracts”, “Digital Twins”, “Simulation”, and “Virtual Environment”.

The second category of terms we searched for was related to deep space missions. These terms included “deep space”, “deep space exploration”, “deep space mission”, “space exploration”, “human space exploration”, “space mission”, “aerospace”, “astronaut”, “satellite”, “asteroid”, “space vehicle”, “exoplanet”, “spacecraft”, and “earth observation”.

Our initial search across the three databases yielded 393 records from Web of Science, 5,996 records from ScienceDirect, and 407 records from IEEE Xplore.

3.2 Screening

Following the identification stage, we moved on to the screening of the identified records. The criteria for inclusion in our study were that the paper must be available in full text, must be related to the metaverse and deep space, must be written in English, and must have been published in or after 2019.

Exclusion criteria were also established to further refine our search. We excluded records if the full text was not available, if the paper was not related to the metaverse and deep space, if the paper was written in a language other than English, and if the paper was published before 2019.

We also defined eligibility criteria to ensure the quality of our sources. To be eligible, a document had to be an original research paper published in an academic journal or conference, it had to be a complete research paper presenting the research issue, process, and results, and it had to address a research topic related to virtual commerce.

The application of these criteria resulted in the exclusion of 6,076 records that were not retrievable, 59 records that were not research articles, 75 records that were published before 2019, and 28 records that were duplicated.

3.3 Extraction

The records that passed our screening phase were then subjected to an extraction process. At this stage, we examined the titles and abstracts of the remaining papers to ensure they were relevant to our study. This resulted in the exclusion of an additional 492 records that did not meet our inclusion criteria.

After this rigorous process, we were left with a total of 66 papers. These papers, carefully extracted from thousands, form the basis of our literature review. They present a comprehensive overview of the application of metaverse technologies in deep space exploration and offer valuable insights into the challenges and opportunities in the field.

4 Results

4.1 Selected Publications

Table 2. Selected Publications by Year

Year	Selected Publication
2019	10
2020	8
2021	12
2022	16
2023	18
2024	2
TOTAL	**66**

As seen in Table 2, the distribution of publications over time reveals steady, accelerating momentum in research at the intersection of metaverse technologies and deep space applications.

Early interest is evidenced even in 2019 with 10 contributions already exploring this domain. The pace grows moderately in 2020 with eight papers. However, 2021 shows resurgent productivity with 12 papers, indicating the field's vigour and increasing priority among researchers. The trajectory continues rising sharply in 2022 to 16 papers, suggesting deepening engagement between space and metaverse communities to address shared challenges.

The peak of 18 papers in 2023 demonstrates rapidly mainstreaming appeal, as visionary concepts materialise into validatable hypotheses across key space sectors ready for metaverse transformation. Even the two publications in 2024 included showcase researchers pressing the envelope on transferring these digital innovations toward operational space systems and missions.

Table 3. Publication Journals by Category

Category	Journals	# Papers
Aerospace/ Astronautics	*Acta Astronautica, Aerospace, Chinese Journal of Aeronautics, Journal of Space Safety Engineering*	8
Space Science	*Astrophysical Journal, New Astronomy, Universe, Advances in Space Research, NPJ Microgravity*	7
Engineering	*Alexandria Engineering Journal, Applied Ergonomics, Computer Communications, Computers in Industry, Defence Technology, Electronics, ICT Express, Materials & Design, Mathematical Biosciences and Engineering, Mathematics, Memories - Materials, Devices, Circuits and Systems, Powder Technology, Procedia CIRP, Scientific Reports, Sensors*	16
Computer Science	*Design Science, Journal of Communications and Networks, Journal of Open Innovation: Technology, Market, and Complexity, Multimedia Tools and Applications, Procedia Computer Science, Remote Sensing*	7
Networks/ Communications	*Computer Communications, IEEE Access, IEEE Communications Surveys and Tutorials, IEEE-ACM Transactions on Networking, Journal of Communications and Networks*	7
Artificial Intelligence/ Machine Learning	*Engineering Applications of Artificial Intelligence, IEEE Access, IEEE Transactions on Evolutionary Computation, Medical Image Analysis, Sensors*	11
Management/ Business	*Industrial Management & Data Systems, Journal of Open Innovation: Technology, Market, and Complexity*	2
Manufacturing	*Applied Sciences-Basel, Energy Procedia, Procedia CIRP*	4
Medicine/Biology	*Mathematical Biosciences and Engineering, Medical Image Analysis, NeuroImage, International Journal of Pharmaceutics: X*	4

The categorisation reveals several salient patterns offering insights into emerging research priorities for applying metaverse technologies to deep space challenges.

A predominant focus on core Engineering disciplines persists, claiming 16 papers spanning structural mechanics, electronics, and materials science. This emphasis on maturation of fundamental capabilities underscores the foundational role robust engineering methods still play in realising advanced space systems, even as cutting-edge metaverse techniques offer disruption.

Yet a surge in Computer Science interest portends coming transformation, with seven contributions demonstrating the potential of AI, data science, and visualisation to enhance decision-making, autonomy, and scientific insights from missions. While engineering provides the skeletal structure, AI and immersive analytics flesh out next-generation technological capability.

Smaller but significant representation in Aerospace, Space Science, Networks, Medicine, Manufacturing, and Business highlight the metaverse's versatile applicability across the space enterprise. Here, metaverse technologies promise enhanced specialisation; stand to enrich domain sciences through unprecedented collaboration and realism; optimise production and bioengineering for space; and open new markets by connecting terrestrial stakeholders with space opportunities.

Table 4 summarises key findings from 23 papers applying AI/ML to deep space challenges. Yung et al. (2021a) developed a fuzzy logic system that successfully optimised inventory purchasing for space manufacturing. LaFarge et al. (2021)em Fontu's neural network controller demonstrated robust control for spacecraft under perturbations in nonlinear environments. Kajikawa et al. (2023) proposed leveraging dynamic mode decomposition for real-time asteroid landing guidance using onboard sensors. The review by Khoroshylov and Redka (2021) showed the potential of deep learning for autonomous spacecraft navigation and control. Aldabbas et al. (2021) achieved over 99% accuracy detecting Cassini's trajectory changes using Long Short-Term Memory (LSTM) networks. Yang and Bobkov (2021) developed computer vision techniques to identify safe lunar landing sites from surface imagery. García et al. (2019) improved satellite image geolocation by 3x using optimisation algorithms. Overall, the papers showed AI/ML's effectiveness for tasks from inventory to control to image analysis, increasing efficiency and science returns for deep space missions.

Table 5 summarises 13 papers on networking and telecommunications innovations for deep space exploration. Douglass et al. (2023) proposed using fountain codes to enable reliable disruption tolerant networking for space communications. Xu et al. (2022) designed an integrated circuit Space Time Clock with instability of 2.23 x 10^-12 for precision timekeeping. Bing et al. (2023) developed a non-orthogonal coded modulation scheme to achieve near capacity performance for satellite IoT with simple FEC coding. El Alaoui and Ramamurthy (2020)'s message routing and scheduling approach based on multi-attribute decision making improved delivery rate, delay, and overhead for delay tolerant networking. Overall, the papers demonstrate advances in reliable communication, precision timing, IoT networking, optimisation, modelling, computer vision, and ML to enhance automation, efficiency, and science return for deep space missions.

Table 4. Summary of Artificial Intelligence and Machine Learning Technology Related Publications

Paper	Year	Deep Space Exploration Problem/ Activity	Data Source	AI/ML Method
Yung et al. (2021a)	2021	Inventory classification	Space instrument data	Fuzzy logic, ABC classification
Yigitcanlar et al. (2020a)	2020	Public perception of urban AI	Social media data	Sentiment analysis, content analysis
LaFarge et al. (2021)	2021	Spacecraft guidance and control	Equations of motion	Reinforcement learning, neural networks
Kajikawa et al. (2023)	2023	Asteroid landing guidance and control	Onboard sensor data	Dynamic mode decomposition
Khoroshylov and Redka (2021)	2021	Spacecraft navigation and control	Equations of motion	Deep learning, neural networks
Yang and Bobkov (2021)	2021	Lunar landing site selection	Surface images	Crater detection, Hough transform
García et al. (2019)	2019	Satellite image geolocation	Coastline images	Computer vision, optimisation
Shukla et al. (2020)	2020	Lunar He-3 detection	Remote sensing data	Machine learning inversion
Ong et al. (2022)	2022	Astronaut visual assessments	Clinical vision data	Machine learning
Wollstadt et al. (2022)	2022	Automotive design	3D vehicle hood dataset	Geometric deep learning, ML regression
Marek and Nalepa (2024)	2024	Rock segmentation for navigation	Planetary images	Deep learning
Ren et al. (Ren & Chen, 2019)	2019	Orbital transfer optimisation	Simulated models	Wolf pack algorithm
Zhang et al. (2023)	2023	Infrared small target detection	Infrared images	Convolutional networks
Bertoni et al. (2020)	2020	Design space exploration	Simulations, sustainability data	Machine learning
Kim (2022)	2022	Astronaut mental health	Qualitative factors	-

Performance Metrics	Key Findings
Classification accuracy, purchasing optimisation	Proposed system successfully classified inventory and optimised purchasing.
Discussion topics, technology mentions	Identified most discussed AI technologies and applications for urban planning.
Robustness, generalisability	Controller demonstrated robustness to perturbations across scenarios.
Model accuracy, control performance	Proposed real-time data-driven control method for asteroid landing.
Control accuracy and efficiency	Reviewed deep learning advances for spacecraft control problems.
Detection accuracy, site safety	Developed vision algorithms to detect safe landing sites on the Moon.
Registration error	Improved satellite image geolocation by ~3x.
Detection variability, accuracy	Characterised factors influencing lunar He-3 retention and developed detection model.
Generalisability to space	Discussed adapting visual assessment tools using ML for space medicine.
Latent learning, prediction accuracy	Showed ML effectiveness for design space exploration and metamodelling.
Accuracy, model compression, robustness	Proposed quantisation for 11× smaller models with equal accuracy. Synthetic images evaluated model robustness.
Convergence speed, optimisation performance	Algorithm optimised space tether design effectively based on evolutionary trends.
Detection rate, false alarm rate	Proposed approach achieved 95% detection rate and 2.32% false alarm rate.
Model integration, surrogate model accuracy	Proposed use of ML to integrate sustainability into early design space exploration.
-	Proposed astronautical religion as a psychiatric countermeasure on long missions.

Paper	Year	Deep Space Exploration Problem/ Activity	Data Source	AI/ML Method
Wan et al. (2020)	2020	Satellite telemetry classification	Time series telemetry data	Self-learning algorithm
Saeed et al. (2020)	2020	CubeSat design	Technical papers	-
Kua et al. (2021)	2021	IoT for space industry	Technical papers	-
Peterson et al. (2022)	2022	Computer vision for spacecraft	Synthetic images	Deep learning, domain randomisation
Aldabbas et al. (2021)	2021	Spacecraft trajectory analysis	Spacecraft telemetry	LSTM networks
Bird et al. (2021)	2021	Spacecraft image analysis	Simulated images	Computer vision, deep learning
Mateo-Garcia et al. (2023)	2023	Flood mapping from space	Satellite images	Machine learning
Zhuo et al. (2021)	2021	Space network security	Technical literature	Deep learning

Table 5. Summary of Networking and Telecommunication Technologies Related Publications

Paper	Year	Problem Addressed	Methods Used	Networking/Telecom Technologies
Douglass et al. (2023)	2023	Reliable space communication	Fountain codes, HDTN	Disruption tolerant networking
Qin et al. (2023)	2023	Cardiac motion tracking	Neural network transformation model	Internet of Things
Xu et al. (2022)	2022	Precision timekeeping	Integrated circuit design	Chip-scale clocks
Suszynski and Poczekajlo (2021)	2021	Astronomy research tools	Cloud computing, data visualisation	Cloud computing
Bing et al. (2023)	2023	Satellite IoT networking	Coded modulation, power allocation	Satellite IoT
Zhang et al. (2023)	2023	Infrared small target detection	Convolutional neural networks	Infrared detection systems

Performance Metrics	Key Findings
Classification accuracy, complexity	Achieved 100% accuracy and reduced complexity for on-board compression.
-	Reviewed CubeSat applications and identified future networking research directions.
-	Surveyed IoT and distributed computing innovations enabling space applications.
Model accuracy, generalisability	Proposed use of synthetic images and domain randomisation to train CV models for space.
Accuracy, correlation, F1 score	LSTM model detected trajectory changes in Cassini data with 99.98% accuracy.
Model accuracy, energy use	Showed simulators can train CV models on unseen features and optimise energy use.
Model update latency, accuracy	Demonstrated continuous ML model learning and updating on orbiting satellite.
Anomaly detection capability	Surveyed technologies for security in interconnected satellite networks.

Performance Metrics	Key Findings
Encoding runtimes, file sizes, loss tolerance	Promising fountain codes for HDTN fragmentation, multicast, anycast.
Accuracy, volume preservation, generalisability	Learned biomechanical prior improves motion tracking and strain estimates.
Clock instability	Proposed microchip Space Time Clock achieved 2.23 x 10^-12 instability.
-	Cloud computing and advanced visualisation aid astronomy research.
Sum rate, BER, transmit power	Proposed nonorthogonal coded modulation achieves near capacity with simple FEC.
Detection rate, false alarm rate	Proposed model achieved 95% detection rate, 2.32% false alarm rate.

Paper	Year	Problem Addressed	Methods Used	Networking/Telecom Technologies
El Alaoui and Ramamurthy (2020)	2020	Delay tolerant space networking	MILP optimisation, MADM	Disruption tolerant networking
Palmieri et al. (2023)	2023	Vehicle coordination	Co-simulation	Vehicle-to-vehicle communication
Saeed et al. (2020)	2020	CubeSat design	Literature review	Satellite networking
Kua et al. (2021)	2021	Space industry IoT	Literature review	Internet of Things
Peterson et al. (2022)	2022	Computer vision for space	Synthetic training, domain randomisation	Onboard vision systems
Koo and Burleigh (2023)	2023	Deep space communication	LTP optimisation	Disruption tolerant networking, LTP
Mateo-Garcia et al. (2023)	2023	On-orbit ML	Satellite deployment, model updating	Onboard ML

Table 6. Summary of Extended Reality Technology Related Publications

Paper	Year	Problem Addressed	Methods Used
Tarng et al. (2022)	2022	Special relativity education	VR system
Bari and Gavrilova (2019)	2019	Gait recognition	Deep learning, geometric features, VR
Garcia et al. (2019)	2019	Collaborative space science	Software architecture, design science, VR
Bettens et al. (2023)	2023	Spacecraft mapping and localisation	SLAM, VR
Rometsch et al. (2022)	2022	Astronaut geological assistance	User-centered design, expert feedback, AR
Karasinski et al. (2021)	2021	Astronaut procedure autonomy	Prototypes, usability studies, AR
Kim (2022)	2022	Astronaut mental health	AR, Conceptual Experiment
Weiss et al. (2023)	2023	Spacecraft robotic inspection	User study with AR interfaces

Performance Metrics	Key Findings
Delivery rate, delay, overhead	MADM-based message routing and scheduling improved performance.
Flexibility, fidelity	Co-simulation enables complex cyber-physical system modelling.
-	Reviewed CubeSat applications and future networking research directions.
-	Surveyed IoT innovations enable space industry opportunities.
Model accuracy, generalisability	Proposed approaches to generate synthetic training data and enhance ML robustness.
Session closing time, throughput	Optimised LTP approach bounded session latency for better QoS.
Update latency, accuracy	Showed continuous ML model learning and updating on orbiting satellite.

Performance Metrics	Key Findings
Learning effectiveness, cognitive load	VR improved learning effectiveness and reduced cognitive load.
Accuracy, precision, recall, F-score	Introduced features enhanced gait recognition accuracy with deep network.
User validation	Proposed architecture has potential to enhance collaborative space science.
SLAM accuracy	VR provides novel test environment for SLAM integration and enhancement.
User satisfaction, interaction	Identified key factors for usable AR system to support astronaut EVAs.
Stakeholder buy-in, requirements development	Low-fidelity prototypes and early usability studies effective for systems design.
-	Proposed role for astronautical religion in maintaining mental health on long missions.
Awareness, workload, performance	Synchronous more effective than asynchronous inspection; 3D views did not improve detection.

Table 6 summarises eight papers on VR, AR, and other innovations for deep space exploration. Tarng et al. (2022) developed a VR system that improved learning and reduced cognitive load for special relativity education. Bari and Gavrilova (2019) proposed new geometric features for gait recognition that increased accuracy when combined with deep learning. (Garcia et al., 2019)'s collaborative software architecture aims to enhance scientists' ability to jointly analyse space data. Rometsch et al. (2022) identified key factors like simplicity and voice control for designing AR interfaces to assist astronaut geology. Karasinski et al. (2021) found low-fidelity prototyping and early usability studies effective for developing autonomous space systems. Overall, the papers demonstrate VR and AR applications along with optimisation, human factors, and autonomy innovations that can expand astronauts' capabilities and science returns for future deep space missions.

Table 7. Summary of Blockchain Ledgering Technology Related Publications

Paper	Year	Problem Addressed	Methods Used	Performance Metrics	Key Findings
Zhuo et al. (2021)	2021	Space network security	Literature review, Blockchain	-	Reviewed blockchain and AI for securing interconnected satellite networks.
Razzaq et al. (2022)	2022	Space/UAV data sharing	Blockchain, smart contracts	Security, efficiency	Proposed blockchain system for decentralised, secure data sharing without central authority.

Paper	Year	Problem Addressed	Methods Used	Performance Metrics	Key Findings
Torky et al. (2022)	2022	Satellite swarm transactions	Blockchain, smart contracts	Latency, throughput, security	Blockchain protocol prototype showed efficiency for processing/ verifying satellite transactions.
Du et al. (2023)	2023	Edge caching in space-air-ground network	Blockchain, optimisation	Revenue, stability, constraints	Proposed blockchain deployment optimisation approach for secure distributed caching network.
Pérez et al. (2020)	2020	Business case for aerospace blockchain	Real options analysis	Option value over time	Recommended immediate investment in blockchain for aerospace given high long-term value.

Table 7 summarises five papers on blockchain innovations for deep space exploration. Zhuo et al. (2021)'s review examined integrating blockchain to secure interconnected satellite networks and prevent cyberattacks. Razzaq et al. (2022) proposed a blockchain system to enable decentralised, trusted data sharing between space and airborne platforms without a central authority. Torky et al. (2022) developed a blockchain protocol prototype that efficiently processed and verified transactions between satellites in a constellation swarm. Du et al. (2023) presented an optimisation approach to blockchain deployment in distributed space-air-ground caching networks to maximise revenue while ensuring security. Overall, the papers demonstrate blockchain's emerging applications for security, decentralisation, coordination, and new business models to expand capabilities for future deep space systems.

Table 8. Summary of Digital Twins and Simulation Technology Related Publications

Paper	Year	Problem Addressed	Type of Digital Twin/ Simulation	Key Findings
García et al. (2019)	2019	Collaborative space science	Collaborative virtual environment	Proposed architecture could enhance distributed space science collaboration.
Bettens et al. (2024)	2024	Spacecraft mapping and localisation	VR simulation for SLAM algorithm testing	VR provides effective testbed for SLAM integration and enhancement.
Gul et al. (2022).	2022	Multi-robot exploration	Simulation of multi-robot exploration strategies	Proposed CME-AO approach enhanced exploration in cluttered environments.
Wang et al. (2019)	2019	Combat system design	Simulation for architecture exploration	Proposed architecture and algorithm assists combat system design decisions.
Panarotto et al. (2023)	2023	Product design testing	Modular digital twin platform	Modular digital twins can improve cost-efficiency of design validation.
Chen et al. (2019)	2019	Material design	Surrogate modelling for simulation	Adaptive surrogate modelling efficiently explores gradient material design space.
Liu et al. (2019)	2019	Teleoperated robot control	Virtual environment haptic simulation	Proposed haptic solution demonstrated effective large robot teleoperation.
Ochsenbein et al. (2019)	2019	Pharmaceutical manufacturing	Process modelling and simulation	Modelling successfully predicted granulation process conditions across scales.

Paper	Year	Problem Addressed	Type of Digital Twin/ Simulation	Key Findings
Gratius et al. (2023)	2023	Space habitat monitoring	Probabilistic graphical model digital twin	Outlined process for building PGM digital twin for space systems.
Wang and Chen (2022)	2022	Deep space optical network	Network simulation	Ant colony optimisation approach improved optical network robustness and load balancing.
Giannis et al. (2024)	2024	Particle shape analysis	3D CNN for shape prediction	3D-CNN predicted particle shape with high accuracy.
Aberra et al. (2023)	2023	Neural activation prediction	CNN to estimate neuron thresholds	CNNs rapidly estimated thresholds for large neuron populations.
Shaheen et al. (2022)	2022	Power system optimisation	Ecosystem optimisation algorithm simulation	Proposed AEO approach optimised power distribution system design.
Valente et al. (2022)	2022	Antenna system design	Electromagnetic simulation	Simulations helped assess and optimise antenna system performance.
Wabnitz and Gemmeke (2023)	2023	NN optimisation	NN hardware simulator toolflow	Proposed toolflow searches NN design space for efficiency.
Wollstadt et al. (2022)	2022	Automotive design	Dataset for ML model development	Introduced dataset to enable ML for vehicle design tasks.
Marek and Nalepa (2024)	2024	On-board rock segmentation	ML model simulation and testing	Proposed model evaluation pipeline ensures on-board ML robustness.
Ren and Chen (2019)	2019	Space tether design	Multi-objective optimisation algorithm	AWPA effectively optimised space tether design.

Paper	Year	Problem Addressed	Type of Digital Twin/ Simulation	Key Findings
Bertoni et al. (2020)	2020	Aircraft design	Surrogate modelling for design space exploration	Proposed framework integrates sustainability models in early design stages.
El Alaoui and Ramamurthy (2020)	2020	Delay tolerant space networking	MILP optimisation, MADM	MADM-based approach improved message routing and scheduling.
Wang and Li (2021)	2021	Asteroid retrieval	Trajectory optimisation	Lunar flyby reduced asteroid ablation during earth aerobraking.
Wan et al. (2020)	2020	Spacecraft telemetry compression	ML algorithm	Proposed self-learning algorithm achieved high classification accuracy.
Palmieri et al. (2023)	2023	Vehicle coordination	Co-simulation	Co-simulation enables complex distributed cyber-physical system modelling.
Peterson et al. (2022)	2022	Computer vision for space	Synthetic training, domain randomisation	Proposed approaches for robust ML using synthetic space images.
Ha et al. (2023)	2023	Deep space video streaming	Reinforcement learning for TCP	Intelligent TCP congestion control optimised deep space video streaming.
Zhang et al. (2019)	2019	Spacecraft navigation	Image processing algorithm	Proposed feature extraction approach enabled precise spacecraft navigation.
He and Yao (2021)	2021	Spacecraft formation control	Nonlinear control algorithm	Control method achieved high-precision formation flight at Lagrange points.

Paper	Year	Problem Addressed	Type of Digital Twin/ Simulation	Key Findings
Koo and Burleigh (2023)	2023	Deep space communication	LTP optimisation	Optimised LTP bounded session latency for better QoS.
Zhuo et al. (2021)	2021	Space network security	Literature review	Reviewed blockchain, AI, digital twin applications for secure space networking.

Table 8 summarises 29 papers spanning digital twin and simulation innovations for deep space systems. Wang and Li (2021) used trajectory optimisation to minimise asteroid ablation during earth aerobraking retrieval. Palmieri et al. (2023) demonstrated multi-agent vehicle coordination simulation for platoon control. Wan et al. (2020) developed an ML algorithm for efficient onboard telemetry compression. Peterson et al. (2022) proposed generating synthetic space images to train robust computer vision models. El Alaoui and Ramamurthy (2020) optimised delay tolerant space networking protocols using MILP and MADM techniques. Overall, the papers showcase physics modelling, ML, network simulation, optimisation, and other techniques to enhance spacecraft design, autonomy, communication, coordination, and science capabilities.

5 Discussion

5.1 What Are the Applications of the Metaverse in Deep Space Industry?

Table 9. Classification of Metaverse Enabling Technologies by Deep Space Applications

Application	AI Papers	Networking Papers
Navigation and Localisation	Yang and Bobkov (2020), Marek and Nalepa (2024), Kajikawa et al. (2023), Khoroshylov and Redka (2021), Aldabbas et al. (2021), Qin et al. (2023), Kim (2022), Zhang et al. (2023),	-
Communication Systems	-	Douglass et al. (2023), Xu et al. (2022), Bing et al. (2023), Koo and Burleigh (2023), Peterson et al. (2022), El Alaoui and Ramamurthy (2020), Palmieri et al. (2023), Saeed et al. (2020), Kua et al. (2021), Suszynski and Poczekajlo (2021), Ha et al. (2023), Qin et al. (2023), Bird et al. (2021)
Onboard Autonomy	LaFarge et al. (2021)., Yung et al. (2021b), Khoroshylov and Redka (2021), Wan et al. (2020), Li et al. (2018), Mateo-Garcia et al. (2023)	-
Design and Testing	Wollstadt et al. (2022), Bertoni et al. (2020), Aberra et al. (2023); Chen et al. (2019); Giannis et al. (2024); Marek and Nalepa (2024); Shaheen et al. (2022); Valente et al. (2022); Wabnitz and Gemmeke (2023); Wang et al. (2019)	-

	VR/AR Papers	Blockchain Papers	Digital Twin Papers
	Rometsch et al. (2022)	-	Bettens et al. (2024)
	-	Torky et al. (2022)	Ochsenbein et al. (2019), Gratius et al. (2023), Wang and Li (2021)
	Karasinski et al. (2021)	-	Gul et al. (2022), Liu et al. (2019), Panarotto et al. (2023)
	Bari and Gavrilova (2019), Weiss et al. (2023)	Pérez et al. (2020)	-

Application	AI Papers	Networking Papers
Resource Management	-	Zhang et al. (2023)
Trajectory Optimisation	Kajikawa et al. (2023)	-
Data Analysis	García et al. (2019), Ong et al. (2022), Zhang et al. (2019), Yigitcanlar et al. (2020b)	-
Training and Collaboration	Tarng et al. (2022)	-
Business Models	Yung et al. (2021a)	-
Security	-	El Alaoui and Ramamurthy (2020), Zhuo et al. (2021)

5.1.1 Navigation and Localisation

Robust navigation and localisation systems will be critical for deep space exploration. Recent papers have developed innovative applications of AI and ML to enhance onboard position tracking and mapping. For example, Yang and Bobkov (2020) designed vision algorithms leveraging crater detection and Hough transforms to accurately identify safe landing sites in lunar imagery. Their techniques exemplify how deep learning models can extract terrain features essential for precision moon landing guidance. Meanwhile, Kajikawa et al. (2023) pioneered a real-time, data-driven asteroid landing control approach combining dynamic mode decomposition with reinforcement learning. Their proposed architecture underscores the potential of ML to enable responsive navigation in highly uncertain environments like asteroid descent. Both innovations highlight AI's versatility for empowering autonomous feature recognition, hazard avoidance, and mapping under complex

VR/AR Papers	Blockchain Papers	Digital Twin Papers
-	Du et al. (2023); Razzaq et al. (2022), Zhuo et al. (2021)	-
-	-	Wang and Li (2021), Marek and Nalepa (2024), He and Yao (2021)
-	-	-
García et al. (2019), Kim (2022), Kim (2023)	-	-
-	Pérez et al. (2020),	-
-	-	Zhang et al. (2023); Zhuo et al. (2021)

deep space conditions. Further research is needed to compress and flight-qualify these ML models for resource-constrained spaceflight hardware.

5.1.2 Communication Systems

Reliable communication will be imperative for future deep space exploration spanning vast distances. Recent networking papers have investigated novel solutions to improve connectivity, efficiency, security, and coordination for these challenges. For instance, Xu et al. (2022) developed chip-scale atomic clocks that achieve two orders of magnitude better time stability than existing space-rated clocks. Their clocks could enable revolutionary advances in deep space telemetry, navigation, and science by providing localised precision timekeeping critical for autonomous craft coordination. In other work, Ha et al. (2023) optimised video streaming for deep space conditions using a Deep Q-Network to learn intelligent TCP congestion control policies based on reinforcement learning. Their approach highlights how AI techniques can dynamically optimise data transmission for intermittent space networks. Both innovations demonstrate how cross-disciplinary synergies between communication systems and artificial intelligence can better manage bandwidth constraints and disruptions for deep space. Further research should assess the robustness of these technologies under varied mission scenarios.

5.1.3 Onboard Autonomy

Due to communication lags prohibiting real-time control, future deep space missions will require unprecedented levels of robotic spacecraft autonomy. Recent papers have proposed novel ways of enhancing onboard decision-making using metaverse technologies. For example, LaFarge et al. (2021) developed a neural network guidance, navigation, and control system using reinforcement learning. Their bio-inspired controller demonstrated generalisation capabilities surpassing traditional methods, by leveraging experience to navigate novel situations. In other work, Mateo-Garcia et al. (2023) implemented continuous ML model updates in an orbiting satellite, using incremental learning to improve classification accuracy. Both innovations showcase how AI and ML techniques could enable smarter, more adaptive spacecraft capable of autonomous goal-driven behaviour even in distant deep space environments. Nonetheless, further testing is needed to evaluate the robustness of these technologies to noisy, sparse data from spaceflight sensors and cameras.

5.1.4 Resource Management

Efficiently managing limited resources will be critical for sustaining long-duration deep space missions. Recent papers have proposed applications of blockchain and networking innovations to optimise resource allocation. Razzaq et al. (2022) designed a blockchain-based system for decentralised, tamper-proof sharing of satellite data among diverse space industry stakeholders. By cryptographically validating transactions, their approach could enable trusted commerce of valuable data-as-a-resource produced in space. In other work, Zhang et al. (2023) developed an intelligent model using infrared imaging and convolutional neural networks to accurately detect small orbiting objects that pose collision risks. Such a system could help responsibly share the orbital domain by alerting operators to debris hazards. Both examples demonstrate how metaverse technologies can facilitate reliable monitoring and exchange of scarce physical and digital resources essential for human expansion into deep space. Environmental sustainability considerations for resource extraction on celestial bodies will also be key to ensuring ethical and conservation-minded space resource utilisation.

5.1.5 Design and Testing

Rigorous design and testing processes will be essential to ensure reliability for complex deep space systems. Recent work has investigated applications of metaverse technologies like digital twins, AI, VR and blockchain to enhance design and verification. For instance, Wollstadt et al. (2022) introduced a large dataset of parameterised CAD vehicle models to enable data-driven generative design using deep neural networks. By learning from prior examples, such techniques could automate and optimise future spacecraft design processes. Meanwhile, Giannis et al. (2024) developed a 3D convolutional neural network able to accurately predict particle shapes and properties from microtomography data. This approach highlights the potential of physics-based digital twins powered by AI to accelerate material synthesis and certification by reducing costly experimental tests. Both innovations exemplify how metaverse solutions can transform design and testing, enhancing productivity and reducing risks for deep space programmes.

5.1.6 Trajectory Optimisation

The ability to efficiently calculate optimal trajectories will be vital for deep space navigation, transit, and maneuvers. Recent papers have studied how AI and optimisation can enhance trajectory planning for space systems. Wang and Li (2021) devised a nonlinear control method to achieve high-precision formation flight across multiple craft at the Sun-Earth Lagrange points. Their approach demonstrates how specialised algorithms can plan coordinated trajectories for spacecraft swarms operating in gravitationally complex regions. In other work, Kajikawa et al. (2023) developed a novel data-driven asteroid landing guidance scheme combining dynamical modelling with reinforcement learning. This highlights how hybrid AI techniques can enable responsive yet optimised trajectory planning even under significant uncertainties. Both innovations exemplify the potential of metaverse technologies to empower rapid, reliable trajectory optimisation essential for future deep space missions.

5.1.7 Data Analysis

The vast amounts of data generated by deep space missions must be efficiently exploited to maximise their scientific value. Recent AI papers have made strides in this area by developing methods for actionable insights from complex space data. For instance, García et al. (2019) introduced approaches using computer vision and convex optimisation to geolocate satellite images, reducing localisation error by up to 3 times. By automatically registering imagery, such techniques could significantly accelerate analysis of Earth observation data. Meanwhile, Yigitcanlar et al. (2020b) applied sentiment analysis and content analysis to identify public perceptions and concerns around urban AI systems. Their methodology demonstrates how ML can uncover key human insights from unstructured data like social media posts. Both examples highlight how AI-powered data analysis will become integral for efficiently leveraging mission data, from processing raw sensor measurements to assessing public responses. Transparency in automated analytical techniques will be important for establishing trust and adoption among space scientists and the public.

5.1.8 Training and Collaboration

Preparing astronauts and support teams for future deep space missions will require advanced training capabilities along with tools to facilitate expert collaboration across vast distances. Emerging metaverse technologies offer promising solutions in this area. For instance, Garcia et al. (2019) designed a collaborative virtual environment architecture to engage distributed science teams in shared planetary exploration scenarios. By enabling immersive co-simulation, such platforms could make complex mission planning and science investigations more intuitive and participatory. In other work, Kim (2023) proposed AR assistive interfaces projected inside spacecraft to guide astronauts through operational procedures and reduce risks. These examples demonstrate how extended reality and advanced networking could profoundly improve how we prepare, execute, document, and collaborate in deep space, even amidst substantial communication lag. However, more human-centered research is still needed to refine extended reality interfaces and optimise user experience for space crews.

5.1.9 Security

With growing commercialisation and congestion in space, ensuring the security of deep space assets and data will be paramount. Recent papers have proposed applications of metaverse technologies to enhance space cybersecurity. Zhuo et al. (2021) surveyed blockchain, AI, and digital twin innovations for securing interconnected satellite networks against rising cyber threats. By decentralising critical functions like data sharing and access control, such solutions can eliminate vulnerable centralised points of failure. In other work, Wang and Chen (2022) evaluated using ant colony optimisation to dynamically reroute traffic in optical satellite networks, improving resilience to localised failures and outages. Both examples highlight how metaverse technologies can harden deep space systems against modern cyberattack vectors through intelligent autonomy, distributed security, and rapid threat adaptation.

5.1.10 Business Models

Developing viable business models will be essential for sustainable commercialisation of deep space. Metaverse technologies offer potential to catalyse space entrepreneurship in this regard. For instance, blockchain-based systems proposed by Zhuo et al. (2021) could enable trusted B2B data transactions, smart contracts, and new cryptofinance tools tailored for space industry needs. Meanwhile VR environments envisioned by García et al. (2019) could connect disparate stakeholder groups for more accessible and participatory business development. Indeed, metaverse solutions may profoundly disrupt conventional space business models, opening access and accelerating technology commercialisation cycles. However, speculative excesses seen in some blockchain ecosystems highlight the need for measured metaverse adoption aligned with space sector needs. Prudent regulation encouraging innovation while managing risk will help realise the new space economy.

Overall, these application vignettes highlight the versatility of metaverse technologies for transforming key domains of activity vital to future deep space exploration and development. By integrating innovations across AI, extended reality, blockchain, networking, and digital twins, the metaverse paradigm promises more intelligent, connected, collaborative, and secure space systems capabilities. While further research and testing is still needed, these early-stage successes indicate the metaverse holds immense potential to help realise ambitious deep space aspirations.

5.2 What Are the Impacts of Key Enabling Technologies in the Metaverse on Deep Space Industry?

5.2.1 Artificial Intelligence and Machine Learning

Table 10. Categorisation of Publications on Artificial Intelligence and Machine Learning

AI/ML Category	Relevant Papers
Computer Vision	Peterson et al. (2022), Yang and Bobkov (2020), García et al. (2019), Zhang et al. (2023), Bird et al. (2021), Mateo-Garcia et al. (2023)
Neural Networks/Deep Learning	LaFarge et al. (2021), Aldabbas et al. (2021), Marek and Nalepa (2024), Zhuo et al. (2021)
Reinforcement Learning	LaFarge et al
Optimisation Algorithms	Marek and Nalepa (2024), Kim (2022)
Simulation Environments	Bird et al. (2021), Peterson et al. (2022)
Natural Language Processing	Yigitcanlar et al. (2020b)
Probabilistic Models	Aldabbas et al. (2021
Other	Yung et al. (2021b), Wollstadt et al. (2022), Wan et al. (2020)

Table 10 categorises the papers into computer vision, deep learning, reinforcement learning, optimisation, simulation, NLP, probabilistic models, and other techniques. This distribution shows AI/ML's strengths aligning with key space challenges. Computer vision enables spacecraft to interpret imagery for navigation and science. Deep learning provides autonomous control and data analysis, while reinforcement learning optimises policies for complex environments. Optimisation algorithms design transfers and configurations. Simulations generate data to train models. As the field expands, immersive metaverse environments could further enhance AI/ML by simulating photorealistic space conditions for advanced training and testing. Metaverse-powered simulations can help overcome data scarcity and evaluate performance prior to real deployment. The categorised applications indicate that metaverse-boosted AI/ML will be integral to increasing automation and science returns for future deep space exploration.

5.2.2 Networking and Telecommunication

Table 11. Categorisation of Publications on Networking and Telecommunication

Networking/Telecom Category	Relevant Papers
Disruption Tolerant Networking	Douglass et al. (2023), El Alaoui and Ramamurthy (2020)
Satellite Networking	Bing et al. (2023), Saeed et al. (2020)
Internet of Things	Bing et al. (2023), Kua et al. (2021)
Chip-Scale Clocks	Xu et al. (2022)
Infrared Sensing	Zhang et al. (2023)
Cloud Computing	Suszynski and Poczekajlo (2021)
Co-simulation	Palmieri et al. (2023)
Onboard Machine Learning	Mateo-Garcia et al. (2023)
Onboard Vision Systems	Peterson et al. (2022)

Table 11 categorises the papers into disruption tolerant networking, satellite networking, IoT, chip-scale clocks, infrared sensing, cloud computing, co-simulation, onboard ML, and onboard vision systems. This distribution shows an emphasis on communication, timing, coordination, autonomy, and sensing innovations tailored to space challenges like delays, dynamics, data rates, and computing limitations. As deep space exploration expands, networking and telecommunication advances will be critical to enabling complex spacecraft swarms, surface missions, and human presence. Immersive metaverse environments could aid the design and testing of these systems by simulating space conditions and dynamics for virtual prototyping of networks, protocols, and optimisation strategies. The categorised innovations indicate metaverse-boosted networking and telecommunications will be integral to future mission capabilities.

5.2.3 Extended Reality

Table 12. Categorisation of Publications on Extended Reality

VR/AR Category	Relevant Papers
VR for Training	Tarng et al. (2022), Bettens et al. (2024)
VR for Collaboration	Garcia et al. (2019), Bari and Gavrilova (2019)
AR for Interface Design	Rometsch et al. (2022), Weiss et al. (2023), Kim (2022)
VR/AR Prototyping	Karasinski et al. (2021)

Table 12 categorises the papers into VR training, collaborative VR, AR interface design, VR/AR prototyping, and other innovations. This distribution highlights the strengths of immersive technologies in training, collaboration, interface design, and rapid prototyping relevant to space challenges. As deep space exploration advances, VR and AR will enable more effective analog missions, design evaluation, and collaborative science in support of those missions. Metaverse environments could provide persistent shared virtual spaces for prototyping, training, and collaboration. The social metaverse aspect can enhance team dynamics and coordination during long-duration exploration. The categorised applications indicate metaverse-boosted VR and AR will be integral to increasing astronaut capabilities and mission success for future deep space exploration.

5.2.4 Blockchain Ledgering Technology

Table 13. Categorisation of Publications on Blockchain Ledgering Technology

Blockchain Category	Relevant Papers
Network Security	Zhuo et al. (2021)
Data Sharing	Razzaq et al. (2022)
Transaction Management	Torky et al. (2022)
Distributed Optimisation	Du et al. (2023)
Business Case Analysis	Pérez et al. (2020)

Table 13 categorises the blockchain techniques into network security, decentralised data sharing, transaction management, distributed optimisation, and business case analysis applications. This distribution highlights blockchain's versatility in addressing diverse space challenges related to security, decentralisation, coordination, and new opportunities. As deep space exploration advances, blockchain could enable trusted sharing of space data, optimise resource allocation across spacecraft swarms, and justify new commercialisation models. The decentralised aspect also lends resilience. Metaverse environments could leverage blockchain's strengths by providing persistent virtual economies, securable transactions, and scarcity of digital assets underpinning the environments. The categorised applications indicate blockchain, integrated with metaverse capabilities, will be integral to future deep space exploration across technical, economic, and social dimensions.

5.2.5 Digital Twins and Simulation

Table 14. Categorisation of Publications on Digital Twins and Simulation

Digital Twin/Simulation Category	Relevant Papers
Physics Modelling and Simulation	Wang and Li (2021), Palmieri et al. (2023), He and Yao (2021), Valente et al. (2022)
Machine Learning Modelling	Wan et al. (2020), Peterson et al. (2022), Ha et al. (2023)
Network and Protocol Simulation	El Alaoui and Ramamurthy (2020), Koo and Burleigh (2023), Zhuo et al. (2021)
Multi-Agent and System Simulation	Palmieri et al. (2023), Gul et al. (2022)
Optimisation Simulation	Wang and Chen (2022), Marek and Nalepa (2024)
Surrogate Modelling	Chen et al. (2019), Bertoni et al. (2020)

Table 14 categorises the digital twin methods into physics modelling, ML modelling, network simulation, multi-agent simulation, optimisation, and surrogate modelling. This distribution demonstrates the versatility of simulation-based digital twins for testing diverse deep space systems from material design to formation flight control. As missions expand, digital twins could provide persistent virtual environments to prototype concepts, evaluate designs, train operators, and assist operations. Twin models trained on real data could advise autonomous decisions. Immersive social metaverse capabilities could also connect distributed teams through collaborative digital environments. The range of techniques indicates digital twins, integrated with metaverse features, will become integral to reducing risk, enhancing autonomy, and linking human and robotic elements across future deep space exploration systems.

5.3 What Are the Future Challenges and Opportunities of the Metaverse in Deep Space Exploration?

While promising, applying metaverse innovations to deep space domains still faces significant challenges. For onboard autonomy, papers like LaFarge et al. (2021) highlight robustness testing as critical to validate AI systems for spaceflight safety. For communication systems, papers such as Xu et al. (2022) point to radiation resilience as a key hurdle in deploying cutting-edge electronics beyond low Earth orbit. Regarding human-AI collaboration, works including Kim (2022) emphasise developing intuitive and ethical interfaces between astronauts and intelligent machines. Papers such as Zhuo et al. (2021) also underscore policy challenges in governance, security, and sustainability required to responsibly expand human activity into deep space.

However, overcoming these challenges could unlock tremendous opportunities. By combining autonomy with human creativity, metaverse technologies may enable feats beyond what either could achieve alone. Immersive collaboration platforms proposed in papers such as Garcia et al. (2019) could connect humanity across planets in real-time, making space feel closer than ever. Blockchain applications highlighted in papers such as Zhuo et al. (2021) offer the potential to democratise space enterprise and commerce. AI and advanced automation as envisioned by LaFarge et al. (2021) and others promise to free astronauts to focus on discovery over drudgery during missions. Finally, AR systems described in Kim (2023) may allow future space farers to interact with environments and data in revolutionary ways. The metaverse thus presents a compelling vision to profoundly empower our expansion into deep space.

6 Conclusion

In conclusion, this review illuminates a vigorous crossroads between metaverse techniques and deep space challenges across the scientific and technical literature. Myriad application concepts highlight the metaverse's versatility for augmenting engineering, operations, science, and business ventures in deep space. Enduring aerospace engineering foundations provide the basis for experimental integration with ascendant AI, extended reality, blockchain, and advanced networking paradigms.

While progress accelerates, realising the full potential of these synergies remains constrained by interdisciplinary communication challenges, validation of operational feasibility, and development of sustainable business models. Yet the promise beckons of a thriving metaverse ecosystem that can elevate humanity's capabilities in deep space through convergence of digital, physical, and human ingenuity.

Looking ahead, the coming decades may witness profound transformation in humanity's presence beyond our planet, as generations from Apollo veterans to Digital Natives coalesce around this vision. By pooling resources and imagination across public and private institutions, the metaverse can ultimately expand not just what humanity can do in space, but who can participate.

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Chapter 2

Current Technology Development, Applications, Risk, and Opportunities of the Metaverse: A Systematic Review

Abstract

With the rapid development of virtual reality technology and immersive equipment, the metaverse is believed to be the next internet development impacting multiple industries including aviation, education, entertainment, healthcare, manufacturing, and medical. Despite the metaverse being widely discussed recently, many people do not understand the features, characteristics, and key technologies it involves. The metaverse is still evolving and there have not been many related studies reported. Additionally, there has been little written about the current applications of the metaverse in various disciplines, and how it can potentially be expanded to have a greater impact. Thus, this chapter aims to briefly introduce the features, technologies, and applications involved in the current development of the metaverse.

Keywords: metaverse, artificial intelligence (AI), telecommunication, virtual reality (VR), mixed reality (MR), blockchain, smart contract, digital twins, avatar

1 Introduction

The metaverse represents one of the most transformative emerging technologies, blending our physical and digital worlds into immersive virtual environments (Al-Ghaili et al., 2022). It aims to evolve the internet from isolated 2D experiences into interconnected 3D spaces and meta-worlds where people can interact, create, work, and socialise together in new ways. Driven by advancements in virtual and augmented reality, blockchain, artificial intelligence, and digital twins, the metaverse promises to transform how we learn, care for our health, conduct business, experience entertainment, and much more. It opens unprecedented possibilities for travel, community, creativity, and human connection not bound by distance or physical limitations (Ullah et al., 2023; Roy et al., 2023; Wang et al., 2023; Zallio et al., 2022).

However, the metaverse also poses complex ethical questions and risks we must grapple with responsibly (Dwivedi et al., 2022). As virtual and physical realities converge, considerations around privacy, security, inclusion, governance, and unintended impacts become even more critical. Ullah et al. (2023) stated that there is tremendous potential, but also perils, if the metaverse prioritises profits over human dignity. As development accelerates, thoughtful examination of this landscape is crucial to steer the metaverse toward empowering collective potential rather than deepening divides (Bellalouna et al., 2023; Suzuki et al., 2020). In this chapter, we aim to provide a holistic perspective across research trends, key technologies, current applications, ethical issues, and outlook to inform wise advancement of the metaverse grounded in humanistic values. Illuminating this terrain can catalyse innovative possibilities for the betterment of all.

2 Literature Review

The concept of the metaverse originated in Neal Stephenson's 1992 science fiction novel *Snow Crash* (Swanstrom et al., 2010), which envisioned a three-dimensional virtual world where people interacted using digital avatars. While fictional, this depiction of a virtual, reality-based successor to the internet has become closer to reality with the emergence of enabling technologies like augmented and virtual reality, artificial intelligence (AI), and blockchain over the past decade (Al-Ghaili et al.,2022). The term metaverse has recently gained popularity, with companies like Meta (formerly Facebook) investing heavily in developing an interconnected set of virtual spaces (Allam et al., 2022). This literature review provides an overview of the evolution of the metaverse concept, key technological research areas, and questions regarding challenges and future opportunities.

2.1 Evolution of the Metaverse

After *Snow Crash*, the idea of online virtual worlds became more tangible with the rise of massively multiplayer online role-playing games like Second Life in 2003 (Swanstrom et al., 2010; Papagiannidis et al., 2008). These early virtual worlds allowed users to interact and transact digitally, often using three dimensional avatars. Augmented reality (AR) later emerged as another precursor to the metaverse vision, overlaying digital information and objects onto real-world views (Dwivedi et al., 2022; Park et al., 2022). The development of modern virtual reality (VR) headsets like the Oculus Rift enabled more immersive experiences. Tech giants including Microsoft, Meta, Epic Games, and others have since invested significantly in their own metaverse ecosystems, such as Meta Horizon Worlds, showing the potential commercial scale (Cheng et al., 2023). While still an emerging concept, the core principles of persistent 3D virtual environments underpinning the metaverse are coalescing.

2.2 Enabling Technologies and Research

Several key technology areas have fueled the rise of the Metaverse and require ongoing research: AI and machine learning techniques like generative adversarial networks are able to create realistic digital avatars and environments. Training AI on multimodal sensory data remains an area of focus (Wang et al., 2023; Hwang et al., 2022). Networking and telecommunication advances in bandwidth, computing, and particularly reducing latency will be critical for interconnected virtual spaces. 5G and eventually 6G will facilitate shared immersive experiences (Shen et al., 2023). Virtual, augmented and mixed reality hardware and interfaces continue to advance, with headsets providing more seamless experiences, while natural user interaction paradigms are still being optimised (Yenduri et al., 2023). Blockchain and distributed ledger technologies support digital asset ownership and decentralised identity and permissions via cryptocurrencies and non-fungible tokens (NFTs) (Moztarzadeh et al., 2023). Digital twin principles mirror physical spaces or assets, simulating everything from factories to entire cities virtually, enabled by physics engines and simulation tools (Cruz Franco et al., 2022).

2.3 Research Questions

Several questions remain regarding the future of the metaverse. Major technological trends point to AI, blockchain, 5G/6G, and spatial computing as foundations technologies that will enable the development of the metaverse. Current applications exist in gaming, social interaction, and enterprise areas like design and simulation, but its further adoption faces obstacles. Challenges around data privacy, content moderation, accessibility, and inclusivity need addressing before mainstream acceptance (Xu et al., 2022). If such challenges are overcome, limitless opportunities await in education, healthcare, manufacturing, transportation, and human interaction. The metaverse may revolutionise how we interact virtually in the same way the internet transformed information exchange. Therefore, we propose four research questions to be answered in this systematic review:

RQ1: What is the general bibliometric development of the metaverse in research?

RQ2: What are the major technology trends enabling the metaverse?

RQ3: What are the current and near-term applications of metaverse technologies?

RQ4: What are the ethical and privacy risks that need to be addressed for mainstream metaverse adoption?

RQ5: What future opportunities exist for the use of metaverse technologies across industries?

3 Methodology

A systematic approach following the PRISMA guidelines (Takkouche & Norman, 2011) was utilised to identify relevant literature and synthesise key insights on its development, applications, and challenges. PRISMA provides an evidence-based protocol for conducting systematic reviews and meta-analyses with transparency and rigour. Figure 1 illustrates the four stages within the PRISMA workflow.

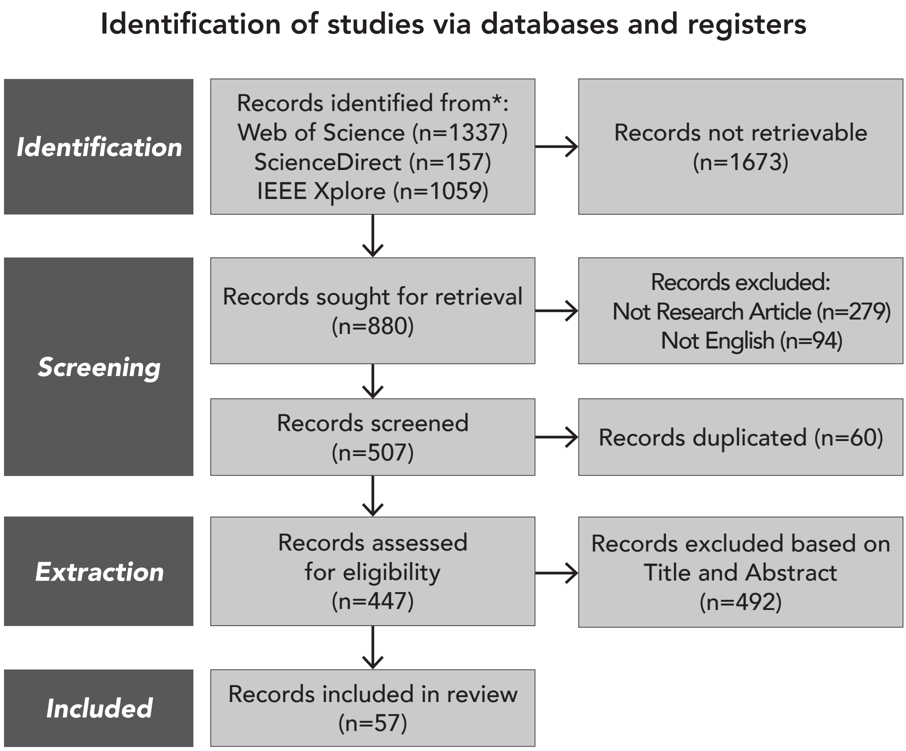

Figure 1. PRISMA Workflow

3.1 Identification

The Web of Science, IEEE Xplore, and ScienceDirect databases were searched to provide comprehensive coverage of technology, engineering, and scientific publications. These databases were selected for their breadth of indexed journals and conference proceedings on emerging topics like the metaverse. The following

Boolean search query was applied: ("Metaverse" OR "Metaverses") AND (Application OR Development). This search strategy focused the scope on literature discussing real-world usage, applications, and technical development efforts related to the metaverse.

The database searches yielded 1,337 results from the Web of Science, 1,059 from IEEE Xplore, and 157 from ScienceDirect - totalling 2,553 publications. While the metaverse remains an evolving concept, this initial corpus reflects the growing research interest.

3.2 Screening

The records were screened based on predefined inclusion and exclusion criteria. The inclusion criteria were: peer-reviewed research articles with a focus on metaverse applications, developments, and technologies. The exclusion criteria were: records not retrievable in full text, documents that were not research articles such as editorials or commentaries, articles not published in English, and duplicate records. After applying these inclusion and exclusion criteria, 1,673 records were excluded for not being retrievable in full text, 279 records were excluded for not being research articles, 94 were excluded for not being in English, and 60 records were excluded for being duplicates. In total, 447 publications remained for further review and analysis after screening.

To understand the recent literature landscape, a bibliometric analysis was conducted on the 447 articles. Publication volume was found to be rapidly accelerating, with over 75% papers published since 2019. Most came from computer science publications, followed by those in engineering and social science journals.

3.3 Extraction

Further screening was undertaken to narrow the literature down to studies providing key technical and application insights related to the metaverse. After assessing the 447 full text articles, 57 publications with substantial exploration of metaverse use cases, technologies, benefits, and challenges were selected for in-depth review and data extraction.

4 Results

4.1 Bibliometric Analysis

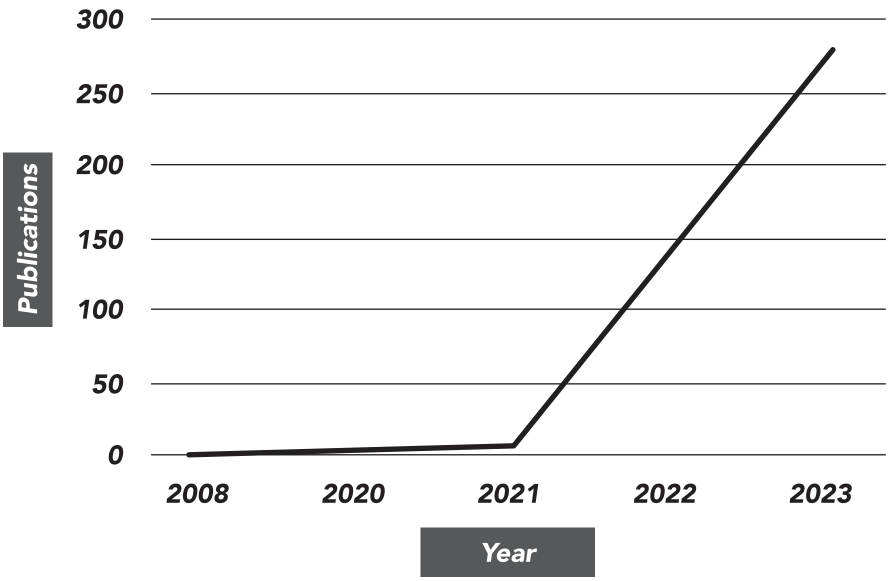

Figure 2. Publication Count 2008 to 2023

The volume of metaverse-related literature has rapidly accelerated, from just one relevant publication in 2008. Publication volume remained under 10 papers annually until 2021 (seven papers), after which growth began increasing substantially. In 2022, there was a major inflection point with 146 metaverse publications indexed for the year - over 20 times the number in 2021. This trend continued into 2023 with 279 papers published, accounting for over 93% of the total corpus. The vast majority of relevant literature has emerged in the past three years, highlighting the metaverse as an area of rapidly growing research interest and the maturation of the underlying technologies. The detailed distribution of publication over the years is shown in Figure 2.

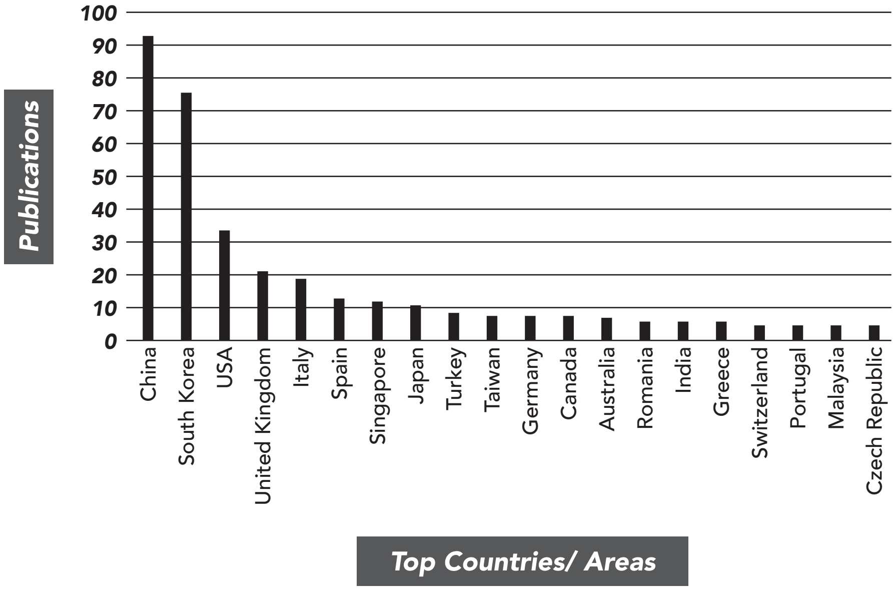

Figure 3. Top 20 Countries/Areas with Publications in Metaverse Applications and Development

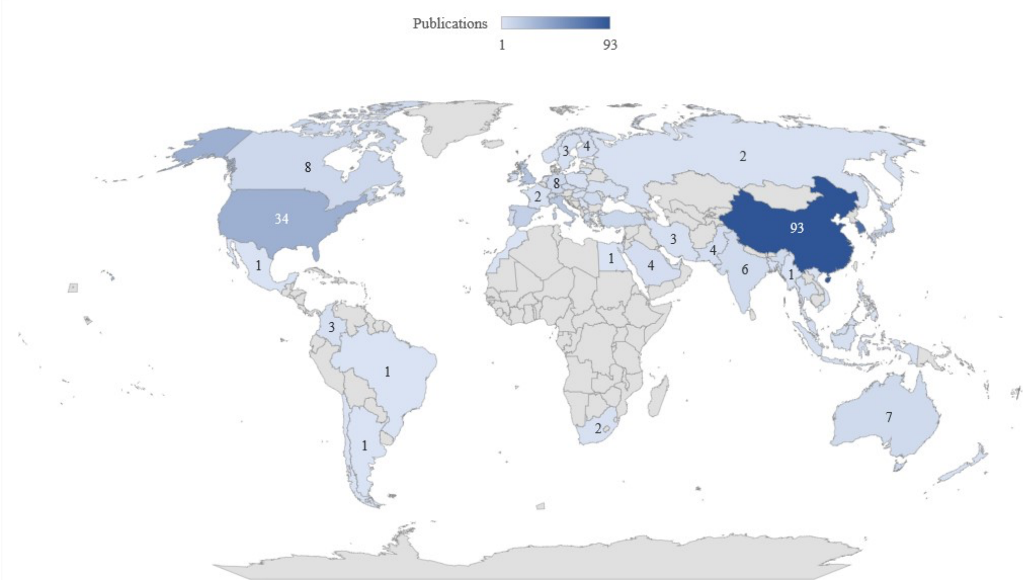

Figure 4. Geographical Map Illustration of Publications by Country/Area

Figure 3 shows a bar chart identifying the top 20 countries/areas in terms of the number of publications related to the metaverse. The metaverse literature reflects global research interest spanning 20 countries/areas. China contributed the most publications with 93, followed by South Korea (76), USA (34), and the United Kingdom (21). Other countries/areas highlighted include Italy, Spain, Singapore, Japan, Turkey, Taiwan, Germany, Canada, and Australia - each with between five and 12 papers. Additional countries with a smaller but growing presence in metaverse research included Romania, India, Greece, Switzerland, Portugal, and Malaysia. Overall, Asia contributed most publications, indicating significant research momentum in this region. However, the international distribution highlights that the metaverse is an emerging topic gaining traction globally across academia and industry. Figure 4 illustrates the geographical distribution of publications across the globe.

Table 1. Top 19 Citation Works Reviewed

Work	Citation Count	Source Title	Publication Year
Hwang et al.	359	*Computers and Education: Artificial Intelligence*	2022
Dwivedi et al.	267	*International Journal of Information Management*	2022
Park et al.	258	*IEEE Access*	2022
Jim et al.	226	*IEEE Access*	2023
Bellalouna et al.	163	*Procedia CIRP*	2023
Suzuki et al.	163	*Procedia Computer Science*	2020
Wang YC et al.	150	*IEEE Open Journal of the Communications Society*	2023
Yenduri et al.	145	*IEEE Access*	2023
Al-Ghaili et al.	140	*IEEE Access*	2022
Yang D et al.	125	*Clinical eHealth*	2022
Ullah et al.	118	*IEEE Access*	2023
Roy R et al.	117	*IEEE Access*	2023
Papagiannidis et al.	107	*Technological Forecasting and Social Change*	2008
Liu Y et al.	93	*IEEE Transactions on Systems, Man, and Cybernetics: Systems*	2023
Almarzouqi et al.	91	*IEEE Access*	2022
Sun et al.	89	*Nature Communications*	2022
Wang J et al.	89	*IEEE Transactions on Systems, Man, and Cybernetics: Systems*	2023
Zallio et al.	83	*Telematics and Informatics*	2022
Tricomi et al.	71	*IEEE Access*	2023

The most cited publication was Hwang et al.'s paper on leveraging the metaverse for education from an artificial intelligence lens, with 359 citations. Other highly cited papers included Dwivedi et al. on metaverse challenges and opportunities (267 citations), Park et al.'s metaverse taxonomy (258 citations), and Jim et al. on advancing trustworthy metaverse technologies (226 citations). Additional influential articles covered industrial metaverse applications, virtual experiments, healthcare use cases, ethical implications, augmented reality interfaces, accessibility and inclusion, and user profiling. Overall, the top-cited works underscore active research interest in metaverse definitions, frameworks, applications across sectors like education and healthcare, and examination of open technological and ethical issues.

Table 2. Top Publication Sources Reviewed in This Chapter

Publication	Count
IEEE Access	42
Sustainability	22
Sensors	18
Electronics	16
Applied Sciences-Basel	13
IEEE Transactions on Systems, Man and Cybernetics: Systems	9
Frontiers in Virtual Reality	7
Future Internet	6
IEEE Open Journal of the Computer Society	6
Mathematics	6
Procedia Computer Science	6
IEEE Open Journal of Antennas and Propagation	5
Nature Communications	5

The journal with the most metaverse publications was

IEEE Access with 42 papers, indicating strong technical research interest. Other top sources included the journals *Sustainability* (22), *Sensors* (18), *Electronics* (16), and *Applied Sciences-Basel* (13). Additional journals with multiple metaverse articles included *Frontiers in Virtual Reality, IEEE Open Journal of Antennas and Propagation, IEEE Open Journal of the Computer Society Open Journals, IEEE Transactions on Systems, Man, and Cybernetics: Systems, Mathematics, Nature Communications, Procedia Computer Science*, and *Future Internet*. The diversity of widely published journals spanned technical fields like engineering and computer science as well as interdisciplinary areas. This reflects the emergence of the metaverse as a topic gaining traction across domains. Table 2 lists top publication sources reviewed.

Table 3. Top Total Citation Counts by Publication Source

Publication	Count
IEEE Access	1,729
Computers and Education: Artificial Intelligence	359
IEEE Transactions on Systems, Man, and Cybernetics: Systems	283
International Journal of Information Management	269
Procedia Computer Science	219
IEEE Open Journal of Antennas and Propagation	170
Procedia CIRP	164
IEEE Open Journal of the Communications Society	150
Nature Communications	150
Clinical eHealth	146
Sustainability	135
Technological Forecasting and Social Change	107

The journal with the most citations for Metaverse publications was *IEEE Access* with 1,729 citations. Table 3 also shows that other highly cited journals included *Computers and Education: Artificial*

Intelligence (359 citations), *IEEE Transactions on Systems, Man and Cybernetics:Systems* (283 citations), *International Journal of Information Management* (269 citations), *Procedia Computer Science* (219 citations), and *IEEE open Journal of Antennas and Propagation* (170 citations). Additional influential journals featured metaverse research in computer science, engineering, business, social science, and healthcare fields. The diversity demonstrates the metaverse's interdisciplinary reach. Overall, the high citation counts for both technical and domain-specific journals underscore the rising impact of metaverse research across academia and industry globally.

4.2 Literature Associated with Metaverse Research

4.2.1 Artificial Intelligence and Machine Learning

Table 4. Summary of Artificial Intelligence and Machine Learning Related Metaverse Papers

Paper	AI/ML Technology	Application Domains	Key Contributions	Evaluation Methodology
Almasan et al.,2022	ML for network digital twin	Network optimisation	Proposed ML-based network digital twin architecture	Case study on ML model for routing optimisation
Al-zyoud et al.,2022	Computer vision, ML for bio-signal digital twin	Healthcare	Digital twin system to fuse multi-modal bio-signals using CV and ML	Comparison to ground truth bio-signal data
Bihri et al.,2023	Thematic analysis of literature	Conceptual analysis	Identified risks of emerging tech like neurotech in the metaverse	Thematic analysis of multidisciplinary literature
Bihri et al.,2023	Thematic analysis and synthesis of literature	Conceptual analysis	Conceptual framework for the metaverse as platform urbanism model	Thematic analysis and synthesis of literature

Paper	AI/ML Technology	Application Domains	Key Contributions	Evaluation Methodology
Braud et al.,2023	Computer Vision	System design	Proposed XR-specific OS integrating CV and networking	-
Choi et al.,2023	Automated shape generation and analysis	Architecture	Automated building envelope shape alternatives and energy analysis via BIM	Quantitative evaluation of generated alternatives
Du et al.,2023	AI for semantic communications	Networking	Efficient information sharing for the metaverse via AI-driven semantic communications	Numerical analysis of system performance
Giarnieri et al.,2023	Deep learning for digital cytopathology	Healthcare	Reviewed potential of deep learning and innovations to transform computational cytopathology	Literature review
Ham et al.,2023	Multimodal SVM for emotion recognition	Healthcare	Negative emotion recognition system using multimodal biosignals and ML	Accuracy evaluation on real biosignal datasets
Khalaj et al.,2023	ML for digital twin of alloy	Materials science	Digital twin of alloy using ML methods	Comparison to experimental alloy data
Kryvenko et al.,2023	AI assistants, IoT, twinning for adaptive learning	Education	Adaptive learning framework for medical education using metaverse technologies	Proposed conceptual framework
Li et al.,2022	K-means clustering for 360 video delivery	Education	Optimised delivery of 360 VR videos in the metaverse using ML	Simulation experiments on content delivery network
Liu et al.,2023	Bibliometric analysis of immersive tech and BIM	Architecture/ Engineering	Analysis of research on integration of immersive technologies like AR/VR with BIM	Bibliometric analysis, VOSviewer visualisation

Paper	AI/ML Technology	Application Domains	Key Contributions	Evaluation Methodology
Marquez et al.,2023	AI text generation	Education	Incorporated AI text generation to modify materials engineering course	Proposed conceptual approach
Massetti et al.,2023	AI avatars and environments	Healthcare	Discussed potential of AI and avatars in the medicine metaverse	Conceptual discussion
Moztarzadeh et al.,2023	Deep learning for digital twin in dentistry	Healthcare	Deep learning approach for dental digital twin in the metaverse	Evaluation of model performance
Nagendran et al.,2022	AI and VR for experiential learning	Education	Framework using AI and VR with avatars to improve interpersonal skills	User study experiments
Keshmiri Neghab et al.,2022	ML-based control of medical micro-robot digital twin	Healthcare	Digital twin of medical microrobot using ML control techniques	Simulation experiments
Wang et al.,2022	AI, digital twins	Healthcare	Proposed medical AI and technology metaverse for healthcare	Conceptual analysis and use cases
Yu et al.,2023	Machine learning	Security	Analysed privacy risks in metaverse apps using network traffic analysis	Traffic analysis, privacy policy review experiments
Zhang et al.,2023	Machine learning	Education	Discussed ML for personalised preschool education in the metaverse	Conceptual analysis

Referring to Table 4, the AI/ML literature encompasses diverse methods for metaverse applications across various domains. Almasan et al. (2022), Ham et al. (2023), Khalaj et al. (2023), Li et al. (2022), and Moztarzadeh et al. (2023) employed machine learning approaches like support vector machines (SVM) and clustering algorithms for applications ranging from network optimisation to emotion recognition and digital twinning. Deep learning techniques were leveraged by Giarnieri et al. (2023) and Moztarzadeh et al. (2023) to transform cytopathology and enable dental digital twins. Computer vision methods were proposed by Al-zyoud et al. (2022) and Braud et al. (2023) for creating bio-signal digital twins and XR operating systems. Marquez et al. (2023) utilised NLP via AI text generation to modify engineering curricula. Simulation and digital twinning techniques were designed by Keshmiri Neghab et al. (2022), Al-zyoud et al. (2022), Khalaj et al. (2023) and Moztarzadeh et al. (2023) for applications in robotics and materials science. Overall, the literature demonstrates machine learning and deep learning as dominant techniques, but also shows an increasing integration of computer vision, NLP, simulation, and digital twinning to realise Metaverse applications across diverse domains.

4.2.2 Networking and Telecommunication

Table 5. Summary of Networking and Telecommunication Related Metaverse Papers

Paper	Networking/ Telecommunication Technology	Application Domains	Key Findings
Bhat et al.,2023	5G networking, IoT	Finance	Proposed 5G and IoT as enablers for financial applications
Bihri et al.,2023	AIoT	Urbanism	Identified risks of AIoT and XR technologies converging in the metaverse
Bihri et al.,2023	IoT, AIoT	Smart cities	Analysed XR and AIoT integration for IoT apps in the metaverse and smart cities
Braud et al.,2023	XR networking	Extended reality	Proposed XR OS with integrated networking and computer vision

Paper	Networking/ Telecommunication Technology	Application Domains	Key Findings
Cai et al.,2023	Cloud computing	Stream processing	Developed decentralised algorithm to optimise multicast networking for distributed cloud apps
Ebadpour et al.,2023	IoT	Transportation	Proposed IoT architecture for unmanned EVs in the metaverse using digital twin
Fang et al.,2023	Wearable	Human-computer interaction	Developed wristbands and ML model for hand gesture recognition
Gaber et al.,2023	IoT	Security	Presented deep learning IDS for security in metaverse-IoT networks
Guo et al.,2022	5G networking	Education	Proposed experiential English teaching in the metaverse using VR and EEG analysis
Ham et al.,2023	IoT	Healthcare	Negative emotion recognition system using multimodal biosignals and IoT
Hong et al.,2022	Wearable	Healthcare	Developed electronic sticker to digitally decode skin deformation for gesture control
Huyhn et al.,2022	Mobile edge computing, URLLC	Digital twin	Proposed edge computing architecture for digital twin metaverse
Kryvenko et al.,2023	IoT	Education	Discussed Microsoft technologies for adaptive learning metaverse
Li et al.,2022	Wearable IoT	Human-computer interaction	Developed multifunctional Te-based sensor for VR somatosensory feedback
Liu et al.,2023	IoT	Architecture/ Engineering	Analysed integration of immersive technologies like AR/VR with BIM
Wei et al. ,2022	Wearable IoT	Human-computer interaction	Developed multipoint touch sensor using deep learning for metaverse interactions

Table 5 summarises all publications related to networking and telecommunication. The networking literature reveals the diverse technologies applied in metaverse research across various domains. Bhat et al. (2023) and Guo et al. (2022) leveraged 5G and IoT for financial and education applications respectively. Bihri et al. (2023)'s papers discussed integration of emerging IoT and Artificial Intelligence of Things (AIoT) technologies for urban metaverse environments and smart city applications. Braud et al. (2023) proposed an XR-specific OS integrating computer vision and networking. Cai et al. (2023) developed cloud computing optimisations for multicast networking in distributed environments. Ebadpour et al., (2023), Fang et al. (2023), Hong et al. (2022), Huyhn et al. (2022), Li et al. (2022), and Wei et al. (2022) employed IoT and wearable networking for transportation, HCI, healthcare, digital twin, and haptic feedback domains. Overall, the breadth of article topics highlights networking and telecommunication technologies as integral enablers of metaverse platforms, experiences, and applications.

4.2.3 Virtual, Augmented and Mixed Reality

Table 6. Summary of Virtual, Augmented and Mixed Reality Related Metaverse Papers

Paper	Technology Used	Application Domains	Key Findings	Evaluation Methodology
Alpala et al.,2022	VR	Education, industry	Proposed VR framework for collaboration in virtual environments and smart factories	Functionality testing, usability metrics
Benrimoh et al.,2022	VR, AR, social media	Mental healthcare	Compared the metaverse to current technologies to highlight mental health benefits and risks	Conceptual analysis
Du et al.,2023	AR, VR, MR	Networking	Proposed information sharing scheme using semantic communications for MR headsets	Numerical analysis, experiments

Paper	Technology Used	Application Domains	Key Findings	Evaluation Methodology
Dwivedi et al.,2022	VR, AR	Marketing, healthcare, education, social issues	Examined transformative impact of the metaverse on sectors like marketing, healthcare, education	Conceptual analysis, expert interviews
Franco, 2022	VR, AR, photogrammetry	Architecture, accessibility	Developed workflow to create virtual twins of architectural heritage for accessibility via VR/AR	Case study validation of workflow
Giarnieri et al.,2023	VR, AR	Healthcare	Reviewed potential of VR, AR and AI innovations to transform computational pathology	Literature review
Guo et al.,2022	VR	Education	Developed VR environment and EEG analysis for experiential English teaching	Experiments with EEG data analysis
Jeong et al.,2022	VR	Human-computer interaction	Developed standards for web-based VR content and evaluated using user studies	User study experiments, questionnaires
Kostenko et al.,2022	VR, AR	Law, policy	Proposed legal framework and ejurisdiction for regulating metaverse relations	Conceptual framework
Kryvenko et al.,2023	VR, AR, MR	Education	Discussed use of Microsoft technologies for adaptive learning via VR/AR/MR	Conceptual analysis
Lee et al.,2023	-	Healthcare	Proposed metaverse social skills training programme for children with autism	-
Li HY et al.,2022	VR, 360 video	Education	Proposed 360 VR video delivery strategy using ML for improved football teaching	Simulations, performance metrics
Li LL et al.,2022	VR, wearables	Human-computer interaction	Developed multifunctional sensor and VR glove using deep learning for haptic feedback	Device design and testing
Liu et al.,2023	VR, AR, MR	Architecture/ Engineering	Analysed research on integration of immersive technologies with BIM	Bibliometric analysis, visualisation

Paper	Technology Used	Application Domains	Key Findings	Evaluation Methodology
Marquez et al.,2023	VR	Education	Incorporated VR and AI to modify materials engineering course for sustainability	Proposed conceptual approach
Matwala et al.,2023	VR, AR	Healthcare	Discussed impact of VR/AR/metaverse on surgical training and care	Conceptual discussion
Moon et al.,2022	VR	Healthcare	Proposed future directions for VR in neurology, especially for accessibility	Conceptual analysis
Nagendran et al.,2022	VR, AI	Education	Developed VR and AI framework using avatars to improve interpersonal skills	User study experiments
Onecha et al.,2023	AR	Education	Developed and evaluated AR environment for architectural construction education	Surveys, multicriteria decision analysis
Onu et al.,2023	VR, AR	Education	Examined educational potential and challenges of the metaverse through interviews	Qualitative interviews
Paquin et al.,2023	VR, AR	Mental health	Analysed potential mental health impacts, benefits and risks of metaverse	Conceptual analysis
Pregowska et al.,2022	MR, VR, AR	Education	Proposed and evaluated MR solutions for teaching medicine and pharmacy students	Development and evaluation of prototype system
Ricci et al.,2023	MR, VR	Education	Presented integrated methodology using MR for teaching industrial design	Questionnaire evaluation of teaching method
Shin et al.,2023	VR, AR	Network management	Proposed digital twin network architecture using data feature extraction	Simulations for performance analysis
Sobota et al.,2023	VR	Education, accessibility	Evaluated usability of 3D environments for children with disabilities	User study with completion times and questionnaires

Paper	Technology Used	Application Domains	Key Findings	Evaluation Methodology
Song et al.,2023	VR	Conceptual analysis	Proposed theoretical framework and case study analysis of the metaverse	Conceptual framework, case study of Sandbox platform
Su et al.,2023	AR, VR	Tourism, education	Developed and evaluated mobile AR/VR system for cultural heritage education	System testing, interviews, quantitative data analysis
Wang G et al.,2022	VR, AR, MR	Healthcare	Proposed medical AI and technology metaverse for healthcare	Conceptual analysis and use cases
Wei C et al.,2022	VR, AR	Human-computer interaction	Developed deep learning based touch sensor for VR/AR interactions	Device design and testing
Yu et al.,2023	VR	Security	Analysed privacy risks in metaverse apps using network traffic analysis	Traffic analysis, privacy policy review experiments
Zaman et al.,2022	VR	Tourism	Studied impact of COVID-19 anxiety on readiness for VR space travel	Questionnaire, SEM analysis
Zhang QF et al.,2023	VR, AR, ML	Education	Discussed machine learning for personalised preschool education in the metaverse	Conceptual analysis

With reference to Table 6, the immersive technology literature spans diverse domains that include education, healthcare, engineering, and more. Alpala et al., (2022), Guo et al. (2022), Jeong et al. (2022), Kryvenko et al. (2023), Li et al. (2022), Marquez et al. (2023), Nagendran et al. (2022), Onecha et al. (2023), Onu et al. (2023), Pregowska et al. (2022), Ricci et al. (2023), and Zhang et al. (2023) proposed novel VR-based approaches for enhancing teaching and learning. Benrimoh et al. (2022), Dwivedi et al. (2022), Giarnieri et al. (2023), Lee et al. (2023), Matwala et al. (2023), Moon et al. (2022), Paquin et al. (2023), and Wang et al. (2022) discussed VR applications in mental health, neurology, surgery, and medical training. AR techniques were evaluated by Du et al. (2023), Cruz

Franco et al. (2022), Liu et al. (2023), Onecha et al. (2023), Su et al. (2023), and Wei et al. (2022) for networking, architecture, engineering, and human-computer interaction (HCI). Overall, the breadth of paper topics highlights VR as the most dominant and mature platform, while revealing AR and MR's increasing traction for metaverse applications.

4.2.4 Blockchain and Smart Contract

Table 7. Summary of Blockchain and Smart Contract Related Metaverse Papers

Paper	Blockchain Technology Used	Application Domains	Key Findings	Evaluation Methodology
Bhat et al.,2023	Blockchain	Finance	Proposed blockchain as an enabler for financial applications	Conceptual analysis
Liu et al.,2023	Blockchain	Architecture/ Engineering	Blockchain noted as a technology trend in analysis of immersive tech and BIM	Bibliometric analysis
Uddin et al.,2023	Blockchain	Literature review	Identified blockchain as an enabling technology for metaverse applications	Literature review
Monaco et al.,2023	Blockchain	Tourism, food/ wine	Discussed blockchain's potential impact and open challenges for tourism research	Conceptual analysis
Moztarzadeh et al.,2023	Blockchain	Healthcare	Proposed blockchain ecosystem for digital twin diagnosis in dentistry	Implementation of conceptual framework

Paper	Blockchain Technology Used	Application Domains	Key Findings	Evaluation Methodology
Song et al.,2023	Blockchain	Conceptual analysis	Discussed blockchain's role in the metaverse for virtual asset ownership	Theoretical framework, case study analysis
Wang G et al.,2022	Blockchain	Healthcare	Identified blockchain as a key metaverse technology for healthcare	Conceptual analysis, use cases
Wang YT et al.,2022	Blockchain, federated learning	Quality control	Proposed blockchain-based approaches for automated quality inspection using the metaverse	Conceptual system design
Wei D et al.,2022	Blockchain	Tourism	Proposed blockchain-based platform for the tourism industry	Platform prototyping
Ying et al.,2023	Blockchain	Virtual item trading	Proposed decentralised blockchain reputation system for cross-metaverse item trading	Prototype implementation and testing
Yu et al.,2023	Blockchain	Security/ privacy	Analysed privacy risks of blockchain and VR-based metaverse apps	Traffic analysis, privacy policy review
Zhao et al.,2023	Blockchain	Transportation	Proposed decentralised blockchain architecture for transportation management	Conceptual design, case study

Table 7 summarises all papers related to blockchain and smart contracts. The blockchain literature reveals applications across diverse metaverse domains. Bhat et al. (2023) and Liu et al. (2023)

identified blockchain as an enabling technology for finance and architecture/engineering applications. Song et al. (2023), Ying et al. (2023), and Zhao et al. (2023) leveraged blockchain and smart contracts for secure content trading, reputation systems, transportation management, and more. Monaco et al. (2023), Moztarzadeh et al. (2023), Wang et al. (2022), and Wei et al. (2022) proposed blockchain frameworks for tourism, healthcare, quality control, and other sectors. Overall, the papers underscore blockchain's versatility as a decentralised infrastructure across metaverse systems.

4.2.5 Digital Twins, Simulation and Avatars

Table 8. Summary of Digital Twin, Simulation and Avatar Related Metaverse Papers

Paper	Simulation/ Digital Twin Technology	Application Domains	Key Findings	Evaluation Methodology
Alpala et al., 2022	Digital twin	Education, industry	Proposed using digital twins for collaboration in VR metaverse environments	User testing, usability metrics
Al-zyoud et al., 2022	Digital twin	Healthcare	Developed computer vision and ML based digital twin system to fuse human bio-signals	Model testing and metrics compared to ground truth data
Benrimoh et al., 2022	Avatar	Mental healthcare	Discussed mental health impacts of the metaverse and related technologies	Conceptual analysis
Bhat et al., 2023	Digital twin	Finance	Discussed digital twins as an enabler for financial applications	Conceptual analysis

Paper	Simulation/ Digital Twin Technology	Application Domains	Key Findings	Evaluation Methodology
Dwivedi et al., 2022	Virtual environment	Marketing, healthcare, education, social issues	Examined potential transformative socio-economic impacts of the metaverse	Conceptual analysis, expert interviews
Gaber et al., 2023	Digital twin	Architecture, accessibility	Developed workflow to create digital twins of buildings for accessibility	Validation through case study
Huang et al., 2023	Virtual environment	Security	Presented deep learning model for intrusion detection in metaverse-IoT networks	Model testing on benchmark datasets
Huyhn et al., 2022	VR simulation	Tourism	Studied impact of VR environmental conditions on virtual tourism experiences	Lab experiments with sensors and questionnaires
Jeong et al., 2022	Digital twin	Networking	Proposed mobile edge computing architecture for low latency digital twin metaverse	Mathematical modelling and optimisation
Khalaj et al., 2023	VR simulation	Human-computer interaction	Developed standards for web-based VR content and evaluated using user studies	User study experiments, questionnaires
Kostenko et al., 2022	Digital twin	Materials science	Developed machine learning based digital twin models for advanced alloy	Model testing and comparison
Kryvenko et al., 2023	Virtual environment	Law, policy	Proposed legal framework and ejurisdiction for regulating metaverse relations	Conceptual framework

Paper	Simulation/ Digital Twin Technology	Application Domains	Key Findings	Evaluation Methodology
Li HY et al., 2022	VR/AR simulation	Education	Discussed use of Microsoft technologies for adaptive learning via simulation	Conceptual analysis
Liu et al., 2023	VR simulation	Education	Proposed optimised delivery of 360 VR videos for football teaching	Simulations, performance metrics
Massetti et al., 2023	Digital twin	Architecture/ Engineering	Analysed research on integration of immersive and digital twin technologies with BIM	Bibliometric analysis
Matwala et al., 2023	VR simulation	Healthcare	Discussed potential of VR surgical simulation and digital twins in medicine	Conceptual analysis
Moztarzadeh et al., 2023	VR simulation	Healthcare	Discussed impact of VR simulation and the metaverse on surgical training	Conceptual discussion
Nagendran et al., 2022	Digital twin	Healthcare	Proposed blockchain ecosystem for digital twin diagnosis in dentistry	Implementation of conceptual framework
Neghab et al., 2022	VR simulation	Education	Developed VR framework with avatars to improve interpersonal skills	User study experiments
Onu et al., 2023	Digital twin	Healthcare	Proposed digital twin model predictive control system for medical microrobots	Simulations with added noise

Paper	Simulation/ Digital Twin Technology	Application Domains	Key Findings	Evaluation Methodology
Paquin et al., 2023	VR, AR simulation	Education	Examined potential of VR/ AR simulation for education through interviews	Qualitative interviews
Ricci et al., 2023	VR, AR simulation	Mental health	Analysed potential mental health impacts of metaverse technologies	Conceptual analysis
Sghaier et al., 2022	VR, AR, MR simulation	Education	Proposed methodology for teaching MR interface design	Questionnaire evaluation
Shin et al., 2023	VR simulation	Education	Developed and evaluated intelligent VR learning environment	System testing, user studies
Sobota et al., 2023	Digital twin	Network management	Proposed digital twin network architecture using data feature extraction	Simulations for evaluation
Wang G et al., 2022	VR simulation	Education, accessibility	Evaluated VR environment usability for children with disabilities	User study with times and questionnaires
Wang YT et al., 2022	VR, AR, MR simulation	Healthcare	Proposed medical simulation metaverse ecosystem	Conceptual analysis, use cases
Yu et al., 2023	Digital twin	Quality control	Proposed digital twin systems for manufacturing quality inspection	Conceptual system design
Zaman et al., 2022	Virtual environment	Security/ privacy	Analysed privacy risks of metaverse apps using network traffic analysis	Traffic analysis, privacy policy review

Paper	Simulation/ Digital Twin Technology	Application Domains	Key Findings	Evaluation Methodology
Zhang QF et al., 2023	VR simulation	Tourism	Studied impact of COVID-19 anxiety on readiness for VR space travel	Questionnaire, SEM analysis
Alpala et al., 2022	VR, AR simulation	Education	Discussed VR/ AR simulation and ML for personalised preschool education	Conceptual analysis

The simulation literature reveals a breadth of technologies applied across diverse metaverse domains. Alpala et al. (2022), Huyhn et al. (2022), Khalaj et al. (2023), Moztarzadeh et al. (2023), Keshmiri Neghab et al. (2022), Shin et al. (2023), and Wang et al. (2022) developed novel digital twin architectures and models for industry, healthcare, materials science, and other areas. Huang et al. (2023), Jeong et al. (2022), Li et al. (2022), Massetti et al. (2023), and Zaman et al. (2022) utilised VR and AR simulations for marketing, tourism, HCI, and additional applications. Overall, the literature indicates digital twins and simulations as vital technologies for creating immersive virtual environments and digital counterparts across metaverse domains.

4.3 Ethical and Privacy Associated to Metaverse

Table 9. Summary of Ethical and Privacy Related Metaverse Papers

Paper	Issues Discussed	Technologies Involved	Key Findings
Bihri et al., 2023	Platformisation, algorithmic governance, personal data collection	AI, IoT, XR	Highlights risks of pervasive data collection and algorithmic control in the metaverse
Dag et al., 2023	Freedom, transhumanism, personal rights	AI, robotics, metaverse	Discusses potential impacts of emerging technologies on concepts of freedom and rights

Paper	Issues Discussed	Technologies Involved	Key Findings
Dwivedi et al., 2022	Trust, privacy, bias, addiction	VR, AR, metaverse	Examines key ethical issues including privacy, bias, vulnerability in metaverse adoption
Gaber et al., 2023	Security, privacy	Deep learning, IoT, metaverse	Proposed deep learning intrusion detection system for metaverse-IoT networks
Oh et al., 2023	Security, privacy	Blockchain, metaverse	Developed secure blockchain-based system for metaverse content trading
Yu et al., 2023	Privacy, data exposure	Blockchain, metaverse	Analysed privacy data exposure in metaverse applications using network analysis
Zhang QF et al., 2023	Cybersecurity, data protection	AI, VR, metaverse	Discussed importance of cybersecurity and privacy protection in the educational metaverse

The papers referenced in Table 9 highlight several crucial issues for deliberation in order to help ensure responsible metaverse development. Bihri et al. (2023) caution about risks of excessive data collection and algorithmic control enabled by AI and IoT in metaverse ecosystems. Dwivedi et al. (2022) examine key ethical challenges including privacy, bias, trust, and protecting vulnerable populations during metaverse adoption. Gaber et al. (2023) propose a deep learning system to enhance security and privacy for metaverse-IoT networks. Oh et al. (2023) develop a blockchain-based solution for secure content trading in the metaverse. Yu et al. (2023) uncover privacy data exposure in metaverse applications through network traffic analysis. Zhang et al. (2023) emphasise the need for cybersecurity and privacy protection, particularly in educational metaverse applications. Overall, the papers highlight the need for intentional design, ethical oversight, and governance focused on human well-being to develop the metaverse responsibly.

5 Discussion

5.1 General Bibliometric Development of the Metaverse Research

Bibliometric analysis shows metaverse research accelerating rapidly, with the number of publications rising steeply from just one in 2008 to nearly 300 in 2023. Contributions span over 20 countries across technical and domain journals, reflecting rising global, interdisciplinary interest. Highly-cited works analyse opportunities and challenges, signaling momentum in both capability development and responsible evolution. Looking ahead, research activity and integration will likely increase as technologies progress, but emphasis on participatory, ethical design is crucial. The metaverse's immense potential requires rigorous, holistic examination centered on human needs and upholding of universal values, not just efficiency, in its realisation (Nalbant & Uyanik, 2022).

5.2 Major Technology Trends Enabling the Metaverse

Table 10. Summary of Technology Related Metaverse Papers

Technology	Technology Category	Papers
Artificial Intelligence & Machine Learning	Machine learning	Almasan et al. (2022), Ham et al. (2023), Khalaj et al. (2023), Li et al. (2022), Moztarzadeh et al. (2023)
	Deep learning	Giarnieri et al. (2023), Moztarzadeh et al. (2023)
	Computer vision and natural language processing	Al-zyoud et al. (2022), Braud et al. (2023), Marquez et al. (2023)

Technology	Technology Category	Papers
Artificial Intelligence & Machine Learning	Simulation and digital twinning	Keshmiri Neghab et al. (2022), Al-zyoud et al. (2022), Khalaj et al. (2023), Moztarzadeh et al. (2023)
	Literature analysis	Bihri et al. (2023), Liu et al. (2023)
	No specific AI/ ML method	Bihri et al. (2023), Braud et al. (2023), Choi et al. (2023), Deg et al. (2023), Song et al. (2022), Wang et al. (2023), Yu et al. (2023), Zhang et al. (2023)
Networking & Telecommunication	Internet of Things (IoT)	Bhat et al. (2023), Bihri et al. (2023), Ham et al. (2023), Kryvenko et al. (2023), Li et al. (2022), Liu et al. (2023), Wei et al. (2022)
	5G Networking	Bhat et al. (2023), Guo et al. (2022)
	Cloud Computing	Cai et al. (2023)
	Wearable/ On-Body Networking	Fang et al. (2023), Hong et al. (2022), Li et al. (2022), Wei et al. (2022)
	Other Networking Technologies	Bihri et al. (2023), Braud et al. (2023), Ebadpour et al. (2023), Gaber et al. (2023), Huyhn et al. (2022)
Virtual, Augmented & Mixed Reality	Virtual Reality	Alpala et al., (2022), Benrimoh et al. (2022), Dwivedi et al. (2022), Guo et al. (2022), Jeong et al. (2022), Kostenko et al. (2022), Kryvenko et al. (2023), Lee et al. (2023), Li et al. (2022), Marquez et al. (2023), Matwala et al. (2023), Moon et al. (2022), Nagendran et al. (2022), Onecha et al. (2023), Onu et al. (2023), Paquin et al. (2023), Pregowska et al. (2022), Ricci et al. (2023), Shin et al. (2023), Sobota et al. (2023), Song et al. (2023), Su et al. (2023), Wang et al. (2022), Yu et al. (2023), Zaman et al. (2022), Zhang et al. (2023)

Technology	Technology Category	Papers
Virtual, Augmented & Mixed Reality	Augmented Reality	Benrimoh et al. (2022), Du et al. (2023), Dwivedi et al. (2022), Cruz Franco et al. (2022), Giarnieri et al. (2023), Kryvenko et al. (2023), Liu et al. (2022), Matwala et al. (2023), Onecha et al. (2023), Onu et al. (2023), Paquin et al. (2023), Pregowska et al. (2022), Shin et al. (2023), Su et al. (2023), Wang et al. (2022), Wei et al. (2022)
	Mixed Reality	Kryvenko et al. (2023), Pregowska et al. (2022), Ricci et al. (2023), Wang et al. (2022)
Blockchain & Smart Contract	General Blockchain	Bhat et al. (2023), Liu et al. (2022), Uddin et al. (2023), Monaco et al. (2023), Wang et al. (2022)
	Smart Contracts	Oh et al. (2023), Song et al. (2023), Zhao et al. (2023)
	Federated Learning	Wang et al. (2022)
	Reputation Systems	Ying et al. (2023)
Digital Twins, Simulation & Avatars	Digital Twins	Alpala et al. (2022), Al-zyoud et al. (2022), Bhat et al. (2023), Cruz Franco et al. (2022), Huyhn et al. (2022), Khalaj et al. (2023), Moztarzadeh et al. (2023), Keshmiri Neghab et al. (2022), Shin et al. (2023), Wang et al. (2022)
	Simulation	Huang et al. (2023), Jeong et al. (2022), Li et al. (2022), Massetti et al. (2023), Matwala et al. (2023), Nagendran et al. (2022), Onu et al. (2023), Paquin et al. (2023), Ricci et al. (2023), Sghaier et al. (2022), Sobota et al. (2023), Wang et al. (2022), Zaman et al. (2022), Zhang et al. (2023)
	Avatars	Nagendran et al. (2022), Benrimoh et al. (2022)

With reference to Table 10, investigation of the AI/ML landscape reveals machine learning acting as a predictive backbone for metaverse development. Meanwhile, deep learning enables the complex renderings for immersive environments. Multimodal interfaces blend computer vision and natural language processing (NLP) to decode natural interactions. Simulation and digital twins replicate physical phenomena in virtual worlds. This mosaic of complementary AI methods appears essential for digitally augmenting realities within the metaverse (Huynh-The et al., 2023).

Mapping the networking technologies highlights 5G and IoT converging to link the physical and the virtual, while cloud computing provides infrastructure scalability. Wearable networks facilitate embodied sensing and interaction (Chandramouli et al., 2023). These heterogeneous ingredients work in concert to bridge physical and digital domains. Their integration seems imperative for the seamless convergence defining the metaverse (Bhat et al., 2023).

Documentation of immersive technologies unveils VR spearheading digital experiences, AR overlaying virtuality into reality, and MR enabling seamless blending. While nascent, their symbiosis appears necessary for natural immersion. VR currently leads, but the rise of AR and MR could accelerate to unlock embodied virtual interactions (Ortega-Rodríguez, 2022).

Illustration of blockchain techniques portrays a broad foundation enabling metaverse architectures, with smart contracts providing automation. Specialised protocols like NFTs and reputation systems address niche needs (Zhao et al., 2022). Advancing customisation, scalability, and interoperability, linking with other metaverse technologies, appears key to unlocking blockchain's full potential (Imperius & Alahmar, 2022).

Finally, simulation technologies highlight the use of simulations for customisable environments, digital twins for virtual-physical synchronisation, and emerging avatars for inhabiting these worlds. Their fusion can potentially enable expansive, yet precise immersion. Integrating these complementary technologies seems imperative for architecting multifaceted metaverse systems spanning virtual worlds, digital replicas, and embodied experiences (Alpala et al, 2022, Tu et al., 2023).

5.3 Current and Near-Term Applications of Metaverse Technologies

Table 11. Summary of Metaverse Applications

Application Domains	Applications	Papers
Education	Medical Education	Massetti et al. (2023), Moztarzadeh et al. (2023), Nagendran et al. (2022), Onu et al. (2023), Pregowska et al. (2022), Paquin et al. (2023), Ricci et al. (2023), Sghaier et al. (2022), Shin et al. (2023), Sobota et al. (2023), Su et al. (2023)
	Engineering Education	Alpala et al. (2022), Bihri et al. (2023), Fang et al. (2023), Gaber et al. (2023), Guo et al. (2022), Ham et al. (2023), Hong et al. (2022), Jeong et al. (2022), Khalaj et al. (2023), Lee et al. (2022), Li et al. (2022), Li et al. (2022), Liu et al. (2023), Marquez et al. (2023), Wang et al. (2023)
	General Education	Dwivedi et al. (2022), Kryvenko et al. (2023)
Social & Cultural	Cultural Heritage	Cruz Franco et al. (2022), Su et al. (2023)
	Tourism	Huang et al. (2023), Monaco et al. (2023)
	Philosophy	Ahmet et al. (2023)
	Privacy	Yu et al. (2023)
	Other	Bihri et al. (2023), Bihri et al. (2023), Dwivedi et al. (2022), Jeong et al. (2022), Marquez et al. (2023), Massetti et al. (2023), Wang et al. (2023), Wang et al. (2023), Zhang et al. (2023), Zhao et al. (2023)
Healthcare	Medical Education	Jeong et al. (2022), Kryvenko et al. (2023), Massetti et al. (2023), Matwala et al. (2023), Pregowska et al. (2022)
	Digital Health	Al-zyoud et al. (2022), Giarnieri et al. (2023), Ham et al. (2023)
	Mental Health	Benrimoh et al. (2022), Lee et al. (2022), Paquin et al. (2023)

Application Domains	Applications	Papers
Healthcare	Surgical Applications	Moztarzadeh et al. (2023), Keshmiri Neghab et al. (2022), Wang et al. (2023)
	Neurological Applications	Moon et al. (2022)
	Healthcare Overview	Dwivedi et al (2022)
Accounting & Trading	Fintech	Bhat et al. (2023)
	Accounting	Kryvenko et al. (2023)
	Trading	Oh et al. (2023), Ying et al. (2023)
Economics, Marketing & Tourism	Tourism	Huang et al. (2023), Monaco et al. (2022), Wei et al. (2022), Zaman et al. (2022)
	Marketing	Dwivedi et al. (2022), Song et al. (2023)
	Education	Marquez et al. (2023)
Sports	Sports Education	Li et al. (2022)
	Sports Healthcare	Hong et al. (2022), Moon et al. (2022)
Architecture Industrial Design	Architecture	Choi et al. (2023), Cruz Franco et al. (2022), Liu et al. (2023), Onecha et al. (2023)
	Industrial Design	Ricci et al. (2023)

Analysis of the education and healthcare categories underscores the metaverse's potential suitability for personalised, immersive learning and clinical experiences, while highlighting the integral priority of developing inclusive and ethical accessibility (Rejeb et al., 2023). The breadth of demonstrated applications across technical simulations, medical training, and enriched pedagogy indicates the versatility of metaverse technologies in adding value in education and healthcare globally. However, fully actualising this potential necessitates interdisciplinary collaboration to responsibly embrace emerging capabilities in the service of elevating human well-being holistically (Qadir & Fatah, 2023).

Examination of the socio-cultural category reveals the metaverse's extensive implications across the spectrum of physical and digital life (Bicri et al., 2022). Ranging from cultural heritage preservation to identity exploration, the applications suggest the metaverse could substantially enhance society's evolution if purposefully designed and directed. However, equitably advancing these possibilities requires empowering diverse human expression while diligently safeguarding agency and ethics. This demands collaborative foresight across disciplines.

The finance category indicates that the metaverse may confer efficiency improvements but also urgently requires accountability to collective well-being, not just profits (Vakiti & S. L., 2023). Approaches which validate diverse perspectives and enact ethical guardrails can help shape responsible metaverse ecosystems in this domain. While offering advantages, technology alone does not determine societal value - systems elevating human dignity above financial incentives do (Dwivedi et al., 2022).

The survey of the tourism category showcases promising innovations yet prudently advises that technological capabilities alone, without social responsibility, may undermine intended benefits. Grounding designs in diverse human contexts while proactively assessing equity impacts can aid in steering metaverse applications toward responsible advancement in this area (Allam et al., 2022).

The sports and healthcare categories suggest potential for more personalised and engaging treatments, while advising a narrow efficiency focus could outweigh considerations of holistic well-being. Thoughtful, inclusive risk-benefit analyses centered on diverse perspectives are imperative to shape metaverse applications so as to improve life universally (Basu, 2023; Mancini et al., 2023). Finally, the architecture and industrial design category points the way towards immersive new opportunities yet underscores the vital role of transparent, participatory processes in order to achieve broad accessibility and inclusivity. Realising equitable benefits across disciplines will require centering human needs, not just expanding technological capabilities alone (Wang et al., 2022). Table 11 summarises the application in every paper reviewed.

5.4 Ethical and Privacy Risk That Need to be Addressed for Mainstream Metaverse Adoption

The analysis reveals some critical insights. As the metaverse aims to merge physical and virtual worlds, considerations around rights, agency, transparency, and accountability become even more salient in order to prevent unintended consequences (Di Pietro & Cresci, 2021). Issues like pervasive tracking, filter bubbles, and addiction already exist today and could be amplified manifold in immersive metaverse environments. Therefore, interdisciplinary collaboration incorporating diverse voices and proactively assessing risks is crucial in metaverse development (Mohammed et al., 2023). In particular, platform governance balancing public interest and corporate incentives requires careful attention along with guardrails to safeguard vulnerable populations. While the metaverse offers immense potential, realising equitable benefits demands centering human needs and values, not just technology, in its evolution. The metaverse should be shaped thoughtfully as a shared, common resource elevating universal principles that serve all humanity (Huang et al., 2023).

5.5 Future Opportunities for the Use of Metaverse Technologies across Industries

The metaverse opens new horizons for transforming industries through human-centric design and emerging capabilities like immersion, interconnectivity, and intelligence (Li K et al, 2022). For example, the metaverse can enable highly customised education where AI tutors adapt to students' needs and interests (Hwang et al., 2022). Virtual tours and simulations can make teaching more experiential and accessible (Ng et al., 2022). In healthcare, the metaverse provides new mediums for telehealth, collaborative diagnosis, surgical training, and therapeutic VR. The finance industry can implement decentralised metaverse ecosystems, thus improving transparency and access. Digital twins and simulation can aid manufacturing, construction, and urban design with interactive prototyping and testing (Sunny et al, 2023). Metaverse events and collaborative spaces hold potential for more engaging marketing and teamwork.

With thoughtful governance and integration of ethics, industries can harness the metaverse for creativity, empathy, equity, and illuminating human experiences. As capabilities mature, this chapter foresees pioneering metaverse industries woven seamlessly into the fabric of life, elevating joy, meaning, and collective potential. The key will be stewarding the metaverse responsibly for the benefit of all, preserving human agency and pluralism while unlocking new horizons. The true measure of success will be enabling more vibrant, just, and sustainable societies, not mere financial metrics. By uplifting the full spectrum of human needs and imagination, the metaverse can help write a thriving next chapter for civilisation.

6 Conclusion

This analysis provides a multifaceted perspective on the emerging metaverse landscape, examining the accelerating research, enabling technologies, applications, ethical considerations, and outlook.

The bibliometric analysis reveals surging global interest in metaverse capabilities and implications, with the number of publications skyrocketing across technical and interdisciplinary journals. Key technological enablers like VR/AR, AI, blockchain, and advanced connectivity are driving more immersive, interconnected environments. Current applications highlight promising domains in education, healthcare, marketing, and beyond, but require thoughtful development factoring ethics, accessibility, and inclusive design. As the metaverse aims to merge physical and virtual worlds, considerations around privacy, algorithmic bias, misinformation, and vulnerability become more salient given potentially broad societal impacts. Realising an equitable metaverse future grounded in human dignity necessitates responsible governance and participation which upholds universal humanistic principles, not profits alone.

Looking ahead, the metaverse presents immense opportunities to advance industries through human-centered innovation and emerging capabilities. However, prudent, holistic development focused on collective wellbeing and pluralism, not efficiency alone, will determine the metaverse's highest purpose. This analysis elucidates the terrain while underscoring that ethical stewardship for societal benefit more than financial gain is imperative as the metaverse's future unfolds.

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Chapter 3

The Metaverse for Sustainable Manufacturing and Space Applications

Abstract

This chapter describes the most recent developments on both of sustainable manufacturing and the metaverse with the objective of examining the potential of using the metaverse for enhancing the sustainability of the manufacturing industry, particular in relation to the space industry. It also establishes the methodology and tools for the development of the theory and practices presented in the following chapters. Firstly, today's manufacturing environment is discussed to elaborate the needs to pursue sustainability in the economy, society, and the environment in order to prolong enterprise lifespan, especially for small and medium-sized enterprises (SMEs). Secondly, a set of criterial functional requirements (FRs) for manufacturing are discussed to identify the limitations of manufacturing theories and enabling technologies. Thirdly, the concept of the metaverse and its relevant technologies are surveyed to highlight its unique features in comparison with

its precursors such as virtual reality (VR) and extended reality (XR). Fourthly, the capabilities of the metaverse are explored systematically in relation to space applications and for enhanced sustainability of manufacturing. Finally, our work is summarised with our recommendations for promoting the uses of the metaverse in the digital era. More examples applying the concepts and tools in the space industry will be illustrated in the remaining chapters.

Keywords: metaverse, digital manufacturing, digital twins (DT-I), digital triads (DT-II), cyber-physical systems, internet of things (IoT), internet of digital triad things (IoDTT), edge-computing, augmented reality (AR), big data analytics, unmanned aerial vehicles (UAVs), brain-computer interfaces (BCI)

1 Introduction

The concept of the metaverse was introduced in Stephenson's book *Snow Crash* as a black planet accessible to users via a VR device and terminals (Stephenson, 1992; Bansal et al., 2022). The term metaverse is a combination of "meta" and "universe" referring to a hypothetical next-generation internet; it connects all virtual things by the Internets for communication and interaction in ways similar to that in the physical world (Cheng et al., 2022). The metaverse comprises immersive worlds where users interact in the form of avatars. It is an evolution of the internet where VR, augmented reality (AR), and mixed reality (MR) are used as a popular modality, and is widely used to support people's interaction and communication (Tian, 2021; Chen, 2022). Metaverse technologies are implemented as user cases in broad areas including agriculture, education, healthcare, manufacturing, real estate, smart communities, socialisation, space and transportation (Felice et al., 2023; Kang et al., 2022; Li et al., 2023). The metaverse is having a growing economic, social, and environmental impact in terms of accessibility, diversity, equity, inclusion and safety (Zallio and Clarkson, 2022). The demand for metaverse-relevant technologies such as VR, AR, XR, artificial intelligence (AI), robotics, and blockchain technologies in education alone are expected to grow from $106 billion in 2021 to $303 billion in 2028 (Barrera and Shah, 2022; Bansal et al., 2022; Kshetri et al., 2023). The economic effect of the metaverse will reach $5 trillion by 2023 (Bansal et al., 2022).

The metaverse is not a technology that starts from scratch. It has evolved from conventional VR, AR, MR or XR. Moreover, the metaverse can be viewed as a cyber-physical-social system (CPSS) that is composed of the things in the physical, mental, and artificial worlds (Wang, 2022a; Wang, 2022b). A CPSS is capable of unifying two essential components of complex science, i.e., (1) emergence in cyberspace and (2) convergence in physical space for problem-solving or decision-making. The metaverse has proven its great potential to expand VR relevant technologies or CPSS for seamless human and machine interactions (Dwivedi et al., 2022). Most people agree that the metaverse era begun in 2021 when the Roblox metaverse was launched which allowed users to play games over the internet interactively. Roblox had over 150 million active users monthly and was used by two thirds of children aged from 9 to 12 and one third of children aged under 16 in the US (Park and Kim, 2022). Two other influential products were the Meta platform rebranded by Facebook and the Mesh platform by Microsoft (Dong and Liu, 2022). The rapid growth of computable power as well as human and computer interactions have allowed the creations of virtual worlds and supported their interactions with the physical world (Faraboschi et al., 2022).

This chapter's section 1 explores the potential applications of the metaverse in manufacturing. Similar to its applications in other domains, metaverses have been widely explored in the primary sector such as in relation to agriculture, fishing, forestry, hunting and mining; in the secondary sector including in manufacturing, construction, chemical engineering, textile, aerospace, shipbuilding, and energy; in the tertiary sector such as in retail, healthcare, entertainment, banking, tourism, transportation, and legal services; and the quaternary sector including in research and development, education, information technologies, financial services, and consulting. For example, the metaverse is used in aerospace engineering and the defence industry to train pilots where anticipated or unanticipated events, weather conditions, and terrains can be modelled virtually to guide, assess, and verify trainees' actions in the virtual world (Huang et al., 2023). The metaverse is a critical part of global industry transformation since Industry 5.0 requires humans to interact in immersive ways with intelligent machines for effective human-machine interactions. From this perspective, the metaverse provides potent emulation tools to support, redesign, reconfigure, commission, and optimise human-centralised systems. The metaverse adds new dimensions of internet data to overcome information blindness in industrial scenarios (Leng et al., 2022). Ning et al. (2023) referred to the metaverse as a general cyberspace where virtual and physical spaces are fused to form a unified physical, cyber-enabled, social, and thinking space.

The rest of the chapter is organised as follows. Section 2 discusses the background of sustainable manufacturing to identify a set of FRs to pursue system sustainability in the economy, society, and the environment. Section 3 examines recent advances in the metaverse and relevant technologies including digital twins, IoT, big data analytics, blockchain technologies, AR, human-robot interaction (HRI), and data-driven decision-making systems. Section 4 examines the roles of the metaverse and related technologies as the solutions to meeting the FRs of sustainable manufacturing systems. Section 5 discusses the limitations of existing metaverse technology and identifies a number of promising research directions to advance the metaverse for manufacturing. Section 6 summarises our findings.

2 Functional Requirements of Sustainable Manufacturing

Despite numerous discussions on the importance of sustainability, the first step in practising sustainable manufacturing (SM) is to develop an evaluation model to measure the sustainability of products or systems quantifiably (Bi, 2011). Sustainability is defined as meeting the present global needs of human society without compromising the well-being of future generations. In the United States, sustainable development is a commitment to creating and maintaining conditions under which humans and nature can co-exist in productive harmony, permitting the meeting of the social, economic, and other requirements of present and future generations (Saari et al., 2022). Many researchers have investigated the development of a smart manufacturing evaluation mode. For example, Dogea and Stolt (2021) argued that the most critical objectives were efficiency and productivity and that these could be met by adopting an increasing number of digital technologies. Bhat et al. (2023) discussed the requirements on modern manufacturing from an economic perspective and added a set of new requirements that included (1) reducing latency, (2) dealing with multi-modal, (3) assuring security, and (4) reducing energy consumption. Fielder (2023) explored new solutions to enhancing efficiency, productivity, and competitiveness by pursuing smart manufacturing. She identified a set of FRs that included (1) digitisation to harness data for success since data is the of primary importance in industry 4.0,

(2) real-time visibility to support transparency and controls, (3) agility to respond to internal and/or external changes promptly, (4) soft automation to redefine efficiency with minimised cost, (5) connectivity to support seamless networking, (6) ease of use to empower the workforce, and (7) sustainability to support net zero by the use of smart technologies.

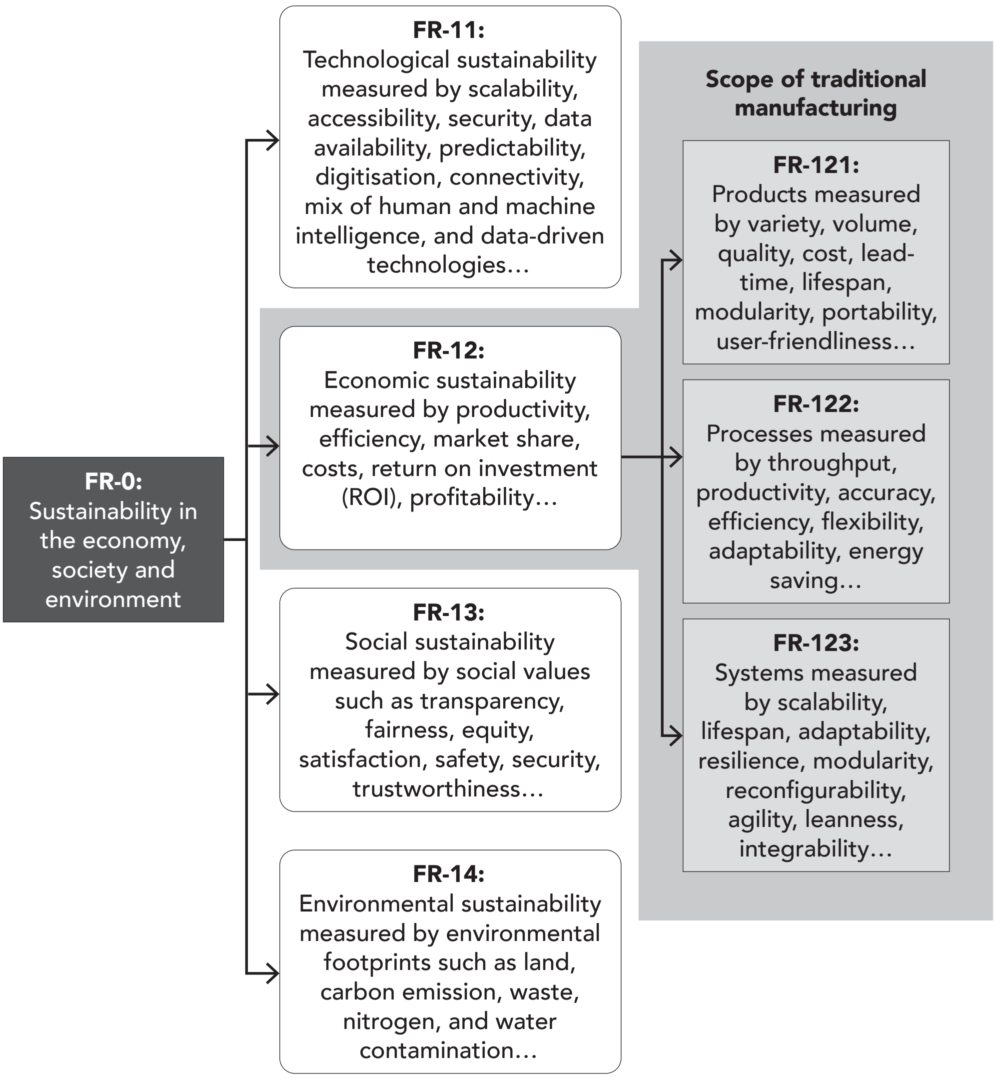


Figure 1. Functional Requirements of Sustainable Manufacturing

Figure 1 summarises the author's findings from the literature survey in regard to the basic FRs of sustainable manufacturing. The top-level functional requirement (*FR-0*) for sustainability in the economy, society, and the environment is divided into (1) three relatively independent sub-FRs (i.e., *FR-12*, *FR-13*, and *FR-14*) focusing on sustainability in these three aspects respectively, and (2) one sub-FR (*FR-11*) related to technology sustainability that is strongly coupled with the other sub-FRs. In applying axiomatic design theory in system design (Cochran et al., 2016a; Cochran et al., 2016b), every sub-FR must be deconstructed and detailed level by level until all of its sub-FRs find corresponding solutions to satisfy the FRs. Taking the example of *FR-12* for economic sustainability in traditional manufacturing, it can be deconstructed into a set of the sub-FRs at the third level related to products, processes, and manufacturing systems, respectively. This section focuses on *FR-11* for technological functional requirements, and other specific FRs in which the metaverses and relevant technologies are contributing.

2.1 Scalability, Accessibility, Security, Privacy, and Legal Issues

Scalability refers to a system capability for adding or removing resources in a cost-effective manner to meet production demands as needed. With the growth of the internet, metaverses show the potential to network with dynamic resources over the internet that are fully scalable. Cheng et al. (2022) conducted their preliminary investigation and showed that social VR platforms such as AltspaceVR and Workrooms were able to support a limited number of partners, while an increasing number of online partners were facing an exponentially increased demand for the bandwidth for uploading and downloading. Metaverses must be scalable before they can be applied to address the scalability of sustainable manufacturing.

Accessibility allows a manufacturing system to access any internal or external resource whenever it is needed. In the metaverse, everything over the internet has its virtual model and users can interact with virtual things freely. However, the interactions rely on traditional interface equipment such as headsets and haptic devices, and this brings inconvenience to users with glasses, contact lenses, or who suffer from motion sickness. There is a need to advance interfaces for users to access resources over the internet with fewer constraints. The accessibility of the metaverse affects the seamless interoperability of accessible manufacturing resources in an enterprise.

Security, privacy, and legality are basic FRs for enterprises to protect their assets and intellectual properties (IPs) in a decentralised and distributed business environment. When metaverses are used to assure security, privacy, and legality, they must assure assets, authentications, and the privacy of all businesses (Viriyasitavat et al., 2022, 2023). Metaverses are also required to address challenges specifically related to manufacturing such as (1) interfaces with digital twins, (2) the limited capabilities to support the free movement of avatars, and (3) copyright issues associated with the metaverse assets.

2.2 First-Time-Right from Virtual to Physical World

Digital transformation has gone far beyond virtual communication to connect the social and healthcare industries with a metaverse that is enabled by AR and VR (Bansal et al., 2022). A manufacturing system comprises various value-added and non-value-added manufacturing operations over product lifecycles. The system can be optimised effectively by minimising non-value-added operations, since non-value-added operations also consume various system resources. In digital manufacturing, decisions related to system operations are made by functional units in the digital twin, and engineers should compete to utilise computer-aided technologies to make right decisions at the first time (Bi and Zhang, 2021).

2.3 Ubiquitous Data and Computing

Distribution and decentralisation have gradually exhibited their values in manufacturing, logistics, governance, and management (Cao et al., 2022). In particular, AI can be decentralised as edge intelligence to promote the applications of Web 3.0 and blockchain in the metaverse. Edge computing allows the connection of isolated end devices in IoT to support decentralised computation,

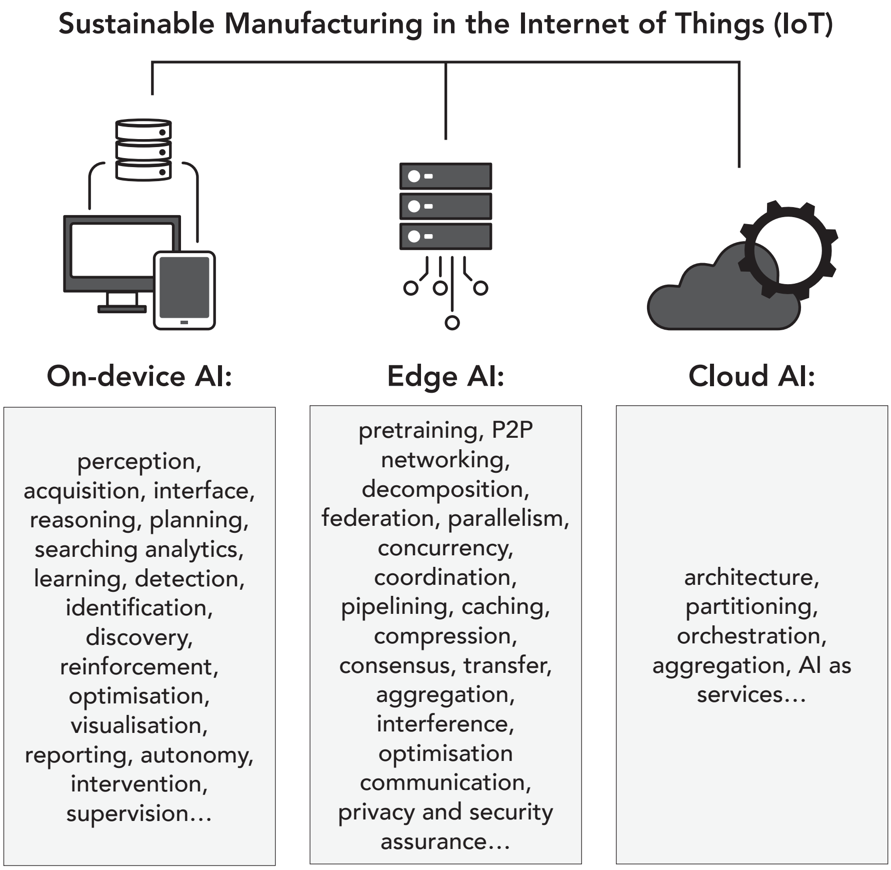


Figure 2. Ubiquitous Data and Computing in Sustainable Manufacturing (Chao et al., 2022; Gorilla, 2023; Telecom, 2019)

storage, and communication. For example, decentralised autonomous organisations (DAOs) and decentralised science have been developed and used in decentralised organisations and are implemented by cryptocurrency, biomedicine, funding, and professional services. Figure 2 shows scenarios where AI and cloud computing are used to enable ubiquitous data and computing in sustainable manufacturing (Cao et al., 2022; Gorilla, 2023; Telecom, 2019). As an application of the internet, every resource in a manufacturing system is connected as a smart thing, and all of the associated data and information are accessible by IoT. Data can be processed and analysed by edge intelligence, and relevant data can be aggregated, processed, and mined to support high-level complex decision-making activities at broadened scopes and longer terms by cloud computing.

2.4 Diagonalisability, Predictability and Adaptability

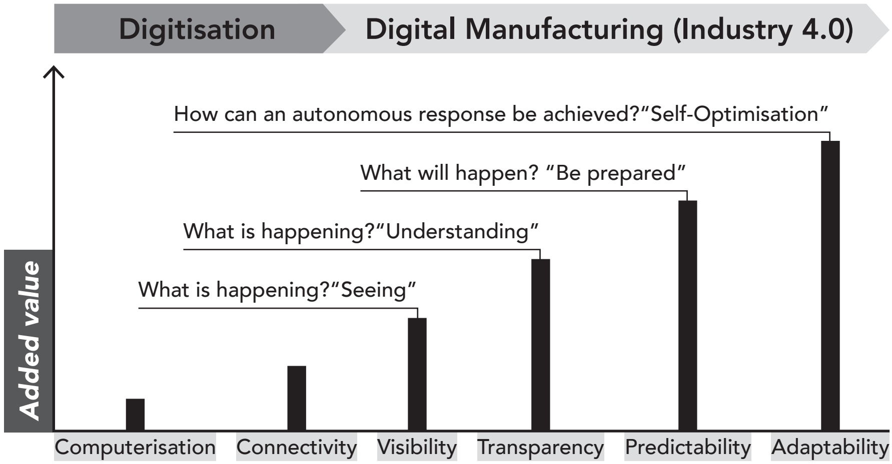


Figure 3. Diagonalisability, Predictability, and Adaptability in Sustainable Manufacturing (Bi et al., 2021a)

The performance of a manufacturing system relies largely on the intelligence of its decision-making units at different levels and domain. As seen in Figure 3, intelligence can be measured by the capabilities of (1) understanding past and current states of the system; (2) the prediction of future system states and changes in the long term. A sustainable system requires (1) collecting data in a real-time mode, (2) networking relevant objects and models as smart things, (3) predicting changes to optimise business plans, and (4) reconfiguring systems to respond to anticipated and unanticipated changes automatically (Bi et al., 2021a).

2.5 Human Intelligence for Uncertainty and Change

Even though full automation is becoming feasible, humans still play critical roles due to our adaptability to deal with change and uncertainty. Traditional machines are generally programmed for sophisticated tasks but are incapable of responding to unexpected events. Cooperation between worker and machine has helped improve system adaptability in dealing with change. In particular, wearable devices with advanced sensing and haptic technologies fill the gap between the human and cyber world for seamless collaboration (Flynn et al., 2019).

A central challenge in industry 4.0 is how to fully utilise human resources to enhance system adaptability and resilience. Industry 4.0 refers to an integrated application of collective digital technologies and concepts in a value chain organisation, with the most critical technologies being cyber physical systems (CPS), IoT, and smart manufacturing (Daling et al., 2018). In industry 4.0, robots are capable of working with humans for many manufacturing processes such as quality control, inspection, picking and placing, parallelising, and assembling operations. Unlike other conventional automated processes, the benefits of HRC can be justified by reliability analysis (Çoban et al, 2019). Bi et al. (2021b) characterised robots that were utilised to deal with uncertainty and change in manufacturing environment as shown in Figure 4a, while Bi et al.

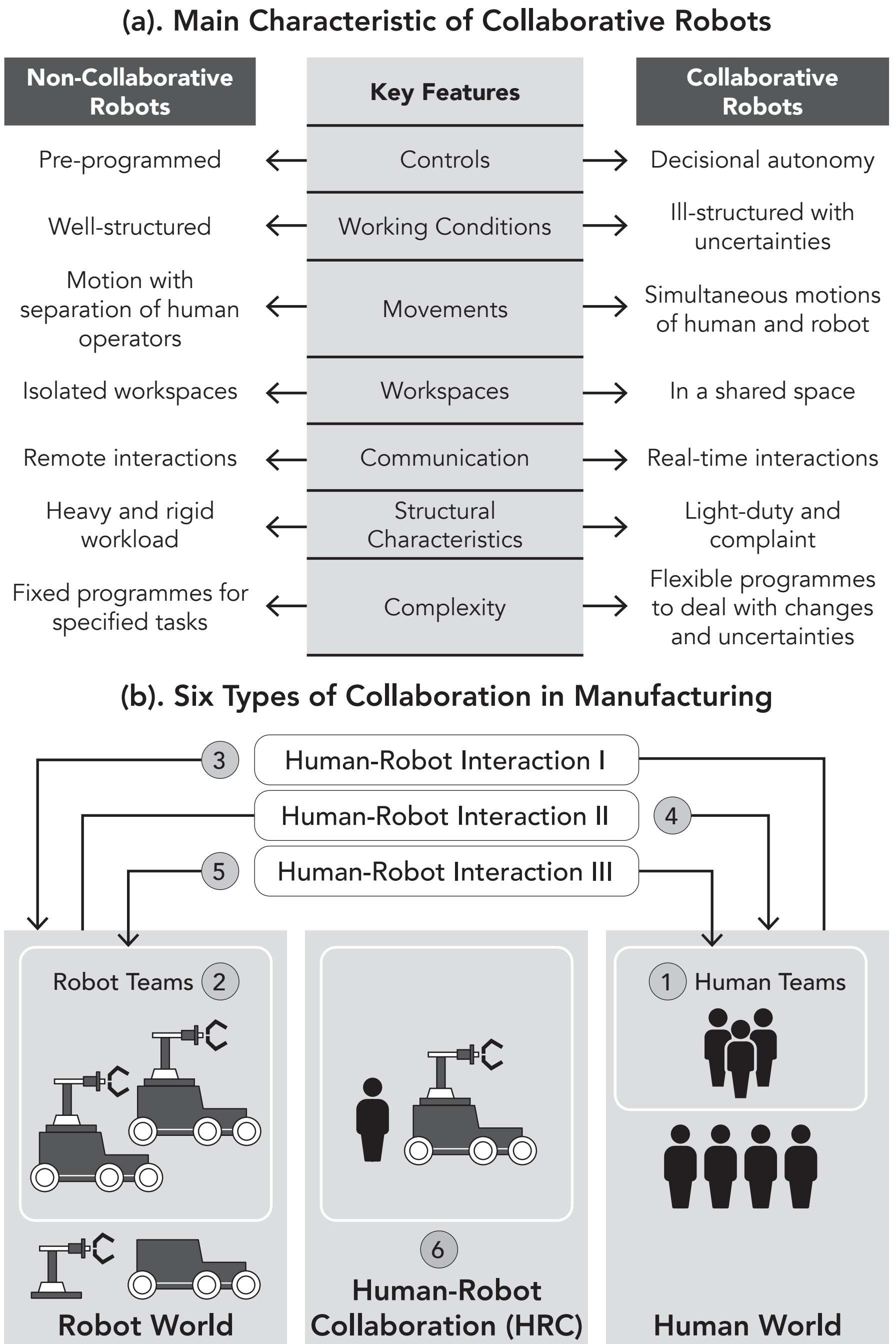


Figure 4. Using Collaborative Robots in Sustainable Manufacturing (Bi et al., 2021b, 2021c).

(2021c) further classified collaborations into human teams, robot teams, HRC, and three types of HRI (see Figure 4b).

2.6 Data-Driven Decision-Making Supports

Any manufacturing system, especially a sustainable manufacturing system, involves numerous decision-making activities. When a system becomes very dynamic, real-time data collection and analysis are essential for understanding current and future states of the system, while the performance of decision-making systems rely greatly on the availability and sufficiency of data and the means to process data and mine the information and knowledge from those data. With the rapid adoption of IoT, the structures of information systems in enterprises have shifted gradually from static and centralised structures to dynamic, decentralised, and distributed structures.

As shown in Figure 5, the operations of a sustainable manufacturing system rely on the decision-making units in different domains and at different levels of system. Each functional unit can be viewed as an information system with specific types of inputs and outputs. When a manufacturing environment or system resources are dynamic, the inputs of decision-making units become dynamic. Therefore, these units must be data-driven to take into consideration of and respond to changes promptly (Bi and Cochran, 2014; Bi and Wang, 2016). Figure 6 shows the scenarios of how metaverses could be adopted in a data-driven sustainable manufacturing system to achieve smartness, sensitivity, safety, security, service, and sustainability (6S) of data-driven information systems (Shen et al., 2022b).

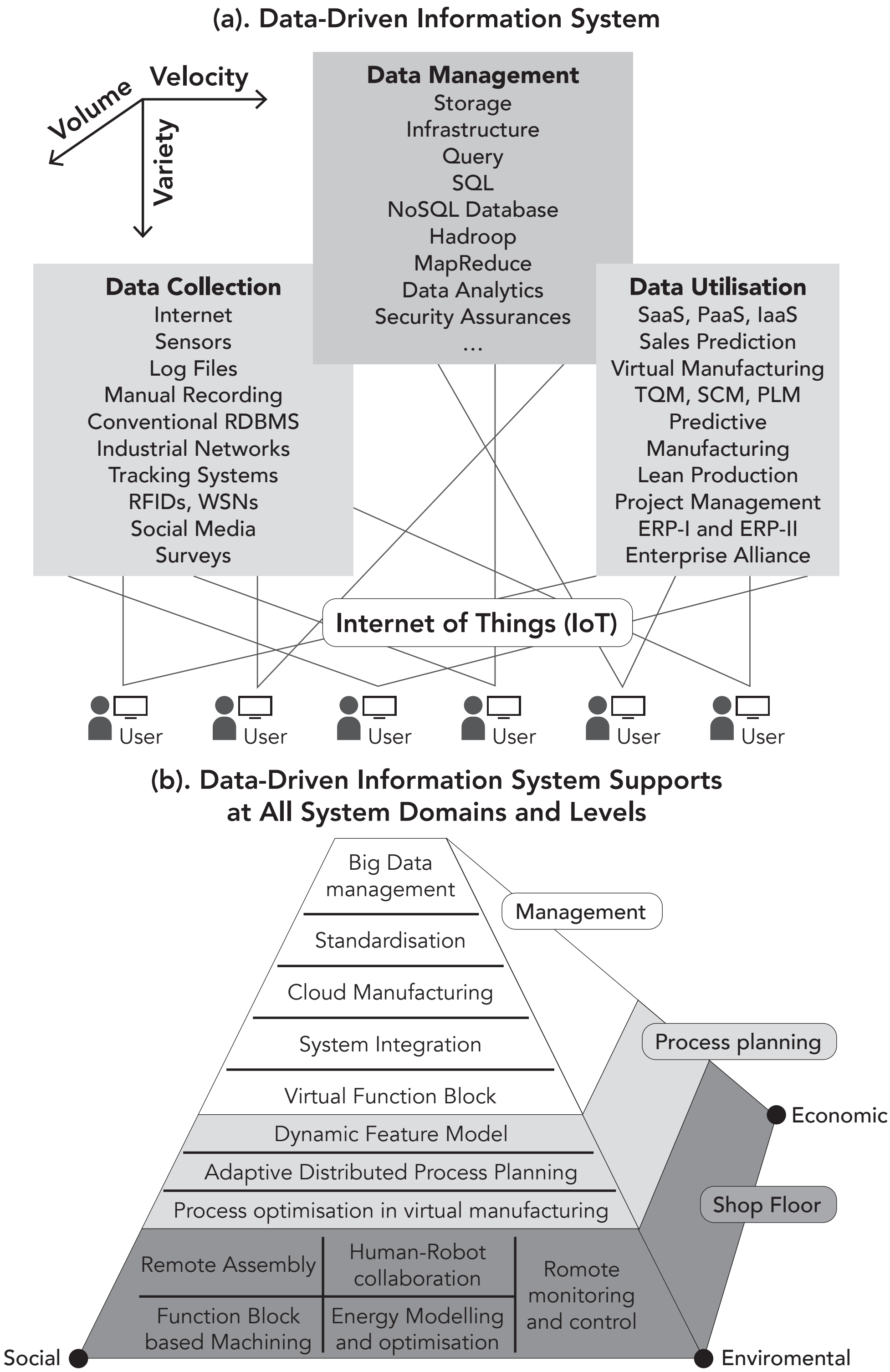


Figure 5. Data-Driven Information System Supports at All Domains and Levels of System (Bi and Cochran, 2014; Bi and Wang, 2016)

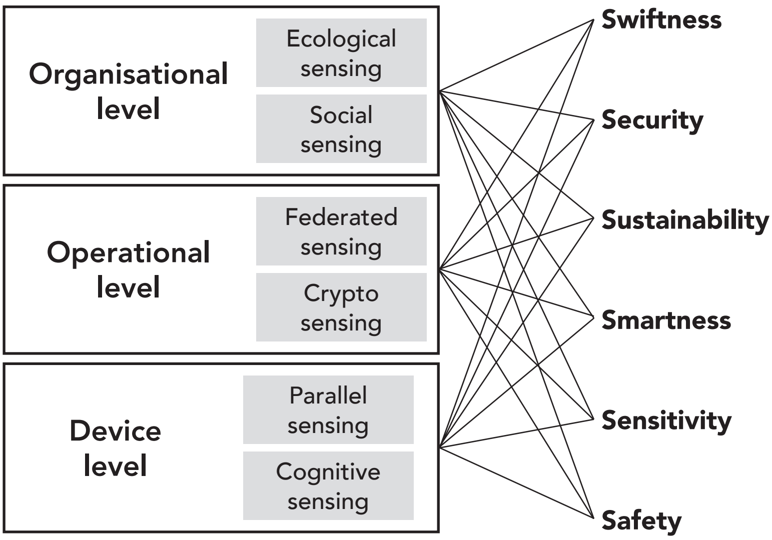


Figure 6. Objectives of Metaverses in Data-Driven Systems (Shen et al., 2022a)

3 Metaverse and Relevant Technologies

Among the 13 aspects of technologies identified by Future Today Institute (2022), those relevant to the metaverse included AI, AR, VR and synthetic media, home of things, logistics, robotics and transportation, decentralisation and blockchain, and telecommunication and computing. The technologies underpinning the metaverse have evolved over the years, creating a believable virtual world in the metaverse which requires a confluence of the most advanced ITs as well as a trustable, reliable, and efficient network with low latency (Faraboschi et al., 2022). For many researchers, metaverses are simply viewed as the enhanced and upgraded versions of today's internet. Even though people have different expectations of the internet and definitions of metaverses are different, some commonly agreed features are: 1) VR, AR, and MR are adopted to create illusionary and immersive environments that can be used to simulate physical worlds; 2) the interactions of decentralised functional units are enabled by blockchain and cryptocurrencies; 3) users are allowed to interoperate across platforms with digital identities and assets; 4) humans present as avatars; and 5) communications are enabled synchronously in a real-time mode (Zainab et al., 2022; Kshetri, 2022b).

Fu et al. (2023) summarised the core enabling technologies of the metaverse in the abbreviation BIGANT, i.e., B from Blockchain technology, I from Interoperation, G from Gaming, A from Artificial intelligence, N from Network and cloud computing, and T from the 'internet of Things'. As shown in Figure 7, in metaverse architecture enabling technologies are discussed with reference to hardware platforms, operating systems, decision-making supports, software tools, applications, and ecosystems.

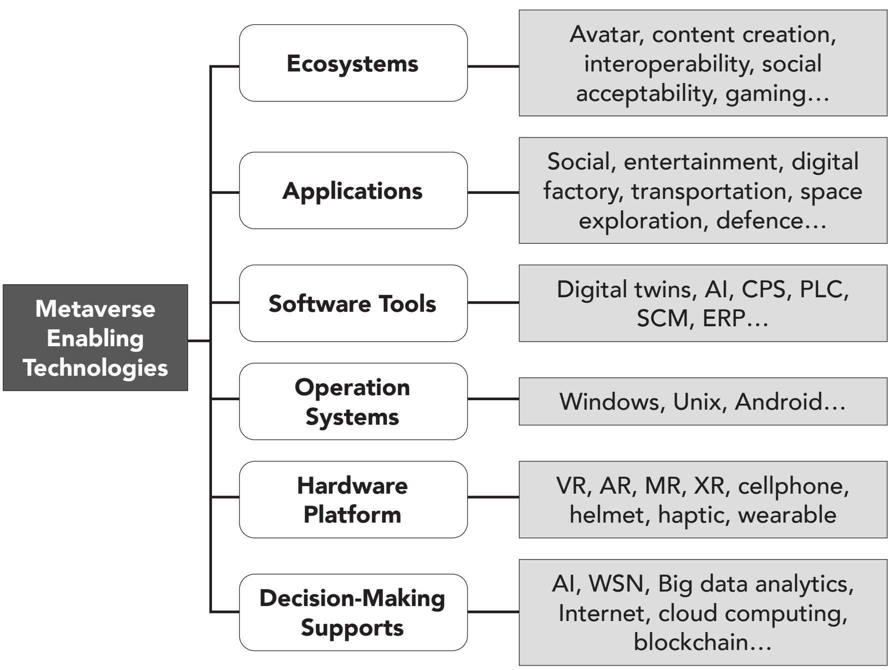


Figure 7. Classification of Metaverse-Enabling Technologies (Fu et al., 2023)

Using the metaverse in an application requires the adoption of a wide range of cutting-edge ITs in various domains and aspects of decision-making supports from smart things over the internet at hardware layer to computing and intelligence and virtual components at the middle layers and to various user services at the upper layers. In this chapter, metaverses will be treated as integrated platforms that will be fused with any cutting-edge technologies when needed to accomplish their missions in sustainable manufacturing, as aligned with that shown in Figure 8 (Bhat et al. 2023).

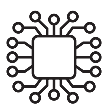
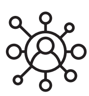
Metaverse-Based Applications	Integrated Technologies
 **User services**	Remote collaboration Skill transfer Immersive banking Virtual asset
 **Functional units**	Digital twins Avatars XR contents Digital economy Holographic data
 **Computing and intelligence**	Big data analytics AI finance Market prediction Regulatory AI insurance
 **Hardware and networking**	IoT Cyber security 5G/6G and edge Blockchain Robotics

Figure 8. Metaverse as an Integrated Platform Rather Than a Specific Technology (Bhat et al., 2023)

The metaverse is able to eliminate geographical limitations since physical locations become irrelevant and apply no constraints on users' interactions. The metaverse can be used to gain immersive experience in a virtual or virtually and physically fused environment, support human and machine interactions, collaborate in a 3D interactive world, develop vivid applications using metaverse infrastructure for various applications, and enrich ecosystems for marketing, and financial, economic and social services (Cao, 2022).

The characteristics of the metaverse are immersiveness, hyper spatio-temporality, sustainability, interoperability, scalability, and heterogeneity. Correspondingly, Wang et al. (2023) summarised the main applications of metaverses in six fields as shown in Figure 9.

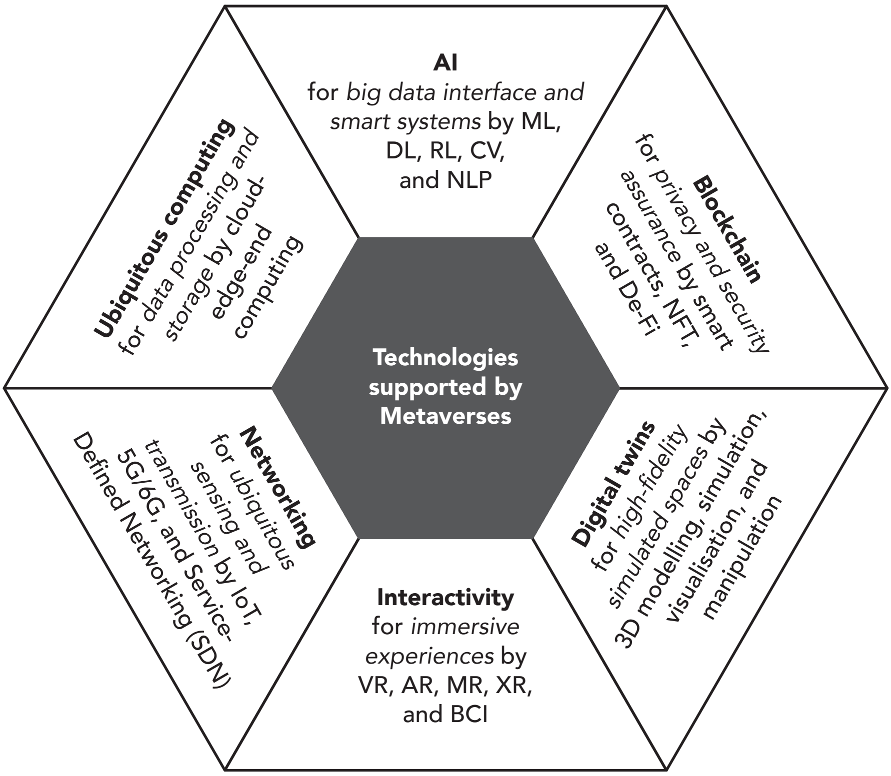


Figure 9. Metaverse Applications in Six Fields (Wang et al., 2023)

3.1 Architecture or Framework

According to the International Organization for Standardization (ISO), metaverse architecture can be instantiated from ISO architecture of an information system that comprises seven layers from the lowest physical device layer to the highest application layer as shown in Figure 10 (Faraboschi et al. 2022). *The device layer* allows users to access a metaverse via sensors and smart things such as Brain-Computer Interfaces (BCIs), for example a haptic device to sense touch or an earbud to sense sound or feel acceleration. The devices are connected at *the communication layer* as support for a data space; current infrastructure based on the 4G cellular networks should be advanced to 5G and 6G to support communication between devices and the cloud as a mesh architecture. *The cloud layer* hosts data and software. It can be fuzzy and embedded down into device and communication layers and uploaded to a virtual cloud to form *fog* or *edge*. *The virtual cloud layer* is formed by a group of distributed data and software on different clouds. Cloud services have been virtualised by a number of IT giants such as Google, Azure, and Amazon. *The data spaces layer* defines the ontology of the metaverse. It is critical to implement the functionalities of an ecosystem, especially by third parties. *The digital twin layer* customises the metaverse for a specific user's experience. It orchestrates various DTs and supports their interactions. *The use case layer* defines the application where users interact in the metaverse, providing the landscape for seamless interactions by using the services embedded in the ambient.

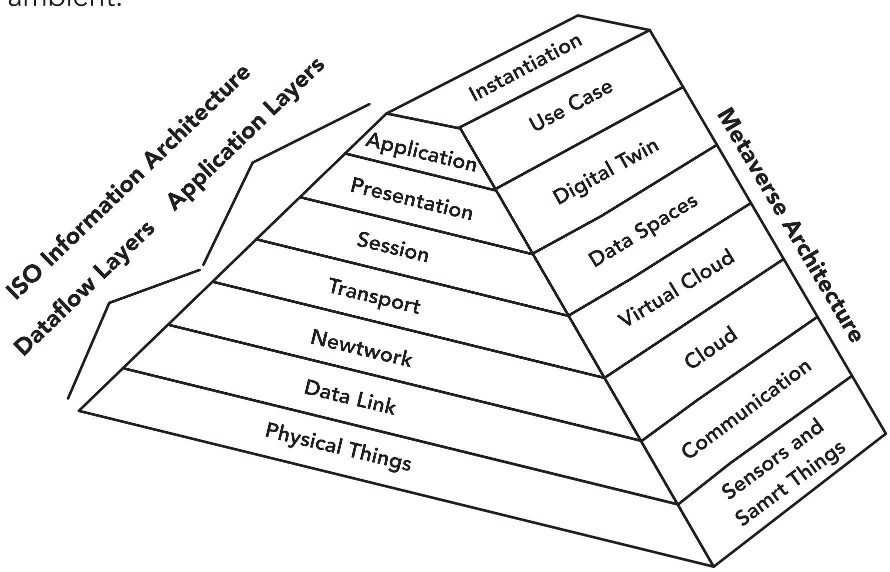


Figure 10. Metaverse Architecture Versus ISO Seven-layer Architecture (Frachtenberg et al., 2022)

3.2 Virtual Reality, Augmented Reality, Mixed Reality, and Extended Reality

Any object in the physical world should be represented in the virtual world in certain contents. For example, people are usually presented as avatars and artifacts are usually represented as their digital twins, and the asset, security, and privacy of objects can be protected by blockchain technology or Nonfungible Tokens (NFTs). Value exchanges can be tracked naturally by distributed ledgers (Far et al., 2022; Faraboschi et al., 2022). These are usually achieved by VR, AR, MR and XR. Walmart has used VR headsets to train their employees and the training time for specific activities was cut from eight hours to 15 minutes. A study by the UK's National Health Service showed 92% of participants using VR gained adequate understanding of infection controls in contrast to 16% of those not using VR (Kshetri, 2022c). The aforementioned technologies have reshaped the physical world into a digital world in the form of the metaverse with the use of smart technologies and avatars (Lv et al., 2022a; Tian, 2021).

VR is a fully immersive virtual world in which users can see, feel, move, and act on virtual objects or features interactively. AR incorporates virtual objects in the physical world by the use of various sensory modalities such as auditory, visual, haptic, and olfactory. MR merges the virtual and physical worlds with a single display, jointly exhibiting virtual and physical objects simultaneously in the same display. XR fuses AR and VR realities for technology-mediated experiences using sensory interfaces, infrastructures, and applications (Bansal et al., 2022). XR, VR, AR, MR, and 360 stereoscopic streaming enable the metaverse for interaction and collaboration in virtual space. From the multimedia perspective, the user's quality of experience depends on the latency, bandwidth, and traffic pattern, and immersive media of the network (Dong and Lee, 2022). Xiao et al. (2022) developed a hybrid user experience by integrating radio frequency identification (RFID) with VR. New architecture was proposed to compose RFID and VR promptly for RFID-augmented VR applications.

VR and AR and other media have been increasingly contributing to digital economics including digital learning (Gugenheimer, 2022; Kanematsu et al., 2022). To support development across different media, Chidambaram et al. (2022) developed a unified platform which was able to capture users' intentions for creation without programming. Berardino and Tucker IV (2022) developed a portable demonstration system to train military space professionals for common operations; immersive experiences were created by MR to facilitate effective decision-making in operations with reduced tactical timelines. The metaverse requires high efficiency of data transmission over the internet. Moving Picture Experts Group 5 (MPEG-5) video standards and low complexity enhancement video code (LCEVC) were discussed and their applications on High Dynamic Range (HDR), 8k-resolution, XR, immersive video, and the metaverse are explored. LCEVC was compliant to other codecs to enhance the compressing efficiency of videos, and it was deployed in a wide spectrum of applications from HDR to 8K, and to the immersive metaverse (Ferrara et al., 2022).

The metaverse is the convergence of VR, MR, AR, DTs, BDA and blockchain that enables multisensory interactions with people, objects, and resources in the physical and digital worlds (Mourtzis et al., 2022). The metaverse gains experiences from an ultra-realistic, pervasive, and decentralised digital world accessed by VR, MR, AR, DTs, and digital triad things (DTTs) and is the most advanced digital transformation (Bi et al., 2022; Leng et al., 2022). It is a virtual universe that goes far beyond traditional three-dimensional and immersive environments (Lv et al., 2022b). De Felice et al. (2022) gave an overview of existing technologies, applications, and challenges, and focused on the challenges of interoperability and interconnection. A virtual world is a simulated environment where users can inhabit and interact with others via avatars, agents, bots, or digital models. The metaverse is distinguished from other online games in the sense that it provides a seamless and persistent virtual world where users can roam around transparently without preset objectives (Kumar et al. 2008). Zhang et al. (2023) discussed AR services enabled by multi-access edge computing (MEC). It allows users to locate and communicate simultaneously to request AR services. In developing a virtual world, metaverses can be used to implement both the Ethereum-based Decentraland and the sandbox (Kshetri, 2022b). Pena et al. (2023) investigated the impact of customised styles of avatar leaders on subsequent altruistic behaviours, and they confirmed that business leaders would affect individuals' behaviours and avatar customisations would affect social perceptions and altruism effectively.

Incorporating VR and other relevant technologies into the metaverse need to address a number of new challenges due to its distributed, decentralised, and dynamic nature. For example, Vondrek et al. (2023) described the security and privacy attacks on VR technologies in the metaverse as a man-in-the-room attack. This new type of attack was associated with worming and botnets over social networks.

As far as the hardware is concerned, HoloLens 2 supports untethered MR over the Windows Holographic Operation System. It comprises four vision cameras to track the head, two infrared cameras to track the eye, one time of flight sensor to measure depth, and one inertial measurement unit (IMU) with an accelerator, gyroscope, and magnetometer. It has a Qualcomm Snapdragon 850 processor for fast processing and a short wake-up time. It has a USB-C port as Bluetooth connection (Bansal et al., 2022). Microsoft Dynamics 365 is an MR for users to collaborate in a distributed environment with Microsoft VR equipment running on iOS, Android, HoloLens, and HoloLens 2.

3.3 Digital Twins, Cyber Physical Systems

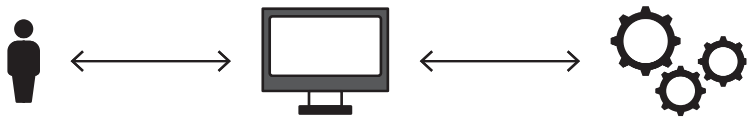
Figure 11 demonstrates how a metaverse is rooted from digital twins. Digital models of physical things used to be represented by 2D graphics and AI engines. They are greatly advanced with sophisticated 3D graphics, kinematic and dynamic models, and AI algorithms to represent their physical behaviours vividly. Key features of virtual models in the metaverse are multimodal input, heterogeneous clients, server scalability, network constraints, object encoding, physics engines, and security, privacy, and fairness (Kumar et al., 2008). In the metaverse, a digital entity coexists with its physical counterpart, empowered by AI for effective interactions between virtual and physical worlds (Shi et al., 2023).

Figure 11. From Digital Twins to Metaverse

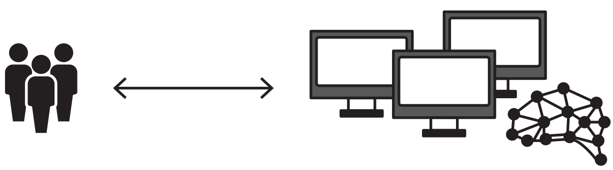
DTs were proposed in 2003 by Grieves for virtual and physical models paired with their connections. The metaverse comprises a number of virtual sub-worlds operated by corresponding virtual service providers, which are DT-enabled. Each DT establishes the communications and interactions of a virtual twin in the virtual world with its physical twin in the physical world (Han et al., 2023a). DTs make significant contributions to conceptualising, prototyping, verifying and validating engineering concepts, empowered by deep learning to deal with an increasing volume, variety, and velocity of data (Huang et al., 2022).

Song and Qin (2022) explored existing metaverse technologies for their applications in healthcare systems. DTs were especially adopted to assess and maintain personal health, based on some commonly used factors such as vital signs, behaviours, and other observed symptoms. On the other hand, the quality of DTs was determined by real-time-ness, completeness, sufficiency, and accuracy of monitoring data. As a hyper-realistic virtual world where users are able to perform their daily activities such as working, socialising, gaming, entertaining, and shopping, the metaverse is required to offer virtual representation of physical objects, their relations, events, processes, states, and activities in a real-time model. The key facets of the metaverse are dataset, simulation engines, artificial intelligence, hardware, and collaboration (Jaimini et al., 2022). Han et al. (2023b) viewed a metaverse as an instance of CPSSs, and they integrated artificial cyberspace, parallel execution, and computational experiments such as ParaDefnder to defend against cyber threats in the metaverse. Corresponding tasks in the physical and virtual cyberspace were executed in parallel for mutual verification and validation to assure security. This parallel execution is event-driven, and an event is one of the possible spatial-temporal combinations of security threats in the metaverse. Huynh et al. (2022) adopted DTs in the metaverse to support communication, storage, and computing in edge computing. DTs were used as a powerful computing infrastructure to offload tasks for reduced latency. They were empowered by edge intelligence to advance the immersive metaverse by improving the allocations and utilisation of computing resources. With the integration of DTs, CPSSs with industry 5.0 supported human immersion in the metaverse and interaction with smart things and other avatars. Jagatheesaperumal and Rahouti (2022) proposed a service-oriented architecture for a metaverse platform for effective human-machine interactions. A CPSS was incorporated into a virtual classroom to standardise workflow and construct a system from off-the-shelf components. The metaverse was introduced to enabled immersion, interactivity, and diversity of education systems (Shen et al., 2022b).

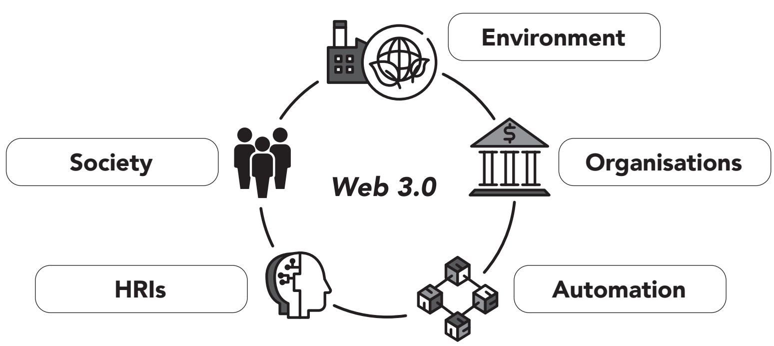
3.4 Internet of Things and Edge Computing



(a) Web 1.0 – static-ready only webpage (1990s–2000)



(b) Web 2.0 – Information-centric and interactive (2000s–2020s)



(c) Web 3.0 – user-centric, decentralised, private and secure (2020s–beyond)

Figure 12. From Web 1.0 and Web 2.0, to Web 3.0

The metaverse has been implemented in Web 3.0, with web technologies having evolved from Web. 1.0 to 3.0 as shown in Figure 12 (Mourtzis et al., 2022). The metaverse comes with Web 3.0 as the two next big things, co-existing and evolving rapidly.

Web 3.0 was expected to have over 1 billion users by 2023. From the perspective of Web 3.0, the metaverse is a virtual world featuring smart things, avatars, and functional units that freely interact with each other (Kshetri, 2022). Moreover, edge-computing has become essential to support on-device XR for metaverse applications. Parmar et al. (2023) used a deep neural network to perform hand detection and eye segmentation to analyse the impact of quantisation and bottlenecks related to hardware systems. The results could be used to select appropriate hardware systems for proposed tasks. The convergence of edge intelligence was incorporated in metaverse architecture; specifically, newly-developed edge-based technologies were introduced to support metaverse engines (Lam et al., 2023).

IoT helps to collect abundant real-time data for prompt and reliable decision-making supports. Dai et al. (2023) discussed the trend of using wearable electromechanical sensors with machine learning for effective metaverse, soft robots, and human-robot interactions. Enabling metaverse technologies are mostly distributed intelligence relying on intensive communications and interactions among networked things over the internet. Metaverse use cases have strict requirements with fully immersive experiences, and a large number of distributed and concurrent users and connections, bring challenges to networks. The sixth generation (6G) becomes an ideal choice with its ultra-low latency, ubiquitous connectivity, and superior reliability and capability. It enables edge intelligence of smart things in IoT where human, device, and smart things can be interconnected, cooperate, and collaborate anywhere and at any time whenever they are needed. The metaverse aims to connect billions of people in a shared world (Chang et al., 2022). The advance of multisensory technologies has enabled the feasibility of collecting, transferring, and sharing the senses over the internet. Digital olfactory stimulation has been utilised to implement digital multisensory communication. It is expected that the Internet of Senses will be commercialised in 2030 so that users can immerse themselves in the intimate nature of multisensory experiences (Panagiotakopoulos et al., 2022).

Tang et al. (2023) discussed the roadmap in advancing networks and communications to enable metaverse technologies, including DTs, MEC and Blockchain. Siyaev and Jo (2021) discussed the importance of speech communication in space applications, and the metaverse was introduced for aircraft maintenance training alongside traditional manuals, 3D models, simulators, and neuro-symbolic speech executor. Shen et al. (2022b) proposed a parallel sensing framework that comprised concepts, backgrounds, and methods for parallel sensing, with sensors generally referring to the integration of physical and software-defined sensors based on parallel intelligence. Parallel sensing allows its physical twin to operate in a discrete time domain to reduce energy consumption, and its virtual twin to offer compensation data and serve as guardian.

The synchronisation between the physical and digital worlds is critical. Meng et al. (2023) proposed a sampling and communication framework to reduce communication loads with the consideration of tracking errors. Expert systems and deep learning algorithms were used to optimise a sampling rate and prediction. The prevalence of IoT makes it possible to build large-scale complex networks such as smart cities from smart things including actuators, sensors, appliances, and cyber services. Abdel-Basset et al. (2022) proposed federated learning with privacy-preserved intelligence to protect data subject to cyber-attack. In the metaverse, IoT provides users with cyber-virtual experiences in immersive mixed-reality environments. IoT maps real-time data collected from the physical world into a digital twin in the virtual world, thus enhancing users' interfaces with the virtual world. For example, smart devices are attached to patients to monitor health conditions and this elicits their responses in the virtual realm, while smart sensors are widely used to track user exercise patterns. IoT data are utilised to establish a network for remote access or control real or virtual things in real-time. In the IoT-based metaverse, the four pillar technologies to enable VR and digital twins are AI, high-speed data communication, MEC, and DTs (Li et al., 2023a).

3.5 Big Data Analytics and Cloud Computing

A metaverse use case usually involves a massive amount of real-time data that needs to be processed and mined in a real-time mode. Bi and Cochran (2014) and Li et al. (2022) discussed existing data analytic methods in solving complex engineering problems from the definitions of customers' requirements to designs, manufacturing, logistics, and services of products. With the growing size of IoT, BDA is in high demand to support various decision-making activities.

In regard to the correspondence of BDA and metaverses, metaverses are enhanced DTs and BDA are the gateways for digital and physical things (Lv et al., 2022b). To achieve satisfactory immersive experiences in a metaverse use case, it is critical to render scenes in a real-time mode. This involves intensive computation and poses challenges to support real-time rendering. Jiang et al. (2023) proposed code distributed computing as a collaborative computing paradigm to offload rendering tasks to other mobile devices, so guaranteeing fault-tolerance by aggregating spare computing resources from mobile devices. The metaverse involves the transmission of massive amounts of sensing data from the physical to the virtual world. Wang et al. (2023c) proposed a semantic framework to encode and transmit sensed data based on semantic information to dramatically reduce the amount of transmitted data without affecting the quality of real-time data for metaverse services.

The metaverse is distinguished from traditional CPSs by parallel intelligence to enable blockchain, smart contracts, web3, DAO, decentralisation (Wang et al., 2022b), with Ye and Wang (2022) viewing the metaverse as an infrastructure for artificial systems, computational experiments, and parallel execution (ACP). They proposed parallel population to manage human behaviours in human hybrid systems. A person's thinking was modeled by heterogeneous learning, and analysed by deep evolutionary reasoning. Yang et al. (2022b) further extended ACP in parallel manufacturing where customers' demands were analysed, extracted, and utilised to plan R&D and production. Meanwhile, Zhang et al. (2023b) proposed a framework of parallel vision for an intelligent transportation system in the metaverse to improve its efficiency, effectiveness, and safety.

3.6 Blockchain Technology

The metaverse and blockchain were integrated to establish digital spatial models of architectural engineering in building information modelling. This was a comprehensive process to collect and utilise building information to support decision-making activities such as in relation to design, construction, use, and demolition in an enterprise's lifecycle. Adopting blockchains ensured security and fairness in transferring resources and assets, protecting data, and executing commercial business matters (Huang et al., 2022). As a decentralised technology, blockchain and similar technologies such as nonfungible tokens (NFTs) and cryptocurrencies are critical to sustain open and safe business environment (Kshetri, 2022). When humans are immersed in the metaverse, they are digital entities who interact with each other by means of ubiquitous access controls. While these provide bridges to shuttle in a virtual world, numerous threats exist, and a blockchain enabled multi-signature lock can alleviate security issues at the access layer in such a control scheme (Gai et al., 2022).

The metaverse has been characterised as providing immersive interaction, socialisation, worldbuilding, and expandability. Meanwhile, numerous security or privacy risks such as leakage of personal information, eavesdropping, phishing, broken authentication, and unauthorised access (Huang et al., 2023) have been exposed. Tao et al. (2022) modelled blockchain transaction networking in the forms of NFTs, Ethereum, and Bitcoin for enabling relations among multiple entities from the perspective of structural identity. A metaverse application involves multiple synchronised data flows among smart things with different quality requirements. A customisable utility function was defined for each data flow, and a service quality model was proposed to allocate and select a data flow using NFTs. This enabled trades among stakeholders in a decentralised mobile environment (Maksymyuk et al., 2022). The metaverse has been integrated with blockchain to collect users' data and improve services in a hybrid framework for decision-making support in sustainable public transportation (Deveci et al, 2022).

The metaverse differs from conventional services such as those provided by microphones or cameras for cultural or economic businesses in the sense that metaverse use cases are vulnerable to various security threats since services are provided through public channels. Ryu et al. (2022) presented a model to manage user privacy securely by mutual authentications using blockchain, while Chen et al. (2023) considered the adaption of digital fair exchange in the metaverse. Most models use a trusted third party to address disputes among stakeholders. Different protocols for cryptographic fair exchanges in a decentralised environment were discussed. The critical properties of fair exchange protocols include fairness, decentralisation, modification-free, privacy, verifiability, efficiency, and interruption. As a fully immersive, hyper-spatiotemporal and self-sustainable space for users, metaverses are challenged significantly by privacy invasion and security breaches, while assuring security and privacy are primary in practical applications with development standards having helped to achieve this goal. Two dedicated standards for metaverse applications are (1) ISO/IEC 23005 as a framework for networked virtual environment and (2) IEEE 2888 as standardised interfaces to synchronise cyber and physical worlds, as seen in Figure 13 (Wang et al., 2023).

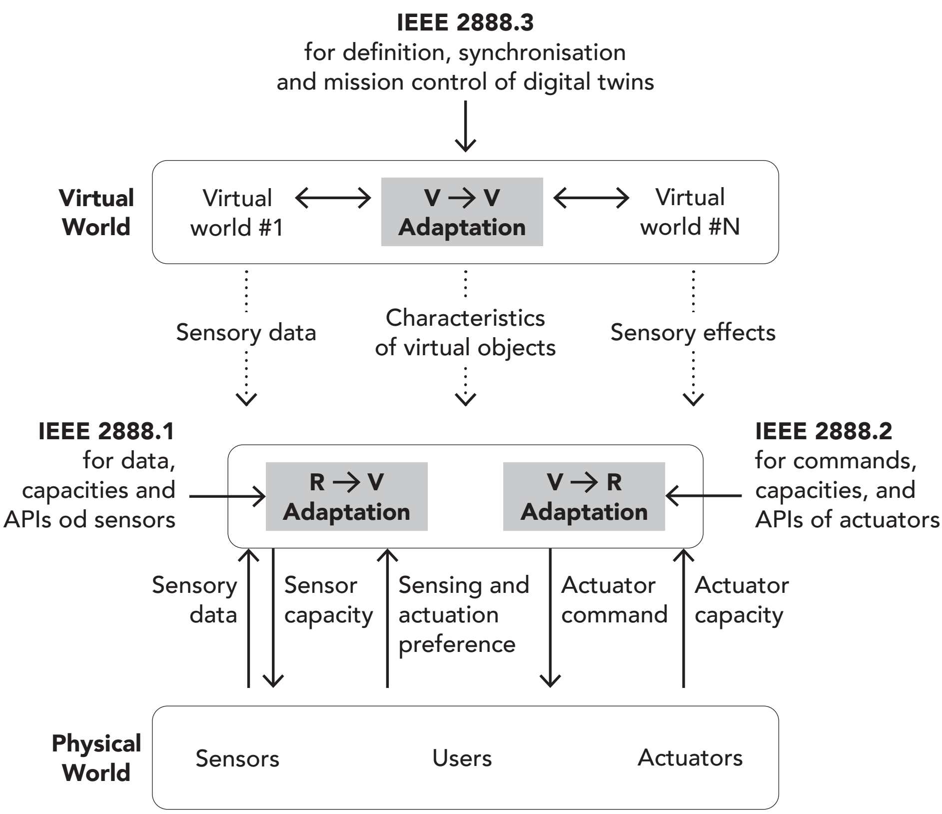


Figure 13. The Architecture of IEEE 2888 for Metaverses

No generic types of blockchain are applicable to any application scenarios. Blockchains with different features and characteristics exist. There is the need to communicate, transfer, and exchange values and data among heterogeneous blockchains. Ou et al. (2022) investigated the development of cross-chain technologies to identify the challenges in supporting the interactions in multiple blockchains. The role of blockchain technologies in a metaverse is to assure privacy and security of interactions as shown in Figure 14 (Wang et al., 2023).

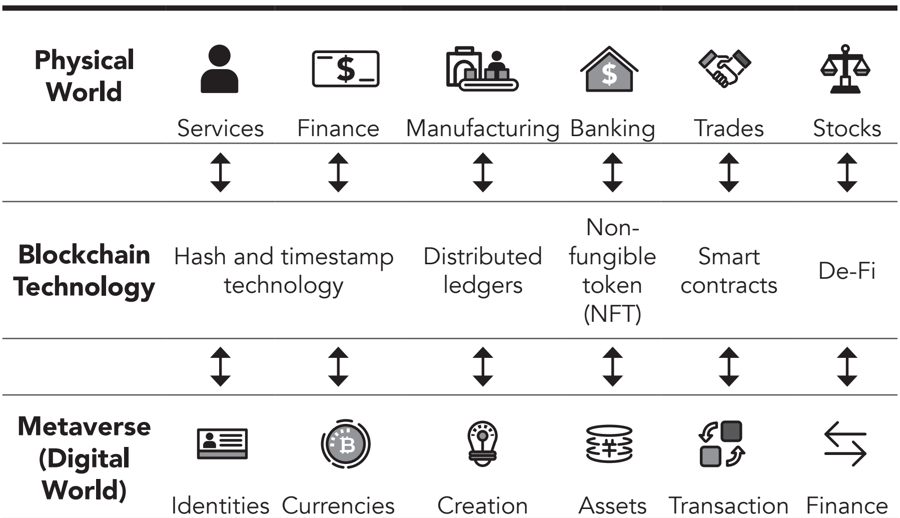


Figure 14. Blockchain as the Bridge between the Metaverse and the Physical World (Wang et al. 2023)

The metaverse improves efficiency and safety of traffic, while also reducing pollution and emissions. However, since wireless communication is open, the data packets transmitted among vehicles expose the risks of public and concomitant leaks that might lead to vehicular platoons. Pan et al. (2023) discussed the control of privacy-preserving platooning of vehicular CPSs. Lv et al. (2022b) integrated blockchain with DTs where blockchain was utilised as the information infrastructure to ensure the security of the digital mapping processes over the IoT. A non-autogenic hash geocoding method was developed to index multidimensional information, avoid information loss in data mining, and facilitate the implementation of the metaverse through spatial DTs. Users in the metaverse interact with one another by digital transformation, and such interactions among stakeholders are established based on assured security, and privacy of data and assets of users. With a rapid increase in the variety, volume and velocity of data, the metaverse faces challenges to ensure security, privacy, and synchronisation of data with a low latency. Blockchain technology and enabled intelligent networking exhibit the potential to support trusted execution of business processes, and transmission and exchanges of data and assets in distributed, dynamic, and decentralised environments (Fu et al., 2023).

3.7 Artificial Intelligence

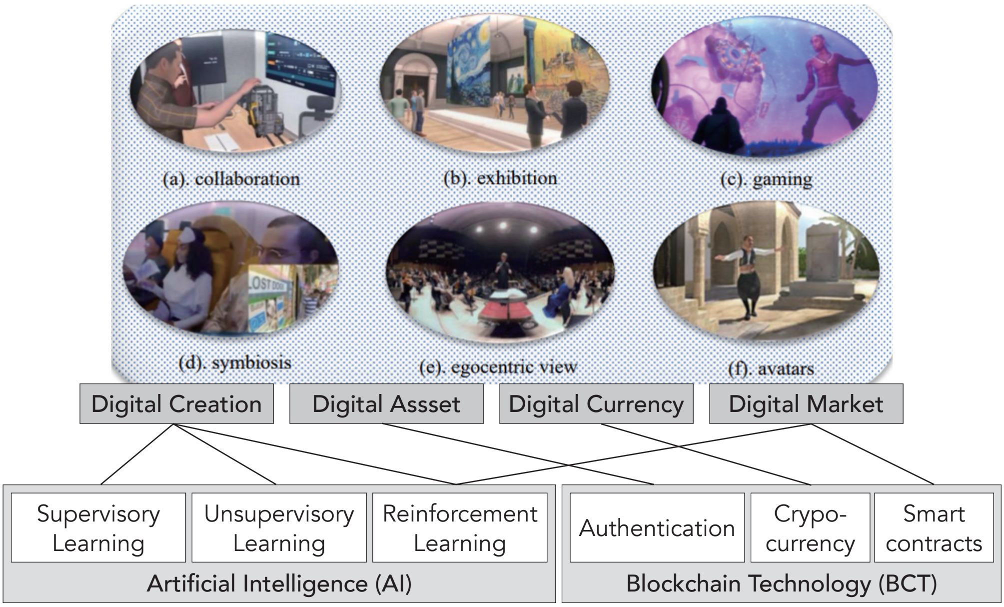


Figure 15. AIs for Metaverses (Yang et al., 2022a; Yang et al., 2022b)

Sustainable manufacturing involves numerous decision-making activities at different levels and domains of manufacturing businesses. Traditionally, computer-aided decision-making has relied greatly on analytical or numerical models. However, developing a functional mathematic model becomes impractical when the system involves too many variables, uncertainties, and changes. While the input, output, and interaction of a system with its environment may be clearly defined, the system itself has to be treated as a "grey" or "black" box, rather than a "white" box which allows for establishing an explicit computer model. Compared to AI, humans have shown superior capabilities in dealing with incomplete information, complexity, dynamics, and uncertainties; AI artificially mimics human intelligence to perform cognitive functions that can be associated with human minds such as reasoning, perceiving, learning, coordinating, and interacting. As shown in Figure 15, to implement typical metaverse applications such as virtual exhibitions, collaborations, and concerts, it is essential to integrate AI to support decision-making activities since these applications are in open networking environments which are highly dynamic and with numerous anticipated and unanticipated changes. Yang et al. (2022a, 2022b) discussed the importance of AI and blockchain in the metaverse and suggested that AI and blockchain must be fused to develop a fair, open, and rational metaverse.

Gu et al. (2023) used deep reinforcement learning (DRL) to model crowd distribution during an evacuation to optimise escape paths in a metaverse-based evacuation training system. The evacuation scene was modelled based on real-time data collected from various sources such as cameras and smoke detectors. Such data were processed by DRL in the cloud to produce evacuation guides dynamically. Hare and Tang (2023) used a hierarchical multi-agent framework where DRL was used to augment the intelligence in personalising learning experiences in the metaverse. Kang et al. (2022) proposed a decentralised agricultural organisation and decentralised science for an agricultural metaverse (AgriVerse) where AI was used to process heterogeneous data, knowledge, and model and support the interactions of production businesses.

The AgriVerse was viewed as a CPSS which was capable of processing heterogenous data in a socio-economic environment in real-time mode. Zheng et al. (2023) developed a data-knowledge-driven group intelligence framework to mine data for wisdom and knowledge. Ubiquitous data become new sources to power AI for both value-added business activities and academic study. The metaverse has become a promising solution to address the limitations of AIs in terms of latency, fragile stability, and security (Chang et al., 2022). Ren et al. (2022) used collective learning and many-to-many matching game-based scheme to deal with insufficient or frequently changed data.

3.8 Human-Machine Interactions

Even with rapidly developed AI, humans still play irreplaceable roles in sustainable manufacturing. Moreover, human creativity can be greatly empowered by machine intelligence. For example, humans and machines can collaborate to create, disseminate, and trade arts effectively. Guo et al. (2023) proposed a parallel system into which machine learning was incorporated to improve human creativity. Machine learning was able to manufacture products subject to human guidance, while humans would perfect creative ideas and improve productivity.

Mourtizis et al. (2022) presented a human-centralised platform to personalise value creation in the metaverse for manufacturing in Web 3.0. To support natural interactions between humans and machines, Wang et al. (2023e) argued that when metaverses were used to support human machine interactions, conventional manufacturing systems would be actually elevated as cyber-physical-social systems, and they proposed an industrial foundation model to provide data and scenarios in managing, operating, and controlling computing resources, digital assets, enterprise resources, and I/O interfaces (see Figure 16).

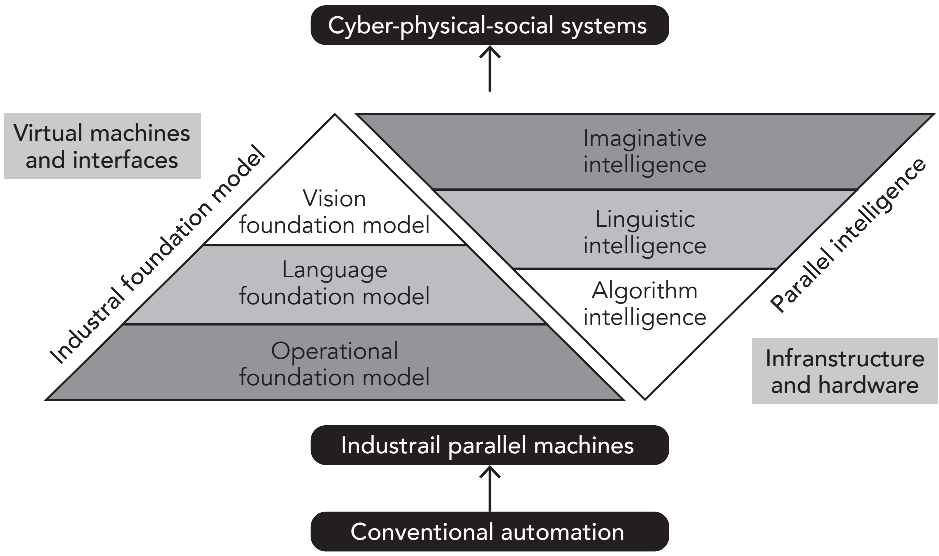


Figure 16. Industrial Parallel Machines for Effective Human-Machine Interaction (Wang et al., 2023e)

Fan et al. (2022) adopted the concept of CPSSs to monitor, simulate, diagnose, and predict road conditions, while the metaverse was introduced in a road maintenance system to assess the surface conditions of a road so as to provide timely alerts about sudden damage. The metaverse was viewed as an extension of CPSSs and was used by Liu et al. (2022b, 2023a) to plan and manage radar systems, with AI integrated with computational experiment and parallel execution for effective decision-making support. Park and Kim (2022) analysed approaches to sensing interactions, and implementations of user experience in the metaverse, finding that comprehensive recognition and interpretation through multi-modal sensors were essential to advance the interactions involved in the metaverse.

3.9 Metaverses in Data-Driven Decision-Making Systems

The metaverse has become a critical infrastructure for implementing a hyper-flexible and self-adaptable smart factory, robotics meta-laboratory for neuro-ergonomics, serious game-based digitally enhanced advanced services, and aircraft maintenance with speech interactions. The metaverse is a shared, persistent and decentralised immersive environment for e-commerce, networking, education, and the digital economy. Many researchers have explored the applications of the metaverse in data-driven decision-making systems. For example, Wang et al. (2022a) proposed a framework using the metaverse for education. The framework comprised an instructional design hub, knowledge hub, research and technology hub, and talent and training hub. All of the four hubs were built upon common (1) infrastructure and communication, (2) technological access and equity, and (3) data security, privacy policy, and user rights. Examples of metaverse platforms for education included Sloodle as an interactive and immersive laboratory to teach programming and immersive journalism; Vortex for collaborative learning, VR-making and metaverse-linking for instructional VR design; and VRChat, AltSpaceVR, Virbela, EngageVR, Sansar, Sinespace, Somnium Space, Mozilla, Decentraland, and Horizon World as the 3rd generation sensory immersions for embodied representations, online meetings and education. Onggirawan et al. (2022) investigated the use of the metaverse in the learning process as a virtual educational space. It was unfortunately found that existing metaverse technologies were capable of supporting only a limited range of educational subjects in comparison with traditional textbook-based or face-to-face learning.

Wang et al. (2023b) discussed the principle of value creation of using the metaverse in the crypto industry, the attention economy, webs and media theory. Wang et al. (2023c) introduced the metaverse to model humans, avatars, and robots, and their interactions in operating oil fields. The proposed system supported parallel executions, and was capable of guaranteeing 6S - security, safety, sustainability, services, sensitivity, and smartness. Wang et al. (2022c) used the metaverse for automated quality inspections to manage the quality of products, manufacturing, processes, systems, and services. The metaverse was also used for agriculture as decentralised complex adaptive systems in agriculture. It was digitised in smart villages with the support of decentralised science, decentralised autonomous organisation and CPSSs. Agriculture 4.0 has integrated robotics, IoT, BDA, and AI into agriculture and incorporating the metaverse has allowed for adequate interaction with human and social factors (Wang et al. 2022d).

The metaverse was used by Lee (2023) in human resource development to (1) provide holistic capabilities for benchmarking, forecasting, and modelling, (2) promote on-the-job learning, and on-the-life training, and (3) standardise communication tools. Deveci et al. (2022b) integrated the metaverse into a two-stage decision-making model to analyse and optimise alternatives for freight fluidity measurement. Liu et al. (2022a) adopted the metaverse to improve efficiency and security in mining. The infrastructure of the proposed MetaMining comprised the human world together with virtual and physical mining systems. Virtual mining was used to test and correct proposed algorithms and systems.

Rahmani and Tienken (2022) used the metaverse to fuse and distribute culture heritage data. The proposed framework allowed connecting massive contexts, objects, and intangible assets via IoT, thus promoting use-driven creation, offset economic models, and rewarded performers and creators. Pamucar et al. (2022) assessed four metaverse applications for sustainable transportation based on thirteen criteria in terms of operation, efficiency, social and health impact, and legislation and regulation. These metaverse alternatives included auto-driving testing, public transportation operation and safety, traffic operation, and economic application sharing. Zhang et al. (2023d) integrated the metaverse into healthcare systems to optimise the utilisation and allocation of healthcare resources, using multiple servers to share data and support deduplications securely.

Li et al. (2023b) proposed a six-layer data-driven information system that comprised infrastructure, operation, knowledge, intelligence, management, and interaction layers. Li et al. (2023c) further proposed a three-layer framework for intelligent box compositions with perception, cognition, and decision-making support for interactions. It allowed perceiving human and provided feedback to assist the human driver for a safe, pleasant, and efficient experience in an intelligent cockpit. Active empathetic auditory was regulated to detect drivers' intentions. Roadside vehicle-to-infrastructure systems were introduced to replace isolated traffic signalling systems to support Connected and Autonomous Vehicles (CAVs). The metaverse was used to manage CAVs at signal-free interactions to maximise efficiency of throughputs (Li et al. 2023d). Echocardiography was use to evaluate cardiac anatomy in detecting congenital heart disease. Qiao et al. (2022) incorporated the metaverse to improve robustness and detection accuracy in fetal investigation by suppressing adverse factors such as instinctive fetal movements, artifacts in ultrasound images, and distinctive fetal cardiac structures.

To share opinions, resources, and interests in distributed environments worldwide, language generation methods can be helpful to regulate a VR environment. Languages can be generated in a number of ways including transfer learning or neural learning such as RNN, GRU and GPT-3. Park et al. (2022) proposed a recurrent voting generator to understand 3D text and perform emotional analytics in the metaverse. The enabling technologies of the metaverse such as DTs, AI, extended reality, and blockchain, are energy-hungry. Zhang et al. (2023c) discussed sustainability-related requirements for its large-scale deployment and development. Key challenges identified were quality of experience, sustainability, energy consumption, trade-off, and new incentive schemes for green technologies. A metaverse may involve billions of hyperparameters that are trained using thousands of gigabytes of data. A foundation model, used to train a generic system for better adaptation to changes of large-scale datasets, is capable of combining all pertinent data and customising tasks across multiple modes. To manage risks from data poisoning attacks, Li et al. (2023b) proposed a closed-loop human-computer environment to validate and calibrate a foundation model.

4 Metaverses for Space Applications and Sustainability

The metaverse has evolved systematically, grown in popularity rapidly, and is now distinguished from conventional technologies for pure virtual worlds such as Second Life; three defining capabilities of the metaverse are immersiveness, sociability, and environmental fidelity (Barrera and Shah 2022). However, a limited number of metaverse versions are available. There is a long way to go for the development of a fully immersive, interoperable, and embodied metaverse. To develop a full version of the metaverse it must be edge-enabled and there are challenges related to computation costs due to the limitations of edge devices. The areas that require further advances include multiple accesses for immersive streaming, multi-sensory and media networking, multi-modal semantic communication, DT edge networks, edge intelligence and intelligent edges, sustainable resource allocation, smart blockchain, quality of experience, markets and mechanisms of services, and an industrial metaverse (Xu et al. 2023).

The metaverse is a scalable and interoperable platform for immersive activities. It supports interactions between the physical and cyber worlds, private and public networks, and open and closed platforms. Many companies have launched metadata

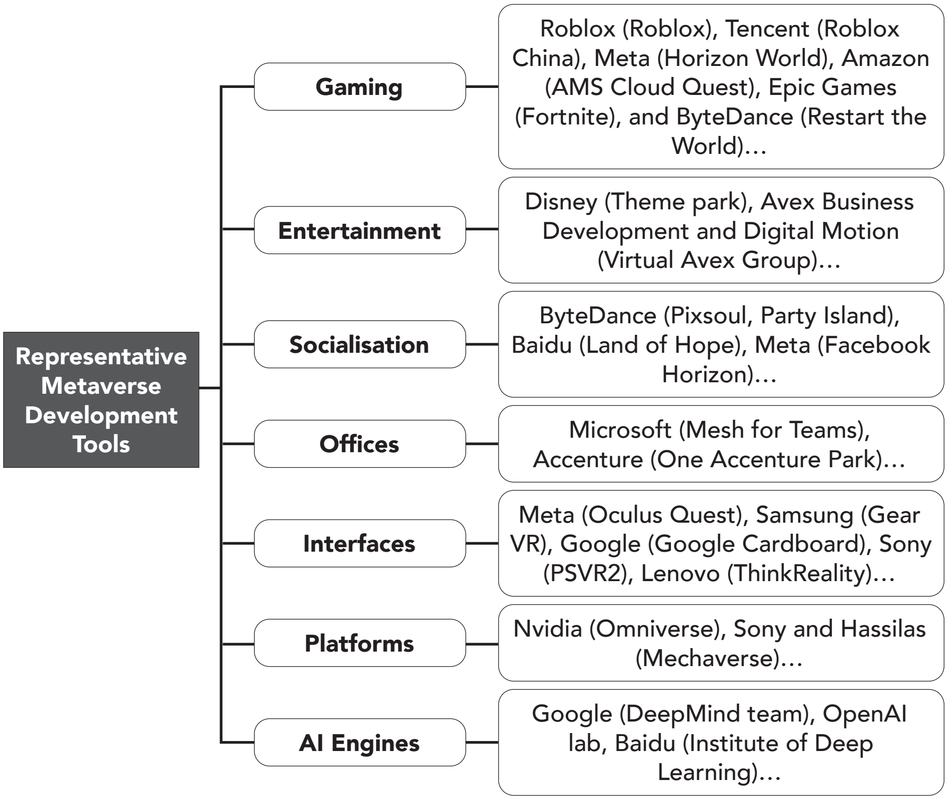


Figure 17. Example Systems for Metaverse Development in Representative Areas (Li et al., 2023a)

systems for metaverse developments in a sophisticated area such as video conferencing, gaming development and entertainment shown in Figure 17 (Zhou, 2022; Li et al., 2023a). Moreover, metaverses can be developed on different platforms, and it will be greatly beneficial to develop a universal framework, such as NVIDIA Omniverse (see Figure 18), to share and exchange user experience across the platforms. NVIDIA Omniverse supports cross-works of sensing and actuating, representation of assets, artificial intelligence, blockchain and cybersecurity (Dong and Liu, 2022).

However, similar to digital twins or the internet, the metaverse is just a tool for users to effectively interact via the internet with

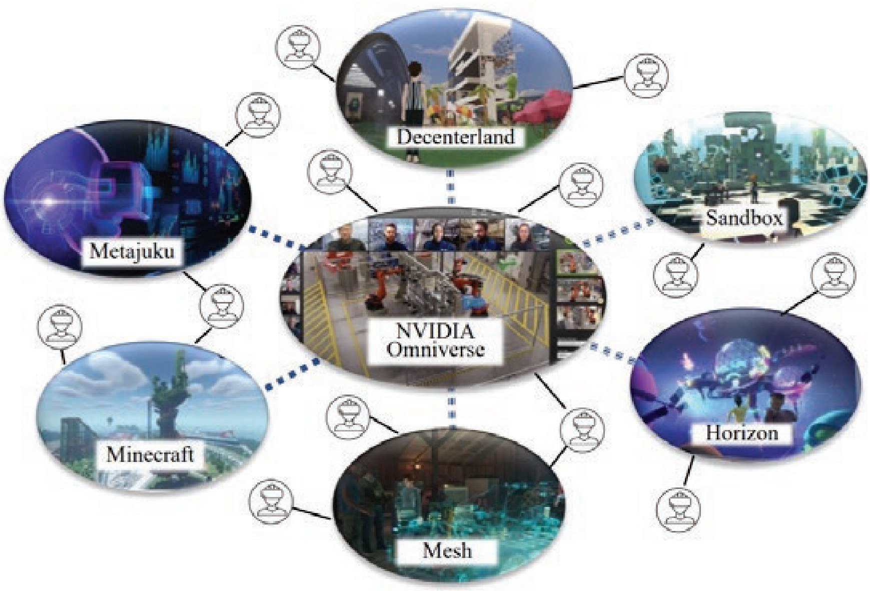


Figure 18. Universal Framework to Share User Experiences across Platforms (Dong and Liu, 2022)

people, machines, society, the environment, and any networked things. It is usually not a standalone technology and must be incorporated with other technologies to exhibit its full capabilities in various applications. Musamih et al. (2022) explored the use of the metaverse in the healthcare sector in areas such as training, marketing, supply chain management, fitness and wellness, and telemedicine. As shown in Figure 19, the incorporated technologies to implement the metaverse applications included distributed computing, AI, IoT, decentralised ledger technology and telecommunication (Cheng, 2022). Cao (2022) referred to such a co-existence of multiple technological environments as a metaverse ecosystem.

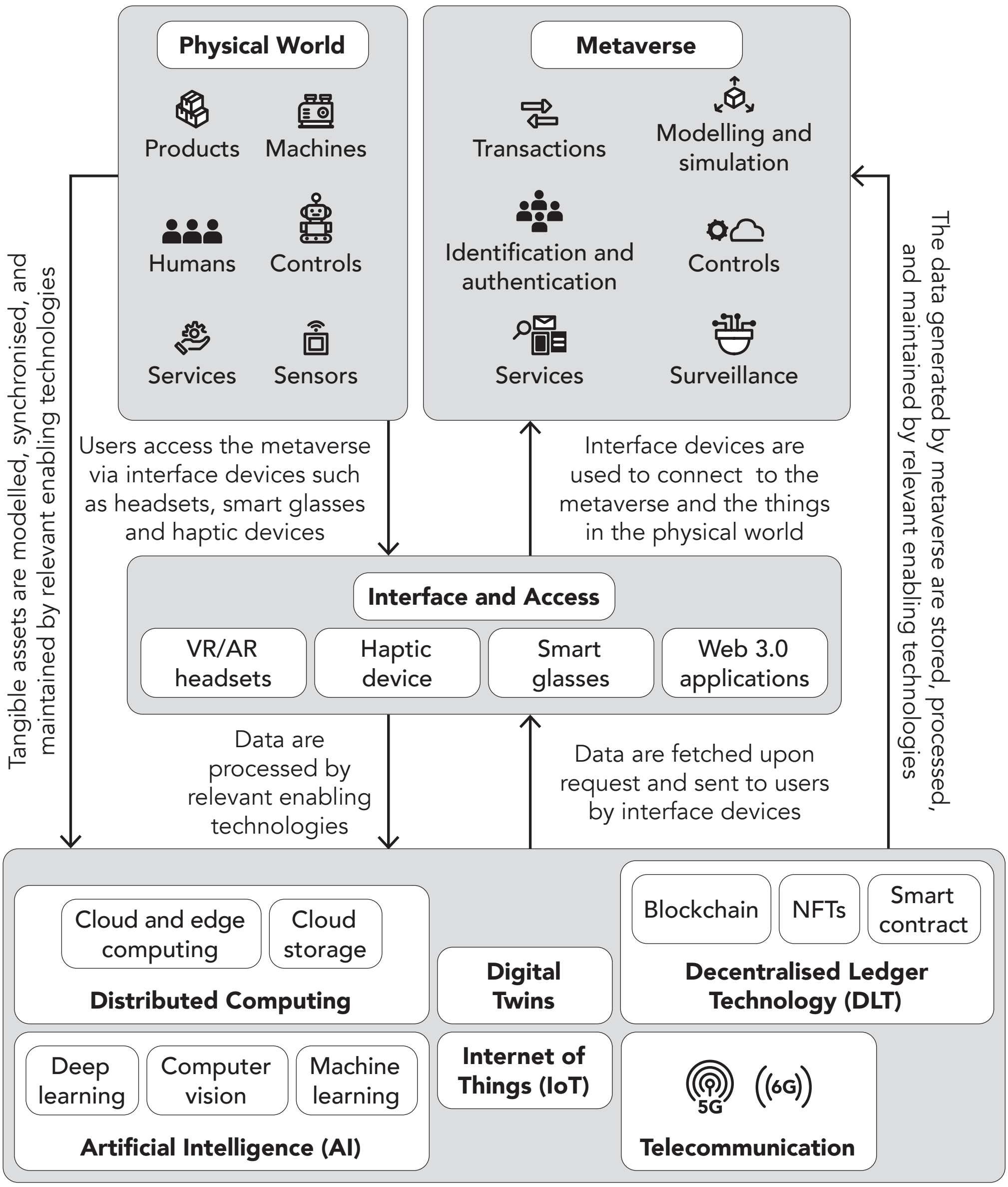


Figure 19. Needs of Incorporating Metaverses with Other Technologies in Applications (Musamih et al., 2022; Chao, 2022; Cheng, 2022)

4.1 Metaverses for Space Applications

Metaverses have been explored to support human-computer interfaces (BCIs) in order to enhance the flexibility, survivability, and adaptability of unmanned aerial vehicles (UAV). Bi et al. (2023a, 2023b) proposed a new platform to enable BCIs in machine control, as shown in Figure 20. Various metaverse devices could be integrated depending on their capabilities to acquire, classify, and utilise user brain signals. The current version of the platform was equipped with Epoc X 14 Channel Mobile Brainwear by Emotive and Muscle SpikerShield by Backyard Brains to collect brain signals from users, while customised programs were developed to train users until correct signal patterns could be produced for the expected motions to be observed on a robot. The platform also included portable drones with cameras to collect data from different environments. Moreover, everything was networked, and the whole platform could be viewed as a portable smart thing in the metaverse, serving for data acquisition, transmission, processing, and communication. For data acquisition, Epoc X 14 Brainwear was equipped with 14 channels for EEG signals to sense a motion in nine axes. This device was connected with other smart things wirelessly. Muscle SpikerShield was used to acquire electromyography signals from users. Electromyography measured muscle physiology to reflect brain activities. When the human decided to make an action, responsible neurons travelled from the motor cortex of the brain (i.e., upper motor neurons) to the spinal cord and synapses with lower motor muscles and neurons to make a motor unit.

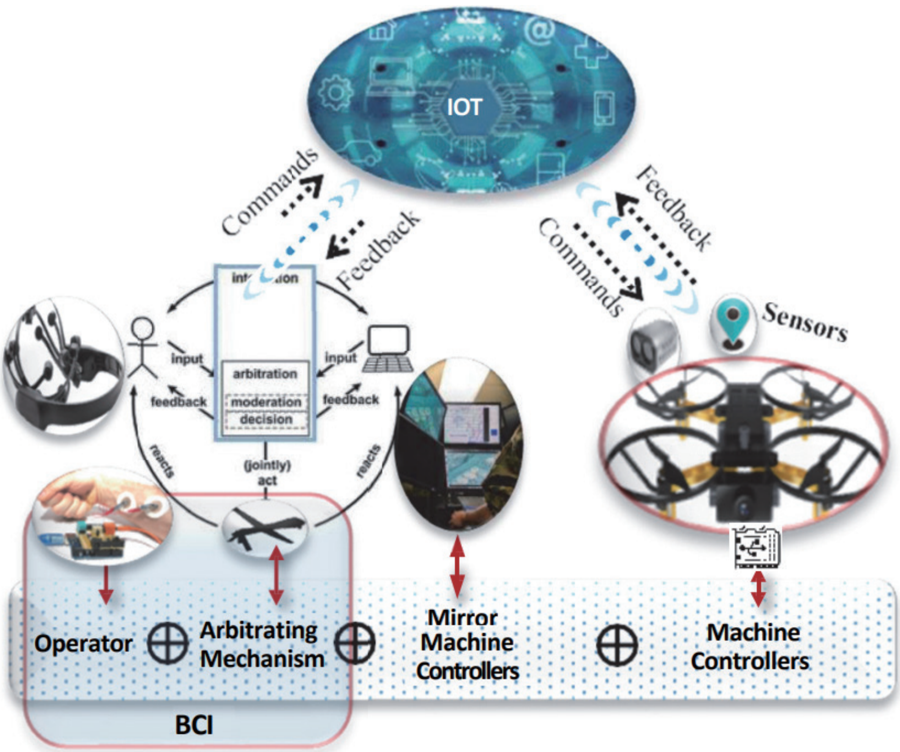


Figure 20. Metaverses for Supervisory Controls of UAVs (Bi et al., 2023)

4.2 Sustainable Manufacturing

Similarly, metaverses must be incorporated with other digital technologies for manufacturing enterprises to fully utilise their capabilities for enhancing sustainability. Section 2 discussed the FRs of technological sustainability that was measured in relation to six aspects. Section 3 discussed metaverses and relative technologies, and Figure 21 below illustrates how these technologies can be used as design solutions to fulfil the technological FRs of sustainable manufacturing elaborated in Section 2.

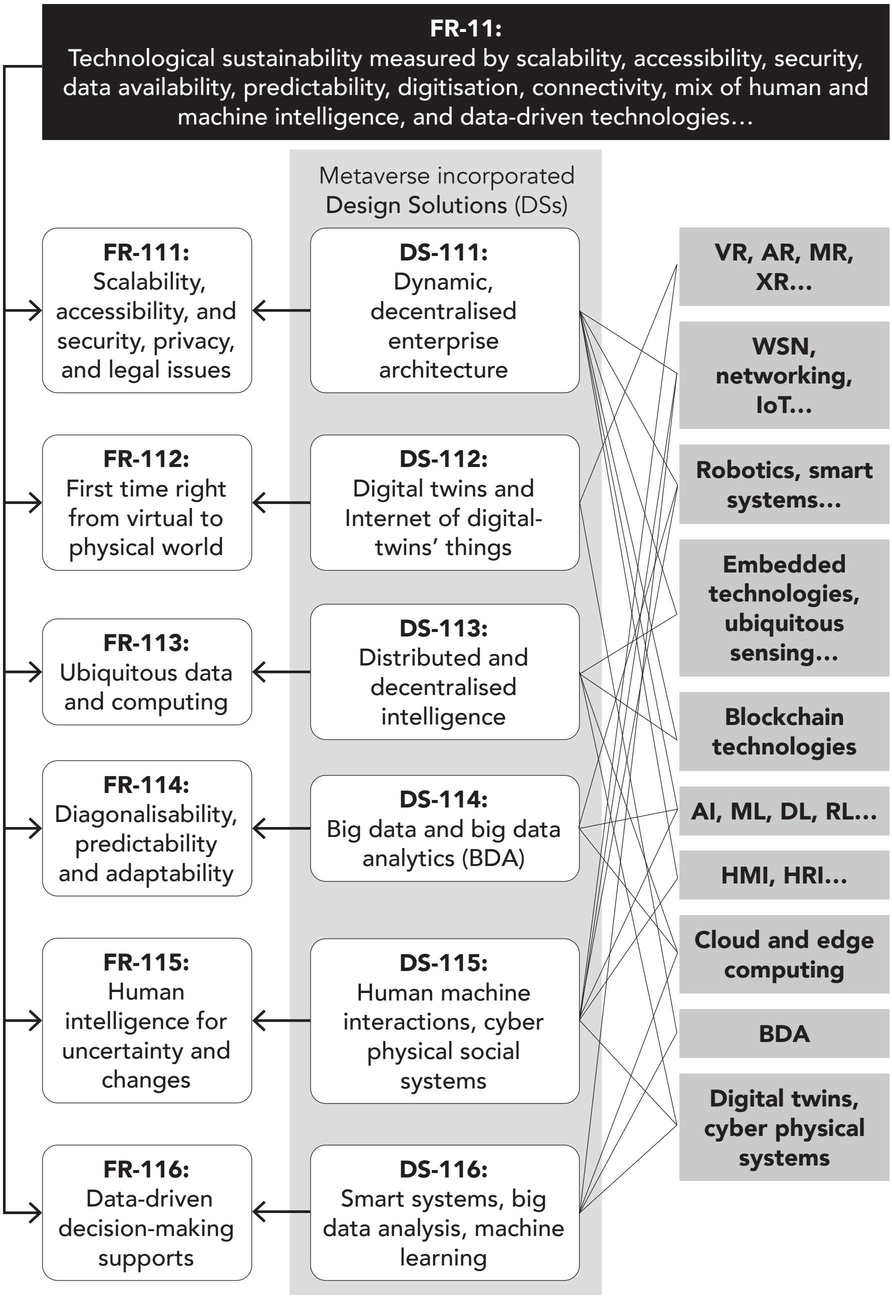


Figure 21. Metaverses in Satisfying Technological FRs of Sustainable Manufacturing

4.3 Framework for Metaverse Use Cases

Designing and operating a sustainable manufacturing system is generally very complex since every system has to be customised to specific products, given manufacturing resources, and business environment. However, the metaverse will be mainly used to support decision-making activities at different levels and domains of manufacturing businesses. Thus, a generic framework can be developed to select the right technologies for implementing certain functional units in a system.

Bi et al. (2021a) viewed any decision-making information system as an analogous manufacturing system whose "raw materials" are acquired data from various sources and "products" are the decisions, knowledge, or information required to operate a manufacturing system, as shown in Figure 22.

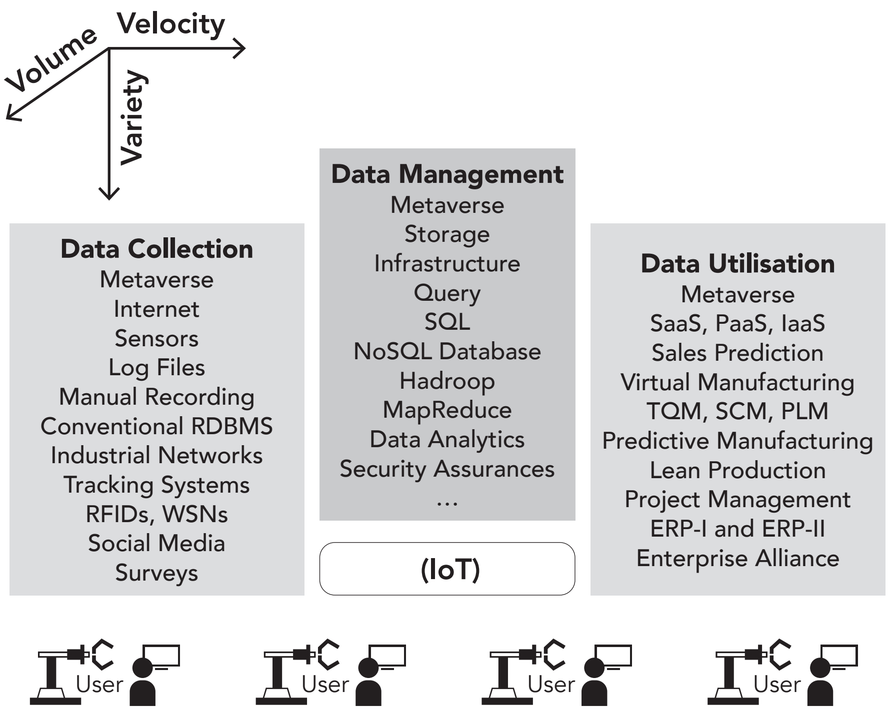


Figure 22. The Metaverse in a Data-Driven Functional Support Unit (Bi et al., 2021)

Accordingly, the complexity of an information system can be tackled by respective digital technologies as follows.

(1) At the data collection phase, the metaverse can be adopted to collect user data, visualise data, and establish the correspondences of relevant data. IoT helps to collect data from the networked things such as machines, operators, computers, sensors, and environments. As an increasing number of businesses are involved in a system, the data become "big" due to a continuous increase of volume, velocity, and variety.

(2) At the data management phase, the metaverse can be used to distribute and classify data, and distributed intelligence, edge computing, and cloud computing can be applied to transmit, distribute, share, and process data in all domains and at all levels of businesses. Some platforms such as MapReduce are adopted to manage distributed and big data and efficiently identify the most relevant data.

(3) At the data utilisation phase, the metaverse can be used to review and visualise data and identify correspondence of data, and big data analytics is adopted to mine and analyse knowledge. Edge computing and cloud computing can be applied for users to access and analyse data from anywhere and anytime as needed.

In developing a metaverse use case for a functional unit in a sustainable manufacturing system, the generic system design approach axiomatic design theory can be applied (Cochran et al., 2016; Cochran et al., 2016b). The system design follows three basic steps as seen in Figure 23. Firstly, a set of the quantified measures are selected as FRs. Secondly, all accessible technologies, including the metaverse, are identified to determine a space for digital

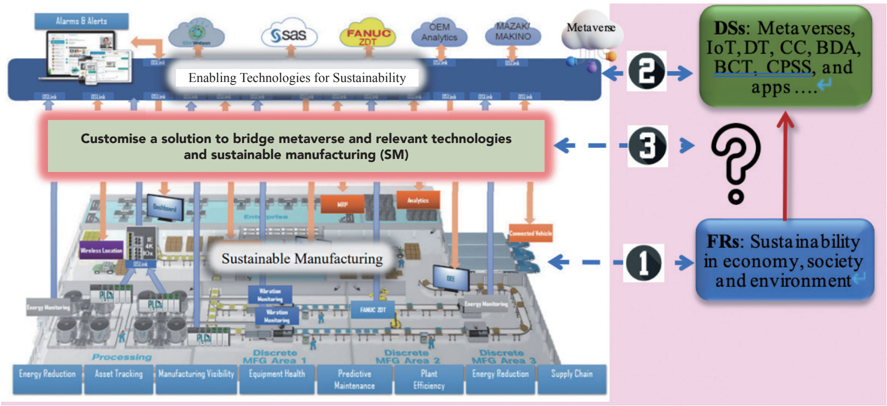


Figure 23. Customised Technical Solution for Sustainable Manufacturing

solutions (DSs). Thirdly, all technologies are evaluated again as the given FRs until an optimised sub-DS is found for any sub-FR.

4.4 Digital Triads and Internet of Digital Triads Things

The metaverse should be one of the critical enabling technologies to elevate digital twins (DT-I) to digital triads (DT-II), and elevate IoT to the Internet of Digital Triad Things (IoDTT) (Bi et al, 2021a, 2012b, 2022).

Conventional DT-I have their limitation in modelling and supporting a sustainable manufacturing system that can vary over time in an extended system lifecycle. DT-II were proposed to address issues of upgradability, adaptability, predictivity, sustainability, and resilience of a sustainable manufacturing system. As shown in Figure 24, DT-II differ from DT-I in the sense that a system life model is introduced to model the evolution of a system over time while a DT-I is an instantiation of system at a specific time. Since DT-II were rooted from DT-I, the metaverse can be fully utilised to develop, sustain, and update the life model of DT-II. Moreover, the technologies we have discussed in Section 3 should also be considered in defining and implementing DT-IIs.

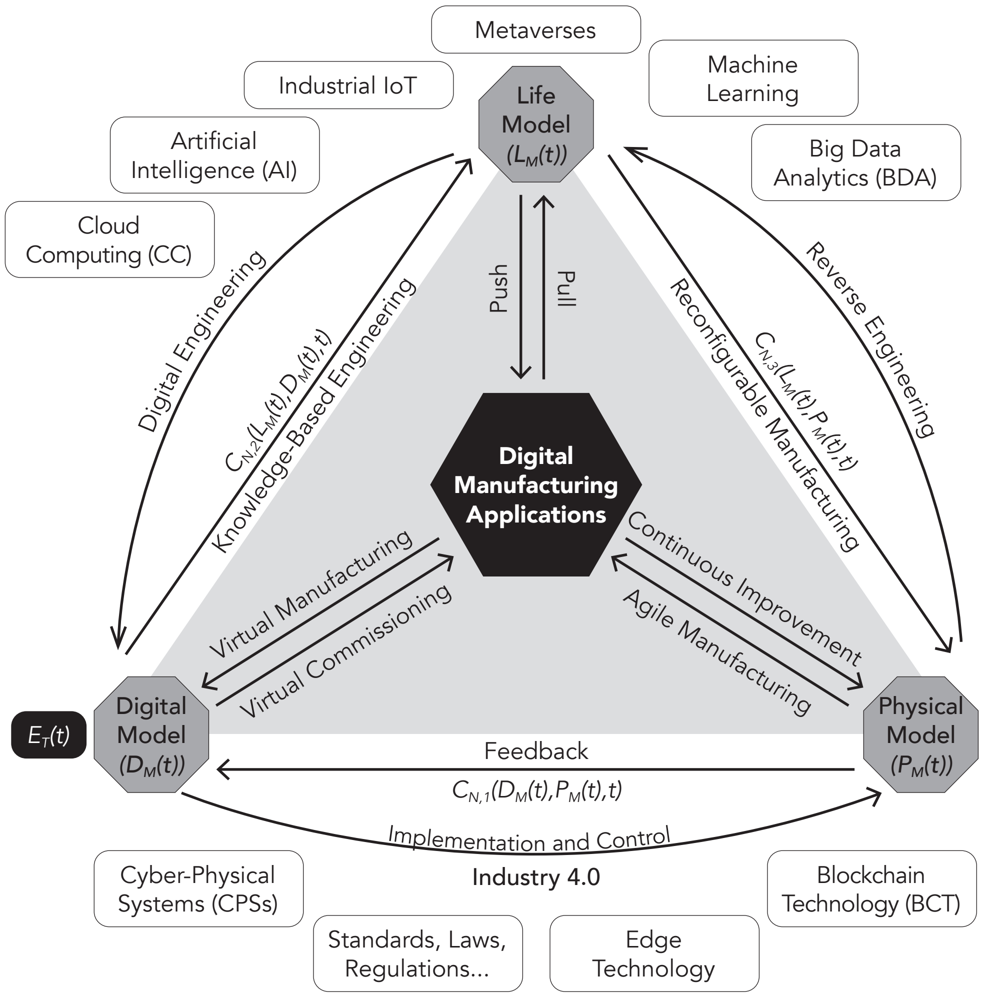


Figure 24. Metaverse and Relevant Technologies for Digital Triad (DT-II(t)) (Bi et al, 2021a, 2012b, 2022)

A sustainable system that is reconfigurable over time is in fact a system of systems (SoS) as shown in Figure 25. In spite of the distributed and decentralised nature of DT-II, it represents the change of one machine type rather than the reconfigurations at system levels. To model the interactions of sustainable system elements, the concept of IoDTT was introduced and is shown in Figure 25. Any instantiated system was established on available technologies *($\{E_T(t)\}$* including the metaverse, and the architecture of IoDTT is flat so that the system elements of {DT-II *(t)*} are all networked and interact equally. Every DT-II (*t*) is reconfigurable to adopt changes, and the lifecycle of a sustainable manufacturing system comprises all that evolve with time. At a given time, DT-II_h (t_i) is the host digital triad, and it is responsible for selecting other DT-II and composing them as an SoS (SoS (t_i)) in the life model $L_{m,h}$ (t_i). The digital and physical models $D_{m,h}$ (t_i) and Pm,h (t_i) are upgraded to meet the changes of their interactions with others. In implementing DT-II and IoDTT, the metaverse can be integrated with cloud computing, AI, and BDA to analyse and predict the changes, and evaluate, compare, and verify system configurations against expected objectives.

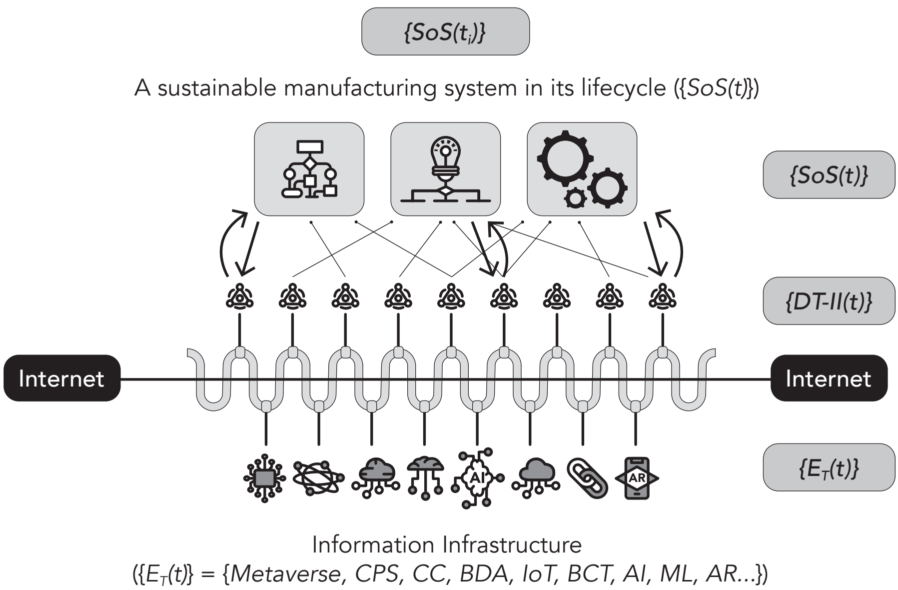


Figure 25. Metaverse and Relevant Technologies in Internet of Digital Triad things (IoDTT) (Bi et al. 2021a, 2021b, 2022)

4.5 Metaverses for Remote Access

The metaverse has exhibited its superior capabilities in accessing resources, collaborating with people, and verifying and validating system solutions remotely and cost-effectively. Sustainable manufacturing can potentially benefit greatly by incorporating metaverses in any business that requires to access remote resources, collaborate with people, or perform rigorous verification and validation in transforming a virtual model into physical model.

Figure 26 shows a concept project where the metaverse is proposed to (1) share a metal printer among geometrically distributed users and (2) verify and validate a design before it is materialised. Similar to operating other precise machine tools, running a metal printer involves many factors and the printing process can be complex and unreliable. Users must be well-trained to set up the machine properly and operate it safely by following correct procedure. We propose to develop a metaverse use case for users to gain hands-on skills of machine operations and then be certified for their qualifications that assure the safe operations of machines. Similar needs were identified by many scholars when Learning Management Systems (LMSs) or digital education systems were widely adopted to manage, curate, and deliver courses remotely during the Covid-19 pandemic. However, no LMS or digital education platform has yet been developed to support interactive technology learning for hands-on training, laboratory practice, experiments, tests, and practices in physical things, virtually.

Metal 3D printing enables the research on the methodologies and tools used to train students and certify them for machine operations. In the proposed metaverse use case, (1) Extended Reality (XR) will be integrated with into the metaverse in an immersive training environment; (2) technical solutions will be developed to digitise laboratory devices, instruments, tools, specimens, and other physical things; (3) a publicly-accessible robot operating system will be adopted to model physical things and their interactions; (4) extended Petri Nets will be used to model users' interactions as events; (5) the solutions to items (1)-(4) will be integrated as a metaverse use case to show the feasibility and the effectiveness of using a precision machine tool and teaching engineering labs in an immersive way.

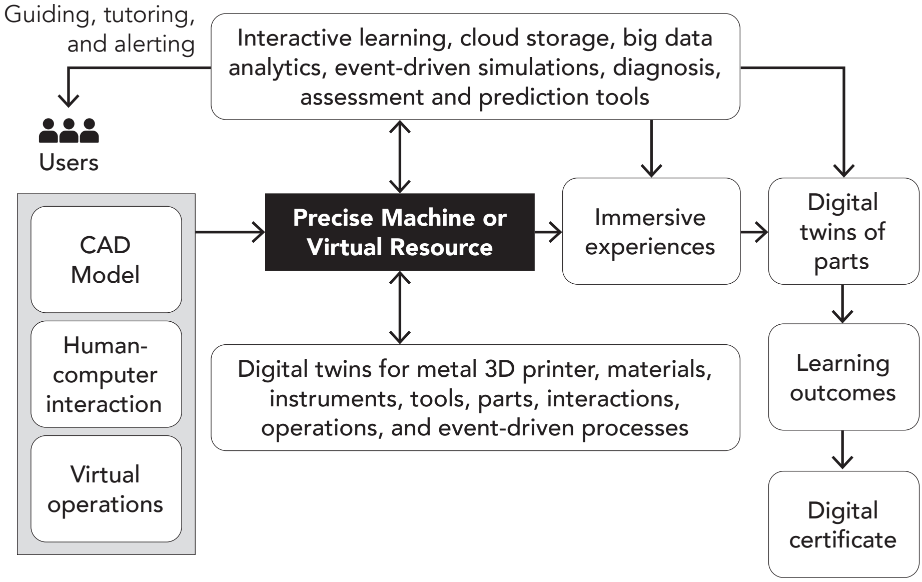


Figure 26. Metaverse Use Case for Metal 3D Printing Training

5 Summary and Future Work

This chapter aims to understand the historical development of the metaverse and relevant technologies, and focuses on its state-of-the-art development and its potential as an enabling technology for enterprises to implement sustainable manufacturing systems which can be applied in the space industry. More examples which illustrate concepts and practices in the space industry will be outlined in the following chapters.

The metaverse has recently attracted increasing attention, as evidenced by the very great number of recent publications in relevant subjects. The metaverse has been identified as one of several disruptive technologies, together with IoT, AI, and 6G (Bhat et al., 2023). Metaverse research has been prioritised to advance intelligence, innovation, communication, experiences, consumer behaviours, and policy formulation (Barrera and Shah, 2022). Metaverses are being widely explored as successors to mobile internets (Lam et al., 2023).

The development and implementation of seamless, interoperative, and shardless metaverses still face challenges in sensing, communication, and computing (Lam et al., 2023). For example, the metaverse brings some security and privacy concerns such as the threats to identity, network, and assets. Dunnette et al. (2022) discussed the use of cyber threat intelligence (CTI) to protect privacy and security. CTI was built upon conventional cyber security risk management for timely, relevant, and actional information about possible threats and attacks. There is the need to use reinforcement learning (RL) for greater awareness of XR contents based on spatial or temporal differences from the perspective of multimedia communications (Dong and Lee, 2022). There is also the need to use RL for awareness of XR contents based on spatial or temporal differences from the perspective of multimedia communications (Dong and Lee, 2022). Moreover, there is an increase in a number of user-demanded network resources, especially on graphical extended reality and rendering a plethora of virtual things. An attention-aware network resource allocation scheme is designed to customise metaverse services such as eye-tracking, remote rendering, and quality-of-experience analysis (Du et al., 2022). The metaverse must be advanced to support (1) green networking with sustainable energy resources to sense things and exchange data for real-time interactions, (2) heterogeneous management to manage diversified resources and services, (3) technology integration to meet strict requirements of 6G for sensing, communicating, and computing in metaverses, and (4) standard specifications for plug and play of network access, routing, and congestion controls.

Most researchers agree that the metaverse has brought numerous new opportunities to enterprises, people, and societies in using cutting-edge digital technologies for immersive interactions, mission-critical services, and omnipresent IoT (Eukdden, 2022). However, we have found very limited use cases in which the capabilities of the metaverse are fully explored to benefit manufacturing enterprises. We suggest that the metaverse must be advanced and integrated seamlessly with other disruptive technologies, especially DT-II, IoDTT, edge computing, ML, cloud computing, and BDA. Moreover, further development of the metaverse should be need-driven, and we will continue our research to showcase the integration of the metaverse with other technologies for enterprises to improve their survivability by developing effective metaverse use cases to support system reconfigurations and extend enterprise lifespans. The space industry examples and case studies will be further elaborated on and described in the following chapters.

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Chapter 4

Advancing Reinforcement Learning with Graph Neural Networks for Intelligent Traffic Flow Management in Future Space Cities

Abstract

In deep space explorations, intelligent vehicles have very many applications in emerging smart transportation systems and future space cities. An intelligent traffic management system is an indispensable component of a smart transportation system. This chapter proposes a hybrid reinforcement deep learning algorithm and graph convolutional neural network for traffic management to improve passage efficiency and ensure travel safety in future space cities. The proposed method has two advantages over existing algorithms: 1) an improved reinforcement graph neural network algorithm that can automate the regulation of red and green signal timing to optimise vehicle throughput at traffic intersections; and 2) a metaverse of a space simulation environment and system based on simulated traffic flow management in a simulated space city, which allows reinforcement learning agents to access and train the model. Overall, this approach provides a promising strategy for

managing traffic flow in smart transportation systems and space cities of the future.

Keywords: metaverse interstellar city, graph convolutional neural network (GCNN), reinforcement learning algorithm, proximal policy optimisation (PPO), traffic flow management, future space city

1 Introduction

1.1 Background

The application of artificial intelligence (AI) in traffic management has been a major focus of research in recent years, particularly in the development of smart transportation systems. However, traffic management in future space cities will present even more complex challenges due to the unique characteristics of space environments. For instance, traffic management in closed environments such as cities on the Moon or Mars will be particularly demanding due to the need for oxygen regulation and other factors. Such challenges will require advanced and innovative approaches to manage traffic flow effectively, reduce congestion, and increase energy efficiency.

With the proposed framework, we aim to address the challenges posed by traffic management in future space cities. Our approach leverages the power of reinforcement learning (RL) to create a dynamic traffic management system that can optimise the timing of red/green lights based on real-time road conditions. This automated approach reduces the reliance on manual control, freeing up valuable human resources for other critical tasks. Furthermore, our method can help achieve significant energy savings and higher population densities, leading to more sustainable and efficient space cities.

This chapter represents a crucial step towards developing an intelligent traffic management system that can adapt to the unique challenges of future space cities. By combining advanced machine learning techniques and a deep understanding of the complexities of Space Metaverse environments, our framework has the potential to transform the way we manage traffic flow in space cities, making them more efficient, sustainable, and safe for everyone.

1.2 Reinforcement Learning Algorithm

The proposed method utilises the RL algorithm of proximal policy optimisation (PPO) to develop a real-time updated traffic light duration change policy. This policy is based on the traffic density and current road condition data collected by cameras. The algorithm combines the PPO algorithm with the graph convolutional neural network (GCNN) to optimise the data obtained from the model.

The improved RL algorithm for PPO has several advantages. It can process data in real-time, and it can perform policy output for the regulation of traffic duration and optimisation of vehicle throughput at traffic intersections. The CTFM-RGNN algorithm can learn from the traffic data and adjust the traffic signal timing dynamically. This leads to optimisation of traffic flow and the reduction of waiting time, resulting in higher vehicle throughput at traffic intersections. Moreover, the combination of RL and GCNN can improve the accuracy and efficiency of traffic flow management in space cities. It can also enable traffic management to be more adaptable to changes in traffic patterns, resulting in more effective traffic management.

The proposed CTFM-RGNN algorithm provides a promising solution for traffic flow management in space cities. Its ability to optimise traffic flow and reduce waiting times can have significant economic benefits by improving the efficiency of transportation in future space cities.

1.3 Significance of this Study

As noted above, the focus of this study is to address the challenges faced by future space cities in terms of traffic flow management. In order to accomplish this, the study has developed an improved algorithm that performs well in virtual reality metaverse simulations. The primary objective of this algorithm is to regulate traffic signal timing effectively, enabling the optimisation of vehicle throughput at traffic intersections.

To achieve this objective, the study proposes an improved reinforcement graph neural network algorithm that uses a combination of PPO and GCNN techniques. By doing so, it enables the algorithm to process data and perform policy output for real-time regulation of traffic duration, based on the traffic density and current road condition data collected by cameras.

In addition to developing the algorithm, the study has also established a realistic simulation environment and system based on simulation of traffic flow management in a simulated city. This metaverse simulation environment is designed to access RL agents and train the model effectively. By doing so, the study ensures that the developed algorithm can operate optimally in a virtual environment, before testing it in a real-world scenario.

This approach enables the design of a comprehensive and efficient traffic management system for future space cities that can effectively regulate traffic signal timing and improve vehicle throughput at traffic intersections.

1.4 Chapter Outline

This chapter is divided into five sections. In section II, related work is presented to give readers an overview of previous research and their limitations in solving the problem of traffic management in future space cities. Section III describes the proposed architecture and algorithm in detail, which includes the RL algorithm of PPO combined with GCNN to optimise traffic signal timing and improve vehicle throughput. This section also explains how the proposed approach can be applied to future space cities and what benefits it can offer.

In section IV, evaluation of the proposed approach is presented, which includes the results of simulations and comparisons with existing methods. This section provides evidence to support the effectiveness of the proposed approach in solving the problem of traffic management in future space cities. Finally, in section V, the conclusion of the study summarises the main contributions of the paper and discusses directions for further research. This section also highlights the significance of the proposed approach in the context of smart transportation systems and future space cities.

1.5 Related Work

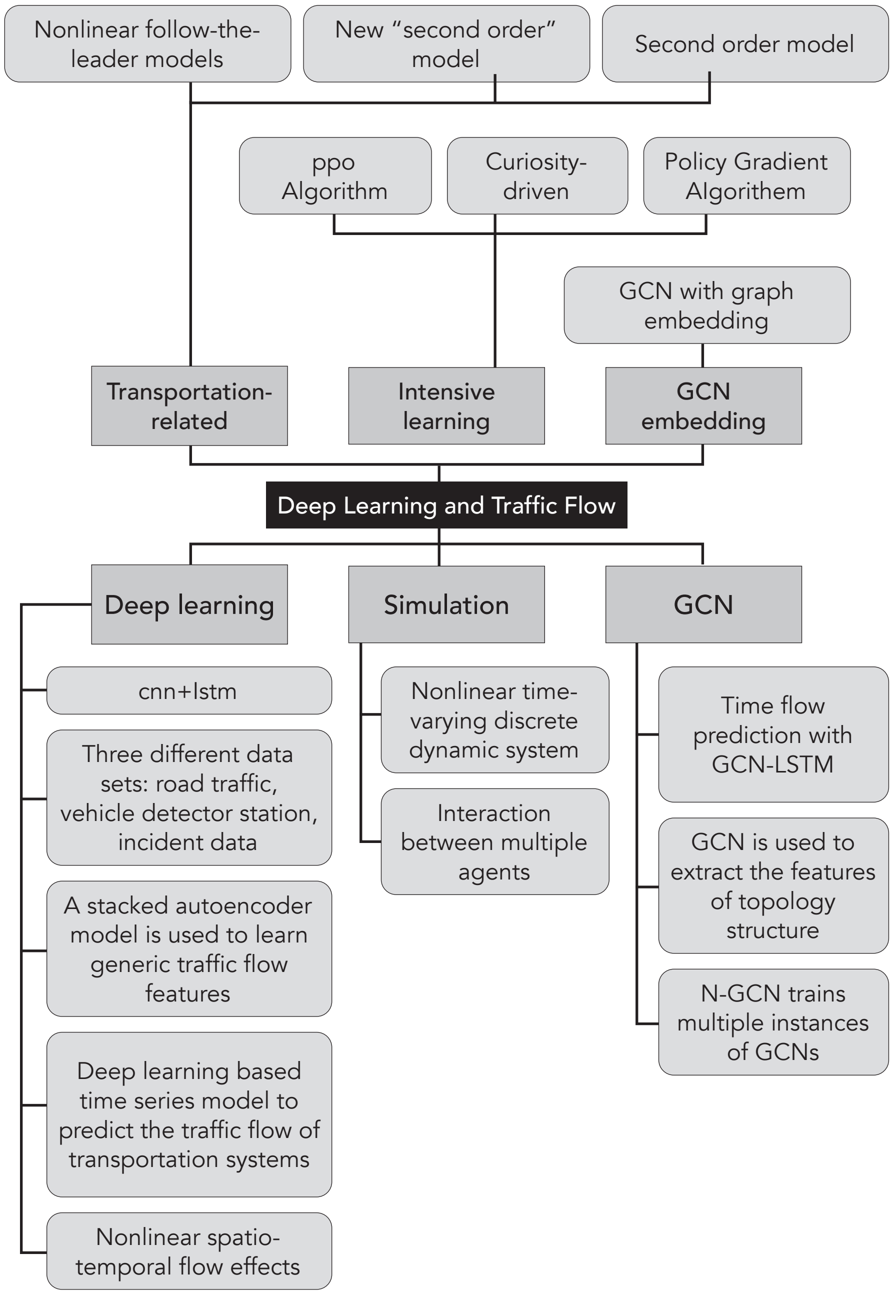


Figure 1. Related Work

We conducted a detailed review of relevant research. Firstly, Khan's paper (2021) proposed the use of the long short-term memory (LSTM) method for traffic signal regulation, which utilises historical data to predict future traffic flow. However, due to the characteristics of the algorithm itself, the overall effect of the signal is not significantly improved, despite various innovations being made. Moreover, the LSTM's long- and short-term memory has a notable drawback for long-time traffic operations in terms of speed and safety performance.

Aqib (2020) utilised three different road traffic datasets along with a vehicle detector station (VDS) and incident data, while Lv (2015) trained a stacked autoencoder model to learn general traffic flow features in a hierarchical manner. Chen (2017) studied a prediction model of traffic flow time series using deep learning, while Polson (2017) and Shimizu (2005) researched nonlinear spatio-temporal flow effects and nonlinear time-varying discrete dynamic systems, respectively. These studies used different datasets to simulate various real traffic road conditions, thus providing valuable insights.

In Jennings (1998) and Shakshuki (2015), the influence of multiple agents in a deep learning environment was studied, aiding the construction of a traffic management network with multiple intersections. Gazis (1900) proposed the nonlinear Aw-Rascle model. Schulman et al (2017) proposed PPO, while Still (2012) and Pathak et al. (2017) refined and initially used the curiosity model for internally-driven learning in RL. These studies serve as important references for improving the performance and accuracy of traffic management systems.

Liu (2020) and Liu (2020) explored the use of GCNNs in traffic flow control, specifically with the GCNN-LSTM model. Similarly, Zhang (2021) proposed the GGCN-SA model, a combination forecasting model based on deep learning, to improve traffic flow forecasting accuracy by capturing spatio-temporal traffic flow characteristics. Chen (2020) proposed the GST-GCNN model for context-aware traffic flow prediction.

Zhao (2019) proposed T-GCNN, a temporal graph convolutional neural network, for traffic flow prediction, which captures temporal dependence under complex traffic network topologies. Zhu (2021) proposed AST-GCNN, a model that adds external factors to traffic flow prediction by modelling them as temporal GCNNs with enhanced attributes. Zhu (2020) also proposed a knowledge-driven approach using knowledge graphs and traffic networks, treating them as heterogeneous networks to improve traffic prediction while considering external factors. These approaches provide valuable insights and ideas for algorithmic optimisation using RL of joint GCNNs, as proposed in the CTFM-RGNN algorithm presented in this paper.

Overall, although there have been previous studies on traffic prediction algorithms that utilise graph neural networks, the proposed CTFM-RGNN algorithm with RL for city-based traffic flow control is a novel approach that fills a technical gap in the current literature. This paper aims to validate the algorithm and demonstrate its practical application value.

2 Proposed Architecture and Algorithm

2.1 Main Idea

Our proposed solution for regulating traffic at city-based intersections involves a combination of RL, a curiosity model, and a

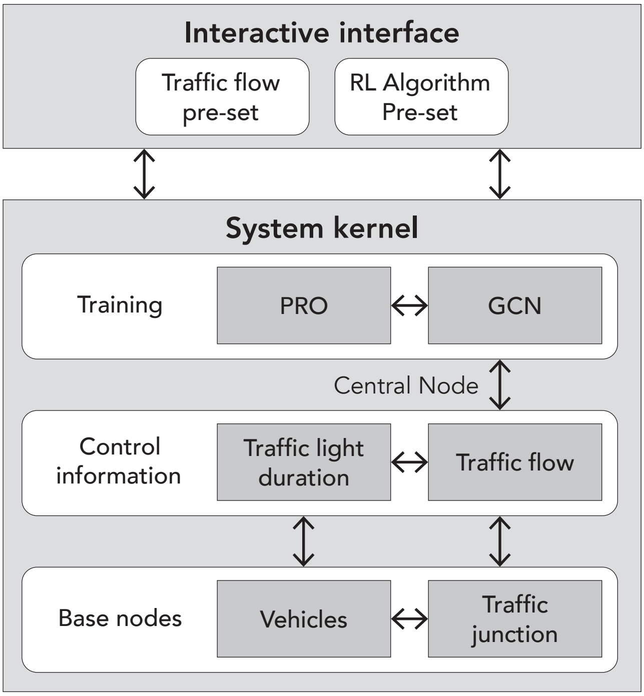


Figure 2. The Framework of the Proposed Traffic Flow Control System

GCNN. To be more specific, we have designed an improved PPO RL algorithm that has the advantage of interacting more efficiently with the environment. To solve the problem of complexity of actual traffic situation at intersections and the need for fast and effective safety adjustments, we have incorporated a curiosity model to generate internal incentives. This helps us make prompt decisions and ensure safety at intersections.

To simulate actual road conditions accurately, we have integrated simulations of various possible scenarios into a constantly updated simulation environment. These simulations are continuously added to the learning process to validate our model. Furthermore, we have refined our model by comparing it with other algorithms in the same domain, resulting in further improvements. The following are the main components of the proposed system.

Street model

A street model of a space city comprises two components: a vehicle component and a traffic light component. The model system generates vehicles randomly and assigns control information, such as speed, direction, and path of travel, to each vehicle entity. The system calculates this information in real-time and sends it to the information acquisition node.

Traffic light

The traffic light component includes its own traffic light duration and intersection block planning. It monitors the vehicles waiting at the traffic light block in real-time and collects and sends them to the traffic information acquisition node. The component receives interactive adjustments from the RL agent in real-time to change the current traffic light duration.

Intensive Learning Agent

An intensive learning agent is then employed to provide an interactive environment and rules for RL. The proximal policy optimisation algorithm requires an interactive environment (Env), where each machine action is fed into the Env as an action (Actor). Each step causes a change in the environment, which can be positive or negative. Therefore, we use reward to evaluate the effect of the action.

The reward generated is our environmental reward, also referred to as extrinsic reward. It is essential as it drives the entire RL process. However, since the traffic system requires high safety and reliability, external reward alone is too smooth for the progress of model learning. Therefore, we use intrinsic reward (internal drive) to optimise our RL. In this paper, we adopt a curiosity-based model to control the internal drive.

$$\nabla \bar{R} \approx \frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{T_n} A^{\theta}(s_t - a_t)\,\nabla \log p_{\theta}\,(a_t^n | s_t^n) \tag{1}$$

$$\mathrm{Pt}_i = \frac{\theta(E_i)}{\hat{e}(D)\theta_{old}(E_i)} \tag{2}$$

$$Ps_i = \frac{\theta(L_i) + \hat{e}(D)\theta_{old}(L_i)}{2} \tag{3}$$

$$J_{ppo}^{t'}(t) = \theta_{((Pt_i,Ps_i),at_i)}\left[\frac{\theta_t((Pt_i,Ps_i),at_i)}{\theta_{t'}((Pt_i,Ps_i),at_i)} A^{t'}((Pt_i, Ps_i), at_i)\right] \tag{4}$$

Where R is the gradient of the return, A^{θ} is the internal drive, P_t is the pass rate prediction, P_s is the congestion level prediction, and $\hat{e}$ *(D)* is the historical time prediction distribution parameter. For the history, we may keep the historical estimates for the previous days, generating different linear counterparts for different time periods. This method will allow the system to generate a sensitive signal for the peak and trough periods of traffic flow each day and make timely adjustments accordingly.

For the intrinsic drive, since the change of the traffic light duration in the traffic system itself cannot occur abruptly, there is less disturbance to the environment. The environment itself can include a variety of factors that affect the traffic system, which are not easy to discover and collect, but do affect the traffic flow in a real way. Therefore, this paper needs to introduce a mechanism that can pay attention to these perturbations and feed back to the RL system. Here, this paper needs an intrinsic incentive function that can infer the direction of the system by comparing the key information in the two key frames before and after.

However, not all information needs to be observed, and it is obvious that some perturbations do not affect the traffic flow. In this paper, we use two separate processing units: unit 1 encapsulates the current frame as a state quantity quantity $\vartheta(s)_t$,and unit 2 encapsulates the next frame as $\vartheta(s)_{t+1}$ and combines $\vartheta(s)_t$ from unit 1 to predict the current action θ_t .This allows the part of the environment that has an influence on the action decision to be abstracted out, i.e., the useful features are separated.

Graph Convolutional Neural Network

The simulation of a single traffic intersection is more successful and can achieve a complete logical closed-loop system optimisation idea. However, this is clearly not scalable as a pilot because a differentiated output adjustment cannot be performed even for two traffic nodes physically separated by a very close distance with the same input parameters.

As can be predicted, the individual adjustment (local optimal solution) for each intersection does not move in the direction of a systematic optimum. After analysing the system with regard to the feasibility of the results, it can be shown that the entire traffic system can be abstracted into a two-dimensional array of points and, after an approximate abstraction process between the nodes, it can be made into an *N*D* matrix.

$$H^{l+1} = \sigma(\widetilde{D}^{-\frac{1}{2}}\tilde{A}\widetilde{D}^{-\frac{1}{2}}H^{l}W^{l}) \qquad (5)$$

Since the separation process for each node is tedious and meaningless, a more reasonable solution is introduced here and it is proposed to use a GCNN as the next focus of the system, which is introduced to be able to handle the node-to-node relationship in a more reasonable way. It is well-known that the GCNN's specialty is to be a feature extractor, and my RL algorithm allows me to make the corresponding adjustments by changing this feature, which makes this system much more feasible.

2.2 Overall Algorithm

Algorithm 1: CTFM-RGNN

Input:	1: Graph G(V, E), K 2: Adjacency matrix A
Output:	T Duration

CTFM-RGNN (probs, probsold):

$h_v^0 = x_v \; \forall v \in V$

For k = 1 to K do:

$h_{A(v)}^k = AGGREGATE_k \left(h_u^{k-1}, \forall u \in A(v) \right)$

$h_v^k = \sigma(w^k * Concat(h_k^{k-1}, h_{A(v)}^k))$

End for

$probs_{old} = probs$

$prbos = h_v^k$

$r_\theta = tf.\exp\,(probs - probs_{old})$

$opt_a = r_\theta * self.advantage$

$opt_b \mathrel{+}= clip\_by\_value(r_\theta, 1.0 - decay_\in, 1.0 + decay_\in) + self.advantage$

$policy_{loss} \mathrel{-}= tf.reduce - mean(tf.dynamic - partition(min(tf.\ opt_a, tf.\ opt_b), self.mask, 2)[1])$

If use_curiosty then:

loss+ = 10 * (0.2 * self.forward - loss + 0:8 * self.inverse - loss)

End if

End function

If we examine our approach from a process perspective, it can be expressed as Algorithm 1, which takes as input a Graph G (V, E), K, where V represents the vertices of the graph, E represents the edges, K represents the depth of the algorithm, and the adjacency matrix A, which represents the direct connection of N vertices.

The output of CTFM-RGNN is T, which represents the traffic light duration of the decision made by our hybrid PPO and GCNN algorithm. This approach allows us to optimise traffic light durations by taking into account not only the real-time traffic conditions at a given intersection but also the broader context of traffic flow patterns in the surrounding area.

By leveraging the power of CTFM and RGNN, our approach is able to handle the high-dimensional and non-linear data associated with urban traffic systems, and effectively capture the complex relationships between traffic flow patterns and traffic light durations. Furthermore, the use of PPO and GCNN allows us to optimise traffic light durations while taking into account both local and global traffic conditions, resulting in a more efficient and effective approach for managing traffic flow in complex urban environments.

3 System Design

3.1 Metaverse Simulation System

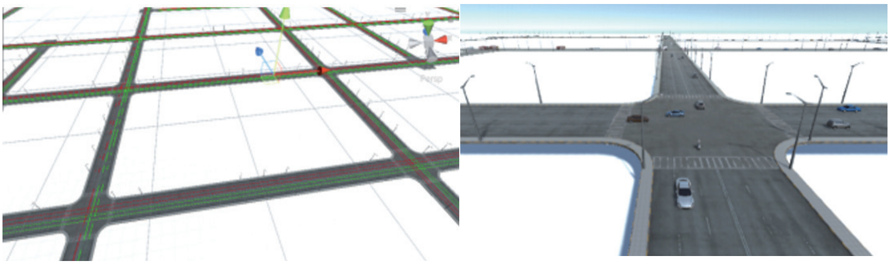
To cater to the demands of both visual appeal and efficient development, this study employs Unity3D (U3D), a lightweight industrial creation metaverse engine development tool. Boasting high flexibility and development capabilities, U3D offers a complete suite of software solutions, including a fully customisable 3D rendering tool. Moreover, U3D's small development door facilitates streamlined and efficient software development, leading to faster product delivery and easier software maintenance.

In order to achieve a simulation environment that is closer to reality and can run smoothly during training, the design of this simulation environment was carefully selected. The entire system is constructed based on a city's transportation system, with traffic flow primarily generated by vehicles entering from outside the system and supplemented by random vehicle generation. The generation of traffic volume follows the basic characteristics of numerous traffic prediction models and is approximately fitted to the daily traffic volume data of the space city in a metaverse.

3.2 Traffic Intersection Traffic Light Control

The traffic signal system is the core of the overall system, and the signal lights are divided into three types: red, green, and yellow (RGY), alternately. The FixedUpdate function natively supported by U3D is used, with a fixed frame rate as the cycle, and the RGY signal update function is periodically called. At the same time, the node information of the signal lights is open and can be interacted with the environmental agent to modify the signal light duration to regulate the traffic system. Each vehicle is controlled by an AI control script, and an important attribute is its interaction with the signal lights. The vehicle will use RayCast to function detect and collide with the traffic intersection in front of it. Once the distance calculated by the ray is shorter than the predetermined distance, it will enter a slow state, and its maximum speed will become half of the normal speed. Once it receives a red signal, it will enter a stop state and gradually decelerate to zero.

In modern traffic intersections, installing cameras has become an essential option for traffic law enforcement, speed measurement, and monitoring important sections to facilitate tracking of fleeing criminal suspects. Almost every intersection has cameras, but these cameras cannot be effectively connected to the traffic system, and this information is wasted. This study aims to use cameras at intersections to detect current traffic flow and congestion, and then input this information into a control device similar to the one shown in Figure 3. The control device will output a decision to control the signal light timing, thus regulating traffic flow and traffic pressure at the intersection. Vehicle information is complex and constantly changing, and the inherent complexity of traffic intersections affects traffic flow at other intersections. Therefore, it is necessary to establish an intelligent traffic network, and each traffic intersection requires such a sub-node, which can be integrated into a complete traffic flow intelligent control system.



(a) (b)

Figure 3. Partial Bird's-eye View of the Simulation System

3.3 Collision Avoidance Function

In order to ensure the normal operation of the system and prevent problems such as traffic path blockage and traffic loss during the training process, each vehicle requires a precise control script and a comprehensive collision detection system. The following rules are used:

a. Each vehicle will have a maximum speed, which is an inherent property of each vehicle, and this property will radiate to every script of the vehicle (including sub-node components), ensuring that the vehicle's speed will not exceed this value from start to finish.

b. Before the vehicle reaches its maximum speed, it will be in an acceleration state. When the vehicle enters a stop state for some reason, it will immediately begin to decelerate until it comes to a complete stop.

c. There will be a minimum following distance between vehicles, which will be maintained by the following vehicle. Once the ray detection of a vehicle detects that the distance between it and the preceding vehicle is less than the minimum following distance, the vehicle will decelerate, and the degree of deceleration will be inversely proportional to the distance between the vehicles, i.e., the closer the distance, the higher the degree of deceleration.

d. When the collision box of two vehicles collides, the vehicles will come to a complete stop. When a vehicle turns at an intersection, there will also be ray detection in the lateral direction to determine the situation of oncoming vehicles in the lateral direction and to warn the driver of the turning vehicle, ensuring safe turning and avoiding repeated occupation of the lanes. Each vehicle has wheels, which are also important sub-nodes of the vehicle. Under normal circumstances, the vehicle only contacts the road surface, i.e., the collision box of the vehicle will always be inside the trigger of the road surface.

e. Once the collision box of the wheel leaves the trigger, the system will trigger an event of the vehicle leaving, and the faulty vehicle will be immediately retrieved and a new vehicle will be generated for the same path. This helps to ensure the stability of the vehicle's path and avoid imbalanced vehicles blocking traffic intersections.

The smoothness of the system is a necessary condition for ensuring stable data output. The FixedUpdate function is called within a specified time period, causing significant deviations in the data, and this has been the goal that the system has been striving for since its initial development. In order to achieve stable system operation, the system provides multiple protection methods. One of the methods is to instantiate the model and build an instance list for calling. The advantage of this is that it can operate through the model pool of instances. Because the entire system needs to maintain a relatively stable traffic flow rate in a short period of time, vehicles that reach the end of the path do not need to be destroyed immediately, but rather wait in the model pool of instances for future calls. When the traffic flow rate of the system surges, such as during rush hour, the system will construct instances by cross-referencing the instance list.

4 Evaluation

To train CTFM-RGNN, simulation data is pre-processed by interfacing with the U3D metaverse simulation environment. The training process involves dividing the simulation dataset and validating the GCNN data processing effect with the subsequent input as the validation set. The RL algorithm receives the output of the GCNN and uses it as observation data of the environment agent to make the corresponding decision and feed back to the simulation environment. The GCNN interacts with the RL module to enhance the final effect of RL.

The RL process takes place over a complete ten traffic light cycles of the whole traffic network and, during this period, the system deducts points from the congestion level of the vehicles and generates a negative reward. The vehicles passing through the intersection and reaching the end of the path will increase some points for the system appropriately, generating a positive reward. This ensures that RL can make accurate judgments and precise decisions.

The simulation system can easily switch between various algorithms, which allows for comparing the experimental effects of multiple algorithms in the same system. Information is collected through independent nodes and, after matrix processing, the data information of each frame is sent through the 5004 system port to the running GCNN. The neural network classifies data using convolutional neurons to find the potential temporal and spatial connections. Features are input into the PPO, which makes corresponding decision vectors based on the feature values and inputs them into the scene agent. The scene agent interprets the decision vector and interacts with the environment based on the decision vector, including information on the duration control of relevant intersection lights.

4.1 Evaluation metrics

To evaluate the performance of different methods, we have selected two representative criteria:

Travel time: This is the most commonly used measure for evaluating the performance of signal control methods in transportation. It refers to the average travel time of all vehicles in the system.

Throughput: This is defined as the number of trips completed by vehicles throughout the simulation process. A larger throughput during a given period indicates that more vehicles have completed their trips, which reflects a better control strategy.

The Empowerment algorithm is used to monitor the current state and make changes as required by the algorithm. Results show that CTFM-RGNN performs better than other algorithms during peak periods of non-holiday and holiday traffic, confirming that the algorithm presented here is suitable for city-based traffic control applications.

4.2 Comparison of Simulation Experiments

CTFM-RGN will first preprocess simulation data through integration with the U3D simulation environment, and then undergo the training process. The training will divide the simulation dataset and use subsequent input as validation data to verify the data processing effect of the current GCNN. The GCNN outputs to the RL algorithm, while the input serves as observation data for the environment agent and makes corresponding decision feedback to the simulation environment. The GCNN then interacts with the RL module to improve the final effect of RL.

In one round of RL, the entire traffic network will complete ten traffic light cycles. During this period, the degree of vehicle congestion will deduct a certain score from the system, i.e., negative rewards will be generated. Vehicles passing through intersections and reaching the end of the path will add a certain score to the system, i.e., positive rewards will be generated. The specific rewards generated by vehicles passing through traffic intersections and reaching the end of the path are different due to the different current traffic density and path selection during runtime. This ensures that RL can accurately judge and make precise decisions.

The displayed data shows the final situation of the vehicle traffic flow under various environments in the simulation environment. The data show the total number of vehicles passing through traffic lights within an hour in the system, which is the sum of vehicles passing through each intersection. Different situations have different basic traffic density and traffic congestion levels.

Table 1. Experimental Results of Traffic Flow in the Metaverse Simulation Environment

Methods	DQN	Horizon3 TPRO	PPO	DQN	Horizon6 PRO	PPO	Horizon12 DQN TPRO	PPO
HA	36047	36933	36213	33044	36399	33221	32034 33927	36220
ARIMA	36135	36945	37254	35019	38563	35764	33372 35693	38487
LR	37732	37546	34331	35816	37737	37045	33664 35943	37991
FNN	37924	37677	37177	35988	37631	36673	35237 36829	37756
DCRNN	38363	38134	39062	36913	39487	38473	352813 38061	39217
GMAN	38141	40943	40450	37262	41556	39177	37601 39664	40793
GWNet	36117	36265	41874	38558	40431	43339	36066 41493	39404
ASTGCN	35216	37865	41961	386961	42436	41284	37461 40513	40687
MTGNN	35352	39434	42789	39416	42343	44889	38359 41507	41936
This work CTFM- RGNN	39825	41543	43583	40137	43428	45732	39624 42839	43726

The experimental results presented in Table 1 reveal several significant insights. Firstly, our comparison of RL algorithms based on direct policy search and value function indicates that the former approach yields better performance when using the same neural network model for prediction. This underscores the importance of selecting the appropriate RL algorithm based on the specific task at hand. Secondly, the evaluation of the PPO RL algorithm reveals its superiority over DQN and TRPO when using the same neural network model. This finding highlights the potential of PPO in improving the performance of RL-based prediction models.

Furthermore, our proposed prediction model outperforms other models using the same RL algorithm. This result suggests that our approach effectively leverages the advantages of RL algorithms to improve prediction accuracy. Taken together, these findings offer valuable insights for researchers and practitioners seeking to develop and optimise RL-based prediction models for various applications in space optimisation problems.

4.3 Ablation Experiment

The ablation study of the model components is shown in Table 2. We can see that simulation system consistently performs well on all generated datasets. In particular, in most datasets, incorporating spatial structure dependencies improves performance more than temporal dependencies. This suggests that learning spatial structure dependencies is more important for improving performance in the cooperation between traffic lights. Tables 3 to 5 illustrate the curves of these model variables during the training process on different datasets. It can be seen that adding spatial structure dependencies greatly improves convergence speed. Increasing temporal dependencies will further accelerate convergence and improve performance. These quantitative results clearly demonstrate the effectiveness of jointly learning spatial structure information and temporal dependencies for multi-intersection traffic light control.

Table 2. Experimental Setup for Ablation Study

Ablation	SP (Adyn)	SP(Adtw)	SP (Aadp)	TP (TCN)	TP (s - a)	TP (s - f)
Ours1	×	×	×	×	×	×
Ours2	×	×	×	×	×	×
Ours3	×	×	×	×	×	×
Ours4	×	×	×	×	×	×
Ours5	√	√	√	√	√	√
Ours6	√	√	√	√	√	√
Ours	√	√	√	√	√	√

Table 3. Results of Ablation Experiments in the Simulation Environment Using the DQN Algorithm

Methods	WH	Horizon3 WNH	NW	WH	Horizon6 WNH	NW	WH	Horizon12 WNH	NW
Ours1	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours2	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours3	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404
Ours4	2.5104	0.0350	5.9526	2.8899	0.0428	7.0407	3.2554	0.0493	7.8060
Ours5	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours6	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404

Table 4. Results of Ablation Experiments in the Simulation Environment Using the TPRO Algorithm

Methods	WH	Horizon3 WNH	NW	WH	Horizon6 WNH	NW	WH	Horizon12 WNH	NW
Ours1	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours2	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours3	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404
Ours4	2.5104	0.0350	5.9526	2.8899	0.0428	7.0407	3.2554	0.0493	7.8060
Ours5	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours6	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404

Table 5. Results of Ablation Experiments in Simulation Environment Using the PPO Algorithm

Methods	WH	Horizon3 WNH	NW	WH	Horizon6 WNH	NW	WH	Horizon12 WNH	NW
Ours1	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours2	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours3	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404
Ours4	2.5104	0.0350	5.9526	2.8899	0.0428	7.0407	3.2554	0.0493	7.8060
Ours5	3.3735	0.0419	5.7254	4.1019	0.0563	7.5764	4.8372	0.0693	8.9487
Ours6	2.8563	0.0381	6.1062	3.4913	0.0487	7.4473	4.2813	0.0613	8.7217
Ours	2.7617	0.0362	6.2874	2.9558	0.0431	7.3339	3.3066	0.0493	8.1404

Based on the experimental results in Table 5, the proposed reinforcement learning algorithm outperforms both DQN and TRPO when using the same prediction neural network model. This indicates the superiority of the proposed algorithm in enhancing the prediction accuracy of the neural network model. Furthermore, our prediction model exhibits better experimental results compared to other reinforcement learning algorithm models, indicating the effectiveness of our approach in improving the performance of prediction models. These findings provide valuable insights for the development and application of RL algorithms in improving prediction accuracy.

4.4 Training Experiment

The first step of CTFM-RGNN involves pre-processing the simulation data through its interface with the U3D simulation environment and conducting the training process. During training, the simulation data set is divided, and the effectiveness of the GCNN data processing is validated using subsequent continued input as the validation set.

The output from the GCNN is then fed into the RL algorithm as observation data for the environment agent to make corresponding decisions and provide feedback to the simulation environment. By interacting with the RL module, the GCNN is able to enhance the final effect of RL.

From Figure 4, it is important to note that, in the training process of CTFM-RGNN in the simulation environment, RL is based on the complete ten traffic light cycles of the entire traffic network in one round. During this period, the system appropriately deducts some points for the congestion level of the vehicles, generating a negative reward. These points correspond to the values of the vehicles passing through the traffic intersection and reaching the end of the path, which are influenced by the current traffic density and the selected path.

Crucially, the specific reward generated during operation is different from the one generated by vehicles passing through the traffic intersection and reaching the endpoint. This distinction ensures that RL can accurately assess the current traffic conditions and make precise decisions accordingly. By taking into account both negative and positive rewards, the algorithm can effectively learn to regulate traffic signals and optimise traffic flow.

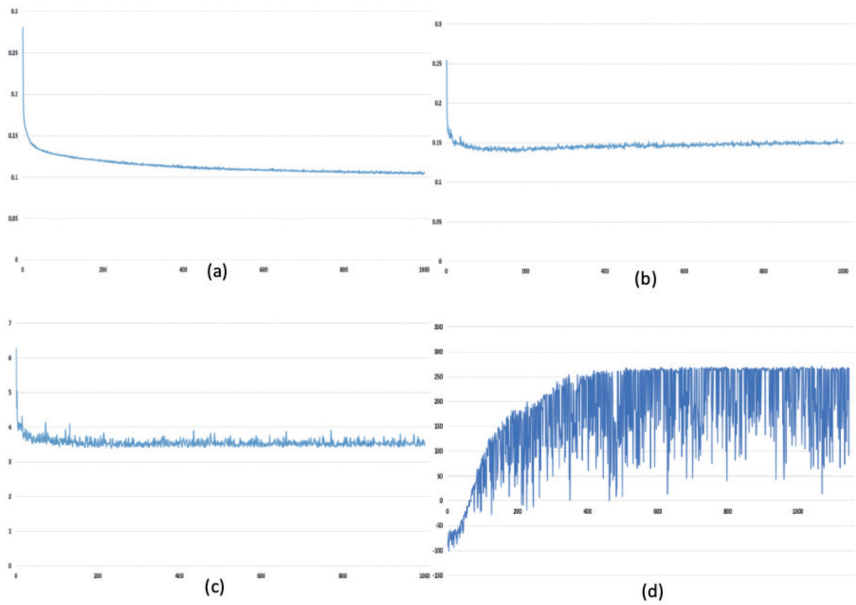


Figure 4. Training and Testing Information for CTFM-RGNN. (a) Train Loss (b) Inference Loss (c) Train RMSE (d) Reward

CTFM-RGNN is a multi-step process that involves pre-processing simulation data, dividing and validating the simulation data set, utilising GCNN output as input for the RL algorithm, and integrating the GCNN with the RL module to improve the overall RL effectiveness. This approach has the potential to optimise traffic flow and improve travel safety in both smart transportation systems and future space cities.

5 Conclusion

This study makes several contributions to the field. Firstly, we have established a reasonable and effective metaverse simulation environment in U3D software, with data channels constructed to facilitate access to the RL agent and model training. Moreover, we proposed an improved PPO algorithm with GCNN as CTFM-RGNN, which exhibits superior performance compared to existing mainstream algorithms. The evaluation was conducted through actual testing of multiple traffic intersections, demonstrating the effectiveness of our approach in regulating traffic flow during peak hours.

In addition, we propose the incorporation of a date and time memory function into the RL algorithm to anticipate traffic flow changes during special periods such as holidays, and enable quicker adjustment of the actual signal plan. Furthermore, we address the issue of multi-dimensional input data leading to overly complex decisions and affecting the final decision effect, by proposing a clustering of data classification process. Accurate prediction of future traffic flow is a crucial component of intelligent transportation systems in space cities. Looking to the future, further research can be integrated with space self-driving vehicles, space safety transportation systems, complex space station designs, space supply chain management, and looped transportation systems to build a more complete space ecosystem for developing smart space cities.

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Chapter 5

Simulating Blockchain Concepts in a Space Instrument Management Scenario

Abstract

Blockchain technology offers advantages like anonymity, immutability, and distributed control. However, understanding its functions and mechanisms remains a challenge for non-technical users. To address this, an online educational game has been developed using React Native. The game focuses on simulating blockchain-based management and traceability of space instruments and parts. Users trade, monitor, and verify components using blockchain technology, with every transaction recorded in the game's blockchain. The game provides a virtual ecosystem where players from various disciplines use block mining, mirroring real-world validation and appending transactions. It guides players through constructing a blockchain, explaining complex concepts like immutability, the Merkle tree, and zero-knowledge proofs. By immersing players in this gaming experience, the tool aims to demystify blockchain technology and bridge the understanding

gap. The space exploration theme adds excitement and context, making it a training platform for users from diverse backgrounds. The goal is to equip users with a knowledge of blockchain technology, particularly with regard to managing precision and high-tech engineering products for deep-space exploration missions. Moreover, the blockchain simulation game described in this chapter will further be developed into the deep space resource management in the next chapter.

Keywords: space missions, instrument traceability, blockchain, metaverse simulation, gamification

1 Introduction

Since its inception in 2008, blockchain technology has been identified as a powerful tool to enhance anonymity, immutability, and decentralised control across a broad spectrum of digital applications, encompassing financial services and supply chain traceability (Sunny, 2022). Beyond the decentralisation of data in peer-to-peer networks, the advent of blockchain has spurred the development of several innovative business models. These include cryptocurrencies and non-fungible tokens (NFTs), fostering the exchange of electronic cash, artwork, and music, among other assets (Ante, 2022; Taherdoost, 2022). Blockchain technology presents technical value through its capacity to reform vulnerable computer systems and deliver market value to the general public. However, despite a steady increase in blockchain's popularity within the marketplace and academic circles, a comprehensive understanding of its functions and mechanisms remains confined to a select group with a deep understanding of computer science concepts. Users from multidisciplinary backgrounds, essentially non-specialists, may often accept blockchain's benefits without fully understanding the underlying technology. This fact underscores the need for an effective educational tool to demystify non-specialist blockchain concepts (Zhao et al., 2021). Such a tool would enable users to grasp why blockchain is secure and reliable within a peer-to-peer network, a critical step in advancing the widespread adoption of blockchain technology in multidisciplinary education.

Regarding space instrument management, this, therefore, presents an opportunity to develop an educational game that can make learning about blockchain more accessible and engaging. Building on the success of a previous game that taught blockchain concepts through a case of managing student grades, the idea is to create a new game that uses space instrument management as the context. Players would learn about blockchain in this game by participating in a simulated peer-to-peer network for trading and tracking space instruments. The game would introduce users to crucial blockchain concepts such as immutability, the Merkle tree, and zero-knowledge proofs, all in a fun and interactive way. By replacing abstract concepts with real-world scenarios, the game would make it easier for users to grasp why blockchain is secure and trustworthy and how it can enhance space instrument management. This game would serve as a valuable educational tool and a means of promoting blockchain technology in multidisciplinary education and expanding its application in different fields. It could also contribute to the research in game-based learning pedagogy, providing insights into how such approaches can be used to teach complex computer science concepts.

In April 2019, a game for teaching blockchain concepts was built to demonstrate the entire block mining process in order to teach distributed ledger technology with transparent, append-only, and immutable characteristics. In the game, the blockchain mechanism is illustrated using a case of building the data chain for students' grades in different courses. More importantly, the concept of the one-way hash function is replaced by the complete division rule so that the ease of completing the block mining process has been greatly improved. The characteristic of the hash algorithm, namely, challenging to produce but easy to verify, can be effectively maintained. Since the game is paper-based and involves role-playing, it is challenging to motivate students to whole-heartedly participate, while it is also not environmentally friendly to prepare the necessary paper-based game materials. Furthermore, amid the COVID-19 pandemic, teaching activities were conducted in a hybrid/blended learning mode, in which only a few students attended face-to-face classes, so the existing game could not match the learning mode (Ramadhan et al., 2023).

Thus, the paper-based and role-playing blockchain game has been revamped on an online learning platform, where a competition-based learning approach enhances students' engagement in learning blockchain concepts. In this study, an online learning platform is designed and developed to address the concerns identified above for learning blockchain in engineering education. Under teacher control, students can participate in the game through the web browsers on their devices anywhere. Under the game settings, students are enabled to experience the learning journey of building blocks in the blockachain, along with essential concepts from the original blockchain game and additional concepts, including immutability, the Merkle tree and zero-knowledge proof for data authenticity.

In summary, the significance of the proposed learning software can be illustrated with reference to two facets of the software. Firstly, the learning environment for blockchain technology can be further enriched to stimulate the attention and interest of students who find it difficult to understand complicated computer science theories. Through the learning platform, their understanding of blockchain can be deepened by their gaining a solid foundation in appraising its functions and mechanisms. Secondly, the proposed platform can contribute to educational research in adopting game-based learning pedagogy for learning computer science concepts, namely blockchain, where learning performance, motivation, and satisfaction can be evaluated.

2 Related Work

In recent years, blockchain has been widely used in education. Blockchain technology has been combined with digital gaming, using games as an effective tool for teaching and training. Gamification learning has become an educational method and has gained popularity as a teaching strategy to improve the learning effects and student motivation. By incorporating game elements and design into teaching, learners can become more actively involved in learning, enhancing their learning effectiveness and ability to concentrate. The higher education landscape is rapidly evolving, with gamified learning becoming a pivotal trend. Many institutions are adopting gamified learning due to its proven benefits in enhancing student engagement, motivation, and learning outcomes. Meanwhile, the ubiquity of mobile devices is driving a shift towards mobile learning and micro-learning, offering flexible and digestible learning experiences. Integrating immersive technologies such as virtual and augmented reality creates immersive and interactive learning environments. The advent of personalised learning paths, facilitated by gamification, enables adaptation to individual learners' performance and needs. The trend of real-world simulation in game-based learning allows students to apply theoretical knowledge in a practical context, while social elements in gamified learning promote interaction and collaboration. Lastly, implementing learning analytics in gamified learning provides valuable insights into student performance, enabling informed decision-making to enhance the learning experience. The gamification of learning in higher education thus presents many opportunities, revolutionising the educational approach in this sector. Numerous research studies have been conducted internationally to investigate the viability and impact of gamifying education and to encourage the learning of blockchain technology, and, for this, there are a series of relevant tools available.

In the field of information and communication technologies, gamification learning can be a convenient tool for in-depth learning of these technologies, with teachers adopting a gamification teaching mode to teach students blockchain technology and cryptography theory. To attract the interest of young people, a university in South Korea has released an instructional tool called "Village Coin", which includes board games and technological games (Choi, 2022) — dealing primarily with concerns related to the value of money, currency exchange rates, currency evaporation, currency security and trust, and blockchain. The complex technology and blockchain concepts are explained through games and an instructional mode. The game design considers a specific information manipulation situation. The board game "BlockTrain" allows players to become familiar with the essential ideas behind blockchain technology (Cortiz, 2021). "Cybersecurity Enhancement through Blockchain Training" is a web-based game that intends to spread fundamental knowledge about blockchain technology and employs AI techniques to take into account players' reactions so as to customise the gameplay using intelligent game objects (Mittal, 2021). This game can help students and professionals learn blockchain technology and operations fundamentals. "Bloxxgame" is a software tool that evolved from a whiteboard-based blockchain game to a web-based simulation game, allowing students to experiment with all blockchain-related operations, such as signing, creating transactions, block building, and more (Dettling, 2020). The "Blockchain Paper Game" is a paper-based simulation card game that explains the idea of distributed ledgers and smart contracts (Abney, 2020). The game is a representative gamification learning method that can help learners understand the hashing principle of the blockchain. In the game, learners must select two words and then write their sum in the worksheet. If the sum of the two words is the same, they can get points. Players learn about distributed ledgers by writing the sum of the points in their respective worksheets.

While there is a growing body of literature on gamification in teaching complex concepts, including blockchain technology, there appears to be a research gap in developing learning games specifically targeted at higher education students for understanding blockchain-based traceability concepts. The existing games provide fundamental knowledge about blockchain technology and its operations. However, there seems to be a lack of focus on blockchain traceability, a critical aspect in various fields, including supply chain management, food safety, and healthcare. Moreover, while the existing games provide an overview of blockchain technology, there is limited evidence of their efficacy in teaching specific blockchain concepts to higher education students. Further research is thus needed to design and evaluate the impact of gamified learning tools that engage higher education students and enhance their understanding and application of blockchain-based traceability concepts.

3 Proposed Game Logic and Process

This section introduces and elaborates on the proposed educational game for learning blockchain concepts in the context of space instrument traceability.

3.1 Blockchain-Based Space Instruments and Parts Traceability

The traceability of space instruments and parts is a complex yet critical process in the aerospace industry. The corresponding information management systems, with the aid of advanced information and communication technologies such as blockchain, play an essential role in supporting space operations and risk management (Li et al., 2021; Zheng et al., 2021). This process involves tracking the lifecycle of each component, from its raw material stage to its integration into a final assembled system. It is a two-fold process involving material and information flows.

Regarding the material flow, space missions involve various instruments and parts, and each is crafted precisely from specific materials. The material flows of these components begin from their origin as raw materials, proceeding into manufacturing processes where they are transformed into specific parts. These parts then pass through various assembly, testing, and integration stages into the spacecraft. Tracking these material flows is crucial. Each stage, from raw material extraction to assembly and testing, must be meticulously documented to ensure quality control, complying with specifications, and identifying and rectifying potential issues.

Parallel to the material flows, the information flows of space instruments and parts are equally critical. These flows include data about the pedigree, specifications, manufacturing processes, testing procedures, and performance characteristics of each component. The information flows provide a comprehensive history of each part, aiding quality assurance, problem resolution, and future development efforts. However, managing these information flows is challenging due to the sheer volume of data and the need for secure, efficient, and accessible data management systems. Mismanagement or loss of this information can have severe repercussions, including mission failure.

Thanks to recent advances in information and communication technologies, blockchain technology can vastly improve the traceability of space instruments and parts in both material and information flows. It can serve as a decentralised, immutable ledger for recording, verifying, and managing all transactions related to the lifecycle of each component. For material flows, blockchain can create a digital twin of each part, recording each stage of its transformation and movement. From raw material extraction to manufacturing, assembly, testing, and final integration, each transaction can be time-stamped and recorded on the blockchain, creating a tamper-proof, transparent, and accessible log. On the information flow side, blockchain can store, manage, and secure vast amounts of data related to each part, including technical specifications, manufacturing and testing data, and performance characteristics. The decentralised nature of blockchain ensures that these data are secure, transparent, and resistant to tampering, providing a single source of truth that all authorised stakeholders can access. Moreover, smart contracts can automate and streamline many processes related to the traceability of parts, such as compliance checks, quality assurance, and problem resolution.

The traceability of space instruments and parts involving material and information flows is a complex but critical process in the aerospace industry. Blockchain technology offers a promising solution to improve this process by providing a secure, transparent, and efficient system for tracking and managing all transactions related to the lifecycle of each component.

3.2 Process of the Educational Game

Many game-based tools and designs are available for training and learning, offering effective learning experiences in the cycle of experimental learning (Law, 2019; Wu et al., 2023). Furthermore, learning gamification can enhance students' motivation and interest in learning complicated STEM concepts (Lu et al., 2022; Tay et al., 2022). The majority of games focusing on blockchain technology simply review the fundamentals. To maximise the potential benefits of blockchain technology, users need to be aware of its implications and applications. This section illustrates how a simulation game can help people better understand blockchain technology solutions (Tsang et al., 2022). The main purpose is to familiarise the user with blockchain applications and provide an interactive learning experience through an example, showing a series of problems that blockchain can solve, such as lack of transparency, insufficient coordination of entities, and insufficient data verification.

The tool is designed as a DApp with React Native, and an online learning platform has been established, as shown in Figure 1. Users can engage with scenarios integrated with blockchain in real-time through the platform. Students can participate in the game from any place through the web browser on their device and be guided by the teacher. In the game, students will experience and learn basic and more advanced blockchain concepts and be placed in a natural blockchain environment. The learning platform has the following essential functions: (i) access control management, (ii) a spreadsheet model of blockchain data, and (iii) display of game results.

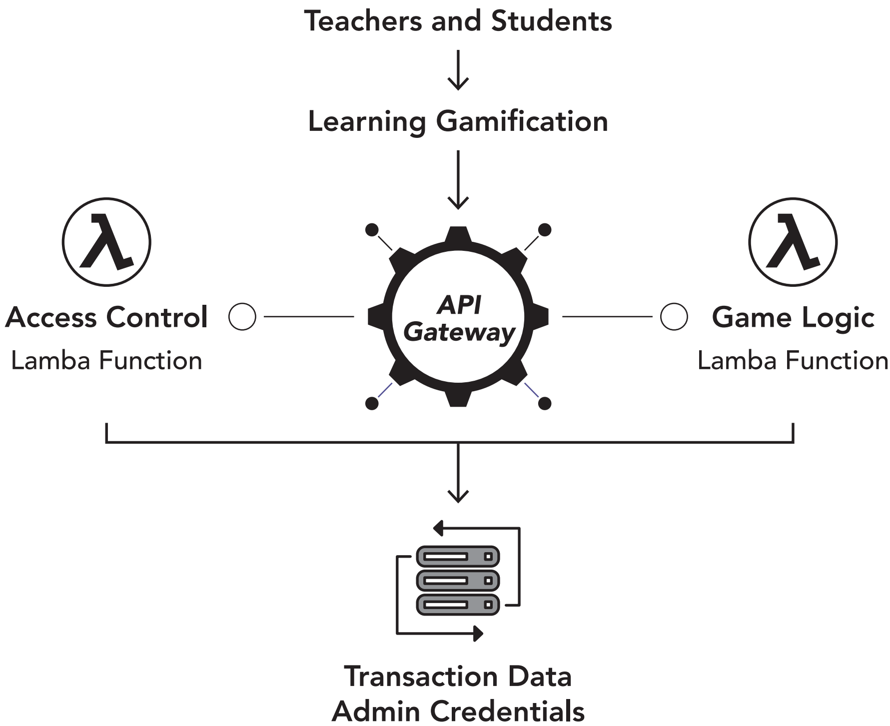

Figure 1. System Architecture of the Proposed Educational Game

First, by entering game settings to generate a password, the teacher effectively partitions the client (i.e. students) and places it under the teacher's control. This setting establishes the teacher as the gatekeeper of access control management. The learning platform allows for the concurrent autonomous control of multiple groups of clients. Second, a spreadsheet model of precomputed block data is created to set up the gaming environment and ensure smooth learning progression. For each round of block mining in this architecture, the proper hash and nonce values are known. Finally, the platform displays the mining rewards graphically to demonstrate the computing power of the client. This illustration promotes a competition-based learning environment. In addition to the fundamental operations, the learning platform allows users to practice block mining and the data structure for handling numerous transactions. A set of public and private IDs is given when a student joins the game to guarantee transparency of transactions while preserving anonymity. Teachers and students take on the roles of nodes and miners in the game environment, respectively.

The game's logic is based on the PoW algorithm and a given transaction data set. There are two games. The main difference between Game 1 and 2 is the number of product transactions processed. In Game 1, students need to mine a single transaction within a block, while in Game 2, students need to mine multiple transactions within a block. The hash algorithm and goal difficulty are customised for teaching and learning purposes.

In Game 1, a node is responsible for creating a transaction that contains the customer ID, product ID, product quantity, product name, and delivery date. Miners need to calculate the correct hash and nonce. Transaction data are converted into a set of variables for a custom algorithm, and the translation between character and decimal values is conducted following ASCII (American Standard Code for Information Interchange). A hash algorithm is then used to determine the hash value. The last three digits of the current hash are taken from the previous block and used as the previous hash of the current block during the calculation. Miners calculate the hash by incrementing the nonce value, and the target difficulty of block mining is that the hash value is divisible by both three and seven. Once the miners complete the hash calculation and upload the result, the consensus of the whole network is achieved. Authorised nodes (teachers) can force the block mining process to be finished with the correct hash and nonce if consensus cannot be reached. The most recent hash will be used as the prior hash in the subsequent round of block mining. These steps of transaction creation, hash calculation, and consensus establishment are repeated until all transactions are mined and added to the blockchain.

In Game 2, block mining is based on the Merkle tree structure. Most game logic and operations are similar to Game 1, but the hash calculation process is different. Using SHA-256 to hash the entire value of all data fields better mimics the hashing technique in real life. Once all the data have been hashed, each transaction can be aggregated and hashed to obtain the Merkle tree root. The last hash value will be replicated once to generate an even number of leaf nodes if the number of transaction data is odd. The new block can be verified and added to the blockchain once the calculation has been verified by more than half of the nodes, setting the Merkle tree root to the previous hash in the next block. The preceding procedures are repeated to mine all the transaction data in the blockchain under the predetermined blockchain data.

4 Metaverse Game Deployment in Space Learning

In education, blockchain concepts and gamification can be used to teach students about space instrument management. Space instruments are crucial to space missions, supporting intelligence gathering, planetary exploration, and environmental monitoring. These instruments typically have advanced technology, intricate functions, and unique requirements. Therefore, monitoring and maintaining them effectively is essential to guarantee that they can operate as intended and give accurate and reliable data in the extreme space environment. A blockchain-based conceptual and applied learning platform allows students to understand the complexity of managing space instrumentation and the significance of high-tech components through gamification. Students can test and maintain their space instruments using the tools and resources provided on the platform. A transaction can be created on the blockchain each time a student completes a test or maintenance task on a space instrument. This transaction may include crucial details regarding the assignment, such as the identification of the instrument, transaction date, measurements, and quantity.

The game's user interface is simple, while its tailor-made consensus algorithm is illustrated in Figure 2. The teacher needs to enter the teacher qualification certificate, set the game and blockchain data files, and specify the corresponding virtual room and password before the game can begin. Students participate in the game by inputting their student ID and matching password. When a sufficient number of students (miners) join the game, and the number exceeds three, the game has reached its formal stage. The teacher (node) can propose a new transaction block for the space instrument, including customer ID, part ID, part quantity, part name, and manufacturing date. Students can then upload their responses for verification until the network reaches at least 51% consensus, such that a new block is published to the blockchain. Students who successfully provide the correct answers will receive bonus points. The rule for receiving rewards is that the first successful student can receive a score equal to the total number of successful miners; the second successful student can receive a score equal to the first successful student less than one, and so on. Teachers can continually propose transaction blocks for space instrument sections until all the predetermined blockchain data have been utilised.

Adding the Merkle tree data structure to the hash calculation in Game 2 is the primary distinction between Game 2 and Game 1. Transactions for space instruments will be permanently and irrevocably recorded in this ledger. The transaction block has the following information: data index, customer ID, part ID, part quantity, part name, and manufacturing date. Following the game, student scores can be displayed in the form of bar graphs and data tables. The entire blockchain can be exported to demonstrate the effect of changing the data and hash.

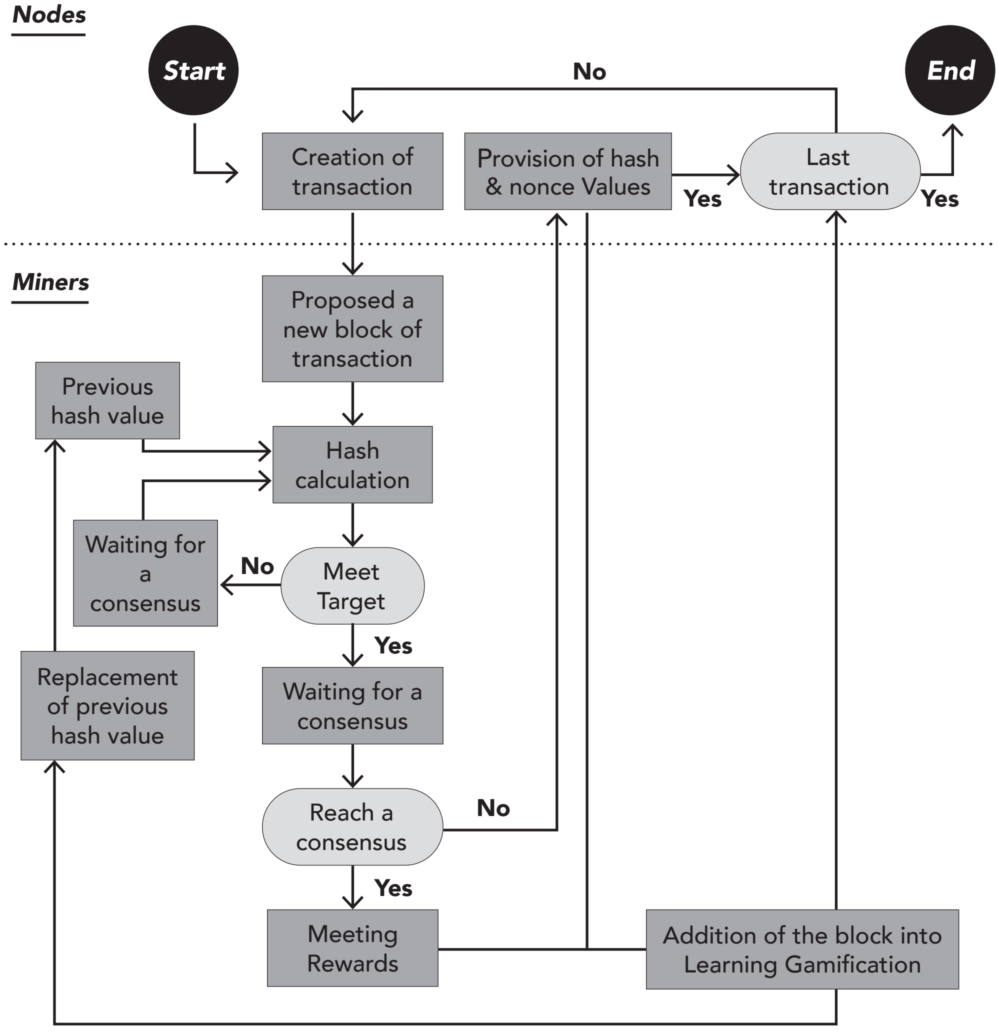

Figure 2. Workflow of the Consensus Algorithm in the Educational Game

Students learn specific blockchain concepts and feature descriptions from Game 1 and Game 2. With features like invariance, decentralisation, security, instant certainty, and network consensus, students can gain first-hand experience of the PoW mechanism and public-private key pairs in Game 1. In addition to these concepts and functions, in Game 2, students can also experience the construction of the Merkle tree with its root computation and zero-knowledge proof for data verification. Both games highlight blockchain's immutability and data integrity while also showcasing how it may be used to track the space instruments.

5 Discussion

Blockchain technology is regarded as one of the fundamental technologies of Web 3.0 and the fourth industrial revolution. It can realise the characteristics of decentralisation, non-tampering, value transmission, and information interaction, as well as provide emerging applications such as smart contracts and decentralised finance (Zhang et al., 2023). As trust in the smart contract public institutions may erode, and the financial crisis due to information security leakages forces people to look for new ways to leverage it, blockchain is gaining traction as an emergent form of transaction and a source of innovation (Lee and Park, 2021). In recent years, many businesses and institutions have begun to focus on the application and development of blockchain technology. They have used games to teach students the principles of blockchain and integrate it into the education system. The proposed game promotes blockchain as a concept for higher education and efficiently solves the problem of learning blockchain in engineering education. Students can participate in the game from anywhere through a web browser experience and learn the fundamental principles of the blockchain building blocks, such as immutability, Merkle trees, and zero-knowledge proof of data authenticity. The platform can also improve students' collaboration and teamwork abilities, actively involve learners in studying blockchain technology via an incentive system, and increase learning enthusiasm and initiative (Wang et al., 2022).

The game logic and structure of the educational gaming platform have been simplified so that students with both technical and non-technical backgrounds can learn blockchain concepts. The hash function has also been modified using straightforward mathematical calculations. The platform can also fill the gap between theoretical understanding and practical application, and offer a secure and immutable record of user achievement so that the details of data credentials can be managed and shared through an indisputable mechanism. In addition, it offers a secure and engaging environment within which students can apply their skills and learn about the widespread adoption of blockchain technology in various fields, including corporate management and the arts, serving as a STEM educational tool to enhance effective teaching and learning techniques. In summary, gamification can play a significant role in making blockchain more accessible and engaging by offering the following benefits:

a. *Improved Engagement:* Games are intrinsically engaging. By transforming blockchain education into an interactive game-based experience, learners can be motivated to participate actively. This can increase their attention, retention, and overall learning experience.

b. *Simplified Learning*: Blockchain involves a variety of complex concepts, such as hashing, distributed ledgers, and consensus algorithms. Gamification can help simplify these concepts for learners by illustrating them through game mechanics, making them easier to understand and remember.

c. *Safe Environment for Experimentation*: Games provide a safe environment within which learners can experiment, make mistakes, and learn from them. In the context of blockchain, this could involve simulating different blockchain networks, experimenting with transaction validation, and exploring the implications of different consensus algorithms.

d. *Immediate Feedback*: Games that provide immediate feedback can help learners understand and correct their mistakes in real-time. This mechanism can be precious for learning blockchain, where understanding the impact of different actions can often involve complex calculations and considerations.

e. *Increased Motivation*: Gamification can increase motivation by introducing elements of competition and rewards. Leader boards, badges, and prizes for achieving certain milestones can drive learners to deepen their understanding and mastery of blockchain concepts.

6 Conclusion

In this chapter, a metaverse for educational gaming platform to learn blockchain technologies and apply them in the management of space resources is proposed. More examples of how the technology is developed are presented in chapter six, which illustrates a hybrid of lectures and game-based courses to help students better understand complex ideas and knowledge in offline and online learning environments and analyses the pedagogical effectiveness of different course content arrangements. With this platform, students can reflect on their content using blockchain technology, build transactional blockchains, and enhance their blockchain technology-related skills, enabling rapid advancement in students' practice in technical and non-technical disciplines. As the use of gamified learning for teaching blockchain concepts in higher education continues to evolve, several potential research directions emerge:

a. *Designing Space Games for Specific Blockchain Concepts*: While existing games provide a broad overview of blockchain technology, there is a need for games that focus on specific concepts such as smart contracts, consensus mechanisms, and blockchain-based traceability. Research could focus on how to design such space games in a way that effectively conveys these complex concepts.

b. *Evaluating Effectiveness*: Rigorous studies are needed to evaluate the effectiveness of gamified learning tools in teaching blockchain concepts. These could involve pre- and post-tests, control groups, and long-term follow-ups to examine whether learning gains are sustained over time.

c. *Collaborative Learning*: Blockchain is inherently a collaborative technology. Research could investigate how to design games that teach blockchain concepts while, at the same time, promoting collaboration and teamwork among learners.

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Chapter 6

Revolutionising Space Resource Allocation through Metaverse Blockchain Technology

Abstract

Many countries are accelerating their space exploration missions to the Moon and Mars with the hope of discovering new energy sources and materials for humanity. The space industry, both private and government-supported, has become a new frontier for competition. However, as space exploration advances, the allocation of resources becomes an increasingly pressing issue. Private enterprises are particularly hesitant to invest in space exploration technologies due to their high R&D capital and development costs, as well as the difficulty in obtaining short-term returns for investors. This chapter proposes a space resource allocation system based on blockchain and metaverse technologies which we described previously. The system employs a decentralised blockchain face recognition system, which uses deep learning to authenticate user identity. Additionally, non-fungible tokens based on blockchain technology can help secure

the ownership of digital assets, and so the binding of physical and virtual assets in the metaverse of space resource allocation can be achieved. The system's advantage lies in establishing a connection and facilitating transactions between the virtual world of outer space exploration missions (the metaverse) and the real world, thereby providing traceability, credibility, exchangeability, and trust to attract and encourage private enterprises and individuals to invest in deep space exploration. This ecosystem, comprising the metaverse, enterprises, government, and individuals, will foster investment, innovation, theory, and practices for future research and development of deep space exploration, producing space science, key technologies, and corporations across countries worldwide with the same mission and vision.

Keywords: space proof of work (POW), blockchain, non-fungible token (NFT), metaverse, space resource allocation

1 Introduction

1.1 Background

Currently, countries worldwide are accelerating the implementation of policies in the space industry and the industry has become a new competitive arena. In the context of national competition, enterprise competition has become more diverse and intense. Employees of China's commercial aerospace enterprises mainly originate from institutions and units within the space ecosystem. However, with the gradual expansion of the aerospace industry, more and more cross-domain enterprises have entered the field.

Although there are many small commercial aerospace enterprises in China, they still lag behind in global cutting-edge technology. The main characteristics of commercial aerospace are large investment, long cycles, and high risks. Despite the large number of commercial aerospace enterprises in China, they are generally small in scale and it is challenging for them to obtain support from major national projects. According to statistics of aerospace and related enterprises, there are about 85,000 aerospace enterprises registered in China, of which only 38,000 are still in operation. Additionally, China's reusable launch vehicle is still in the early stages and there is still a considerable way from large-scale application. All these will pose challenges to China's future ability and costs to enter space.

1.2 Space Resource Allocation with Metaverse Blockchain

In the previous chapter, we described a game for learning blockchain technology to manage a space mission. Given that humanity has not yet begun to utilise the space resources of other planets, these resources currently exist primarily in a virtualised state. This makes blockchain technology an ideal tool for their allocation. There are two main benefits of using blockchain for space resource allocation: 1. Facilitating a more equitable distribution of resources. By recording the process of resource allocation on the blockchain, we can ensure greater fairness and transparency in the allocation process. 2. Directing blockchain funds towards the development of space research. Blockchain-based currencies can be utilised to attract funding for the development of space resources.

1.3 Problems of Blockchain Digital Assets

In recent years, blockchain technology has garnered significant attention for its potential applications, but it also poses challenges such as its highly speculative nature and security concerns. Currently, blockchain applications face the following issues:

Digital mining is often wasteful due to the excessive energy consumption of mining machines, which hoard coins for sale and charge high fees during transactions. In addition, third-party blocks are evaluated and publicised on a project-by-project basis in the US and Europe.

Digital assets can be overhyped, as evidenced by the recent explosion in the value of non-fungible tokens (NFTs). NFTs are a type of cryptocurrency token used to represent digital assets, with ownership recorded on the blockchain and traded in token form. While NFTs provide a way to verify digital asset ownership, the trading mode carries a risk of speculation.

Anonymity in blockchain has legal loopholes and is susceptible to illegal use. Most common blockchain systems lack a real-name system, which can facilitate illegal transactions. Additionally, the current identity authentication in the blockchain system is often too simple and fails to protect user account privacy and security. As a result, accounts can be easily stolen, leading to increased management difficulty and costs.

The goal of this blockchain and metaverse-based resource allocation system is to address the challenges facing the application of blockchain technology and the attraction of investment in commercial aerospace, with the aim of enhancing the practical implementation of blockchain technology. This system includes a combination of virtual and real-world offline and online applications, including:

POW certification: A mechanism to encourage positive workload design, whereby the workload in the real world is mapped to the blockchain system, creating a more diverse workload proof method.

Digital workload certification: User contribution to the system is used to assess the amount of work earned by the user. By digitising work, manual operations are no longer required and the efficiency of management can be improved by adopting an automatic update workload mode.

Real-name authentication blockchain: This system incorporates real-name authentication using multiple biometric features and utilises a deep learning-based blockchain face recognition system to address the limitation of previous blockchain systems lacking real-name authentication.

2 Related Work

The research reviewed in this article is mainly categorised into two parts: studies related to blockchain and federated learning technologies, and articles that explore the applications of these technologies in space research.

2.1 Blockchain with Federated Learning

With the advancement of network technology, blockchain and federated learning (FL) have become popular technologies. Blockchain is essentially a digital ledger of transactions, where the information is organised in blocks that are replicated and distributed across the network of computer systems on the blockchain (Zhang, R, et al., 2019). FL is a machine learning tool for distributed experiments where the data are located in multiple nodes and the training is conducted across multiple edges or servers holding local data (Lyu, L., et al., 2020). The aim is to cultivate high-quality data and resources around the network. Biometric features have become increasingly useful, as they can be used as payment methods, recognition systems, and more (Acquah, M. A, et al., 2020). Previous studies have shown that blockchain is an excellent architecture for managing sensitive and private data stored in biometric tools in a decentralised environment such as FL (Delgado-Mohatar, O., et al., 2020).

FL is an increasingly relevant machine learning tool for distributed experiments where the data are located in multiple nodes. A significant advantage of this approach is the decoupling of model training from the need for direct access to the raw training data (Hard, A., et al., 2018). This method uses different datasets for training, and the hyperparameters include the number of clients (how many nodes are in the network), the number of clients selected, the number of rounds, the epoch (the number of local training rounds per client), and the batch size (which loads data into the loader) (Bonawitz, K., et al., 2019).

FL combined with blockchain is a powerful tool, as blockchain is an immutable database where each block contains verified data, which is authenticated by all nodes in the network instead of any central authority (Mandloi, J., et al., 2020). Each block in the chain contains a unique fingerprint in the form of its hash value and the hash value of the previous block, making it impossible for anyone to tamper with the data stored in it. Furthermore, the information stored on the blockchain will never be deleted or changed (Martinez, I., et al., 2019). Instead, new blocks need to be added to the chain to update the information. In FL, the central aggregator accumulates local updates uploaded by participants to update the global model (Liu, Y., et al., 2020).

2.2 The Metaverse and Blockchain for Space Research

Few articles on the metaverse and space research have proposed AI systems. An AI system is proposed in a planetary augmented reality environment with space robots (Reddy, P. P., 2022). Lee, L. H. et al. (2022) present a vision of an interplanetary metaverse that connects aviators of earth and other planets and Martian users in a turn-based metaverse. However, there are few applications of the metaverse in space and these articles mainly focus on the virtual reality of alien planets.

There has, however, been research on the integration of the metaverse and blockchain, with many articles in this area. For example, Yang, Q. et al. (2022) write a survey article, while Yao, N. et al. (2022) study how the Dark Forest game can challenge centralised social structures using blockchain technology while subjected to social surveillance. Cao, L. (2022) reviews decentralised AI and edge intelligence with smart blockchain, while Dawson, A. (2022) presents issues related to blockchain-based digital assets in the retail metaverse. Goldston, J. et al. (2022) study the problem of more popular cosmic digital assets. There are many applications of the integration of the metaverse and blockchain, but few related studies are combined with space applications.

There are also related papers that research blockchain application in resource allocation, such as Wang, Z. et al. (2022) focus on blockchain-based edge resource sharing for the metaverse, and Jiao, Yutao et al. (2019) research the allocation method of computing resources in blockchain networks. He, Ying et al. use reinforcement learning to allocate blockchain-based computing resources. However, while there is much research in this area, more attention is paid to the allocation of computing resources rather than space resources.

3 System Design

3.1 Space Metaverse

To avoid the aimless hype of virtual space resources, the system has designed a Space POW that certifies workloads generated through space learning, research, or work. The goal is to guide social forces towards the development of the space industry.

Workload certification can be carried out by enterprises, governments, or the United Nations, entities that have the ability to develop space. Additionally, these organisations can authorise cooperative enterprises and local government units to share the workload of certification task and expand the market share. To increase participation in the system, workload certification can be provided not only by offline virtual and real POW certification centres but also online digital world POW certification centres. This offers more opportunities for space industry participants. The online certification method consists of relevant space work, study, or game software, which allows participants to learn and understand the corresponding amount of work after completing the software simulation system tasks.

To improve the system's attractiveness, the game value chain has been redesigned to allow investors to inject funds into the system and improve its value function. Finally, to enhance the system's security and reliability, real-name authentication, space

POW updates, and investor game transactions will be recorded using blockchain technology, which increases security and reliability.

3.2 Architecture Design

The Space Metaverse Blockchain system is a virtual-real hybrid internet application architecture comprising three parts: blockchain services, an offline POW centre, and online POW APP.

The blockchain services are the core components of the system, comprising the following main parts:

Space POW Chain: This chain records the workload collected by the certification authority and digital APP software. The certification centre is an offline unit that can authenticate user activities in the metaverse and convert them into corresponding virtual currency. The platform also offers an online APP interface to automatically update the user's work or learning in the metaverse into this chain.

Investor Game Chain: The blockchain coins obtained through POW can provide value enhancement services through games to increase the attractiveness of the system. Investors can purchase virtual currency through a trading system and then participate in games offered by the system, increasing their return on investment by taking risks. For instance, an investor can perform activities in the metaverse to obtain virtual currency, which can be exchanged for NFT items in the metaverse. The NFT items in the system are certified by the company operating the system, making them valuable as real goods.

Real-name Chain: This chain uses a deep learning-based blockchain face recognition system for identity authentication, ensuring the security of the blockchain system.

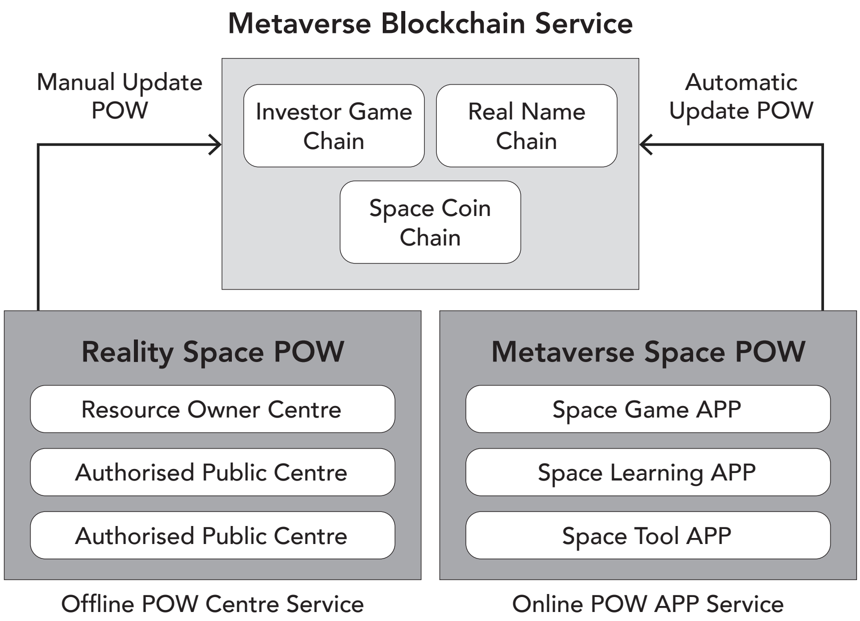


Figure 1. Space Metaverse Blockchain Architecture

The architecture also includes two important services:

Offline POW Service: In these organisations, a shared blockchain authentication centre can be established to identify the amount of virtual currency corresponding to the workload and record it in the blockchain system. For instance, system operators can collaborate with government agencies to establish government certification centres, or private aerospace companies can themselves establish enterprise certification centres.

Online POW APP Service: This service is primarily responsible for defining standard interfaces and mapping various digital metaverse systems with Space POW. It automatically updates and transforms users' workload after connecting with the workload measurement software APP. If a user's work in the metaverse can earn virtual currency, the user's contribution to the system can also earn virtual currency.

3.3 Metaverse Workflow

This section describes the primary workflow of the system.

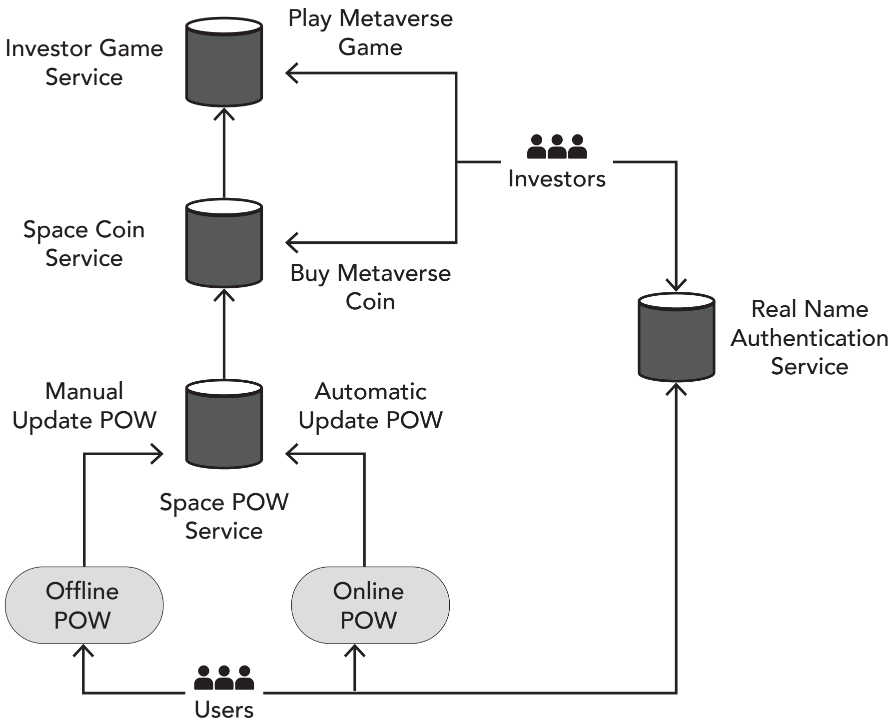


Figure 2. Investor Game Chain Workflow

Figure 2 highlights the main participants in the process: users and investors. Users can obtain virtual currency corresponding to their workload from the authentication authority or the application in the metaverse. Each time they obtain virtual currency, the amount is updated in the workload record chain. Investors can purchase virtual currency from the virtual currency trading chain server, with the price of the virtual currency fluctuating according to the market mechanism. The added value of the virtual currency serves as an incentive for users. Additionally, investors can participate in the game's value chain investment game, where the outcome determines whether the value of their virtual currency increases or decreases. The aim is to make the system more engaging and drive the value of the virtual currency. Throughout this process, the Real-Name Authentication Service is responsible for identity authentication of investors and users, while the Investor Game Service provides investment games in which investors can participate. The Space Coin Service manages transactions for Space Coin, and the Space POW Service manages offline and online operations for Space POW.

3.4 Real-Name Authentication Service

The architecture for user verification using the real-name chain is managed solely by the real-name identity authentication server. This authentication process utilises the face recognition system of the FL chain, which ensures both the security and robustness of the system.

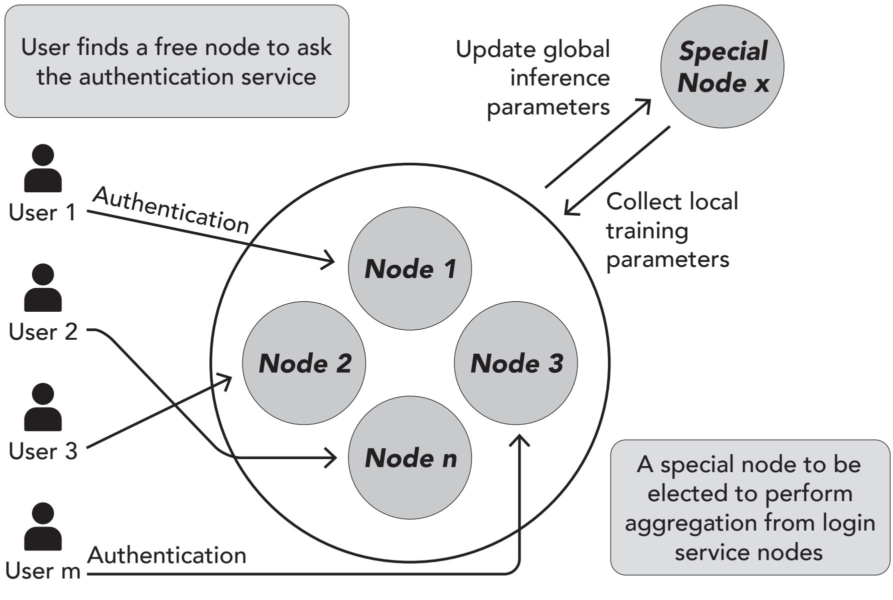


Figure 3. Real-Name Authentication Service

The proposed architecture addresses the authentication process from registration to the matching phase. The main components of the process are presented in Figure 3. Each authentication node can act as a central server, a blockchain node, or a single node for federated training. When the nodes work together, they form a centreless and scalable network topology. However, when one node takes on the server role, the other nodes should behave as a single training blockchain node. The roles are selected for the server in turn, as determined by the algorithm. Single nodes can only passively receive orders and perform tasks delivered by the server.

3.5 Real-Name Authentication Service Algorithms

Federated Blockchain Biometric

At the outset, the primary server in the system generates the genesis block, which serves as the first block in the chain. During the global model training process, the local model weights are stored in cached local transactions. These model weights recorded in the transaction cache stores the relative paths to the weights file, which is stored on the hard disk. Due to its large size, the local model weights file is stored on the server. The local model weights are packed into a new block only when it is mined, with users determining when to begin mining.

As noted earlier, the client and server use different mining methods, as illustrated in Algorithm 1: servers mine new blocks using the POW algorithm, whereas clients must obtain the most recent blocks from servers before mining new blocks. If a new block is mined by a server, the miner who mined the block will pack the transactions into the block and then broadcast the block to every device in the system. If a new block is mined by a client, the miner will send the hash of the last block to the server, which will be responsible for packing and broadcasting the blocks since the client does not cache the local model weights file itself. A new round of block mining will then be carried out.

Algorithm 1: Main Procedure of Federated Blockchain Biometric

```
procedure CLIENT TRAIN LOCAL MODEL
for ( i = 0; i ≤ N_C; i ++ ) do
    client i uses local data to train local model
end for
end procedure
procedure CLIENT UPLOAD LOCAL MODEL
if (local model training completed) then
    client uploads local updates to primary server
    client records model weights in the transaction cache
    client broadcasts the transaction to other devices in the system
end if
end procedure
procedure CLIENT DOWNLOAD GLOBAL MODEL
if (global model aggregate completed) then
    for ( i = 0; i ≤ N_C; i ++ ) do
    client i downloads global model from server
    client i updates local model
    end for
end if
end procedure
procedure SERVER AGGREGATES MODEL
primary server computes Equation (13)
if (global model aggregate completed) then
    server records model weights in the transaction cache
    for ( i = 0; i ≤ N_C; i ++ ) do
        primary server sends global model to client i
          primary server broadcasts the transaction to other devices in the
          system
    end for
end if
end procedure
```

Blockchain with Federated Learning Algorithms:

Algorithm 2: Main Procedure of Blockchain

```
procedure SERVER GENERATE BLOCK
if (hash satisfies target) then
    server execute proof-of-work
    server create new block(cached transactions)
    server broadcast new block
end if
end procedure
procedure CLIENT GENERATE BLOCK
client ask the server if the local block is up to date
if not (local block is up to date) then
    update local block
end if
client execute proof-of-work
send the hash of new block to server
server create new block(cached transactions)
server broadcast new block
end procedure
```

Based on the previous discussion, we have developed an algorithm for the miner, as shown in Algorithm 2. It is important to note that traditional global FL is highly susceptible to malfunctioning centralised servers, which can cause distortion to the global models of all devices. In contrast, our algorithm uses blockchain to store the locally-trained model weights uploaded by users, increasing the system's robustness against centralised server malfunctions. Additionally, we use blockchain to record user login information. The blockchain function in this system is responsible for the following tasks:

The primary server cluster maintains a blockchain that backs up global model parameters. It records the weight of update data provided by all authentication servers in all rounds and the aggregation results of the model by the primary server.

In the event of primary server failure, the system can elect a new primary server from the authentication server. The newlyelected primary server can quickly restore normal system operation by reading the backup of model information in the blockchain.

A blockchain recording user login information is maintained in the distributed server cluster. When a user initiates a login request, the login information will be recorded in the blockchain.

4 Evaluation

To conduct the evaluation, we utilised a portion of the datasets from CASIA-WebFace and evaluated the model using the Labelled Faces in the Wild (LFW) dataset. The selected model was Facenet, which employs either MobilenetV1 or Inception-ResNetV1 as its backbone. All experiments were conducted using the same hyperparameters: clients=5, train_rounds=4, local_epochs=5, batch_size=96, and FedAVG. Table 1 presents a comparison of various face biometrics.

1) Dataset

We utilised the CASIA-WebFace dataset to train our model. This dataset is a freely available and open source, specifically designed for face recognition purposes. It sources data from the IMDb website, which hosts numerous photos and names of celebrities. To obtain the data, the author of CASIA-WebFace developed crawler software to extract photos and names from IMDb and save them.

For evaluating our model, we used the LFW dataset. This dataset contains over 13,000 images of faces collected from various web sources. Each face in the dataset is labeled with the name of the person pictured, and 1,680 of the individuals have two or more distinct photos within the dataset. The primary purpose of this dataset is to test the accuracy of face recognition models.

2) Accuracy Experiment of Federated Learning Blockchain

Table 1. Comparison of Federated Blockchain with Different Backbones

Backbone	Round	Accuracy	
		Standalone	Federated
MobilenetV1	1	0.799500.02496	0.538830.02319
	2	0.852500.02164	0.607330.01752
	3	0.861170.01424	0.644670.02111
	4	0.856170.01495	0.700670.02037
Inception-ResNetV1	1	0.892830.01406	0.711000.01734
	2	0.909330.01555	0.812170.02392
	3	0.917000.00718	0.852000.01441
	4	0.913500.00861	0.867330.01422

Table 1 presents the experimental results, indicating that the Inception-ResNetV1 backbone achieved better accuracy than the MobilenetV1 backbone in our federated blockchain system. This outcome can be attributed to the significantly higher number of parameters in the Inception-ResNetV1 model compared to the MobilenetV1 model.

3) Time Experiment of Federated Learning Blockchain

In the FL experiments, we utilised a network environment comprising five clients. Before being broadcast, multiple transactions were integrated into a block. Our blockchain algorithm was implemented in a real-time hardware testbed to evaluate its performance. The testbed was based on a personal computer equipped with a Six-Core 2.60 GHz Intel(R) Core(TM) i7-9750H CPU, an NVIDIA GeForce RTX 2080 graphics card, and 32 GB DDR4 RAM. We deployed the system with one server as the core and five clients in the FL experiments. The network topology adopted a hybrid architecture, with a star as the primary structure and graphic as a supplement. The device also had the capability of connecting to a wired network, which provided it with the advantage of better and faster network connectivity. This testbed was sufficient to enable real-time evaluation of our blockchain algorithm and was not intended as a commercial deployment demonstration.

For the experimental setup, the computer was connected to a router and utilised wired connectivity. The transactions load was distributed across the network participants, with each storing the blockchain ledger locally using Numpy. Once a training round was completed, one device was randomly selected from the server and client to calculate the hash of the last block, which contained the local model weights and the previous hash. This hash was then added to the new block to be added to the blockchain at the server. The new block was subsequently transmitted to the other clients to replace their local block. Throughout our experiment, various timestamps were generated for different processes. The following provides the formal definition of each processed time.

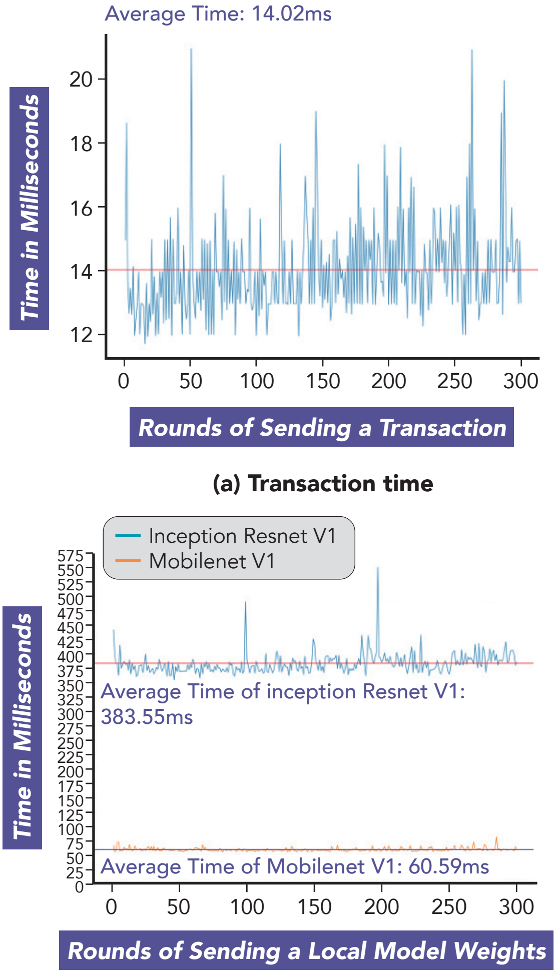
Table 2. Time Comparison of Federated Blockchain

Name	Equation	Description
Transmission Time	$\Delta t_{ransmisson} = t_{te}$ - t_{ts}	In each round of training, timestamps and are generated when the client finishes training and sends the local model weights and transaction, respectively.
Transaction Time	$\Delta t_{ransmisson} = t_{we}$ - t_{ws}	When the server receives the local model weights in each round of training, timestamps and are generated when the client finishes training and sends the local model weights as a transaction.

Name	Equation	Description
Hash Time	$\Delta t_{hash} = t_{he} - t_{hs}$	When a new block is mined (puzzle solved), a timestamp is generated at the miner. After the hash of the current block is calculated, a timestamp is generated. The time required for block hash is calculated by the miner.
Packing Time	$\Delta t_{pack} = t_{pe} - t_{ps}$	The miner then generates a new timestamp for starting packing the new block. After the miner packs the cached transactions with the previously calculated hash value into a new block, a timestamp is generated, at which point the block packing is complete.

Figure 4(a) shows the time required for 300 transactions to be added from one device to another, with each transaction taking approximately 10ms to 15ms. Figure 4(b) compares the transmission time of a set of weights for Inception-ResNetV1 and MobilenetV1 from the start of sending to the completion of receiving at the receiver.

Before mining, miners are required to compute the hash value of the current block. The hash computation time for blocks containing different numbers of local model weights differs, as illustrated in Figure 5(a). Once a device has successfully mined a new block, the server aggregates the cached transactions into the new block and broadcasts them to the other devices in the system. Figure 5(b) depicts the time required for the server to pack blocks containing different numbers of transactions using Inception-ResNetV1 versus MobilenetV1. Similarly, different block sizes require different propagation times. It should be noted that in our test bed, we attempted to use compression methods to reduce transmission time. However, we observed that the transfer time is primarily consumed in compression and decompression, which is dependent on the device's performance rather than network transfer and is much more time-consuming than for the uncompressed case. Once the other devices receive the new block from the server, they add



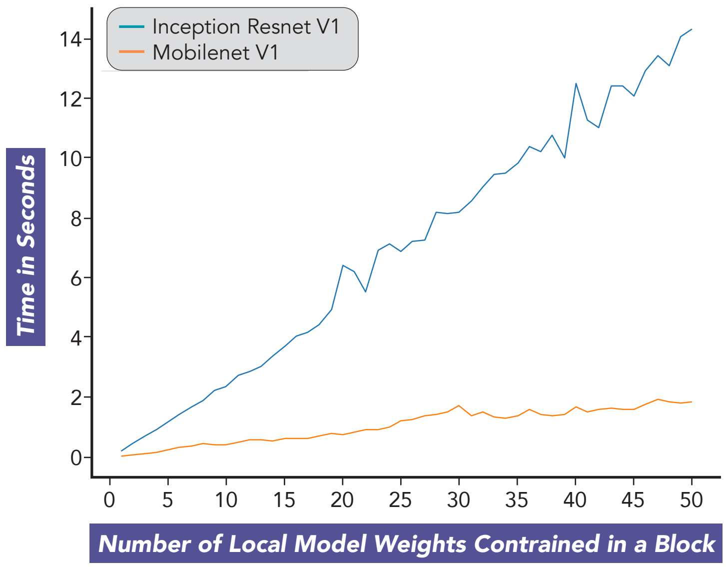
(a) Transaction time

(b) Transmission time

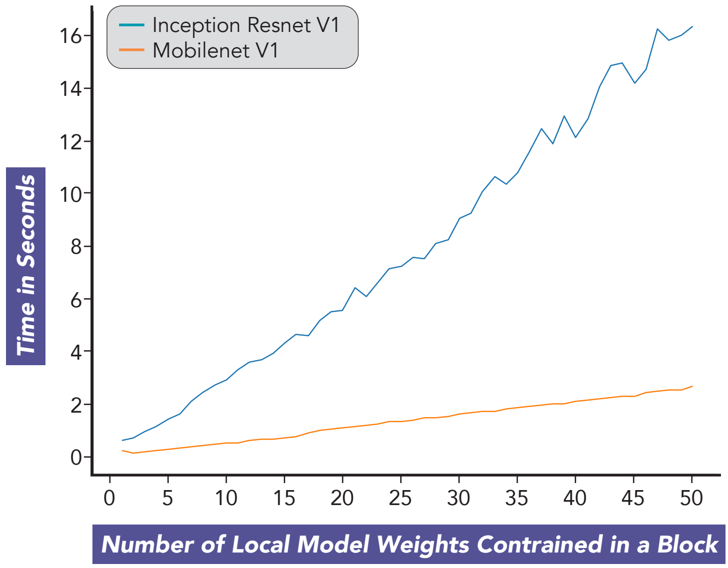
Figure 4. Transaction Time and Transmission Time

it to their local blockchain. Upon completion of this process, one round of mining is considered complete.

In terms of time efficiency for each stage of the process, MobilenetV1 outperforms Inception-ResNetV1 due to its smaller number of parameters. Through this experiment, we have also demonstrated the feasibility of the system designed within this framework in terms of speed.



(a) Computation time of block hash



(a) Packing time of new block

Figure 5. Computation Time and Packing Time

5 Discussion and Future Development

This section focuses on the issue of land allocation between the Moon and Mars, which are the closest outer space lands to Earth and the outer space resources most likely to be developed by humans in the short term. Although humans cannot currently establish a habitable environment on the Moon or Mars, exploring their resource allocation problems and solutions are still important. Possible resource allocation problems can be categorised in the short and long terms. In the short term, there is no feasible solution for humans to settle on the Moon and Mars, so human exploration of these spaces there is a reluctance to allocate too many resources to developing them. To address these problems, we proposed a space digital coin in the form of the metaverse blockchain to attract people to develop space resources. Even if the Moon and Mars are not currently attractive, the virtual meta-cosmic currency could attract more funding for the development of space resources.

Through the notarisation function of the blockchain, more people can share in the achievements of future exploration of space resources, which can promote greater fairness and grant equality as a goal for many people. Organisations can use rewards to encourage scientific research personnel. At the same time, investors and game features can be introduced to attract money to fund related scientific researchers and promote the progress of the space exploration programme. Organisations involved in space resource exploration can attract investors and users to contribute to their high-risk space exploration with space coins. Investors can participate in the investment game and potentially achieve greater returns if they can bear the risks. Users such as students, workers, engineers, and researchers can contribute to the space business and ecosystem.

6 Conclusion

In conclusion, the proposed metaverse blockchain system provides a novel and promising solution to the space resource allocation problem. With the comprehensive method, architecture, and process for space resource allocation, the system covers both online and offline POW conversion methods, which enhances its adaptability and effectiveness. Moreover, the system design includes real-name authentication, space POW updates, and investor game transactions, providing a fair and transparent platform for space resource allocation and rewards.

It is expected that this study can stimulate further research in this field and encourage further investment and participation in space exploration and resource development. Although exploration and resourcing require significant investment and present technical challenges, the proposed system provides a promising way to attract more funding and improve the efficiency of space exploration and development. In summary, this study provides insightful ideas and approaches for future space research. We believe that the proposed system will have a positive impact on the development of space exploration and resource utilisation in the future.

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Chapter 7

Mixed Reality with Blockchain for Space Mission Management

Abstract

Efficient freight loading and inventory management in mission-critical space logistics operations require effective interaction with front-line operators and the use of immersive technologies. This chapter proposes the integration of mixed reality (MR) technology to visualise operational instructions and create a digital twin of picking and packing operations. Merging physical activities and virtual instructions into a closed-loop structure allows operators to follow optimised loading instructions and handle uncertainties and changes. Logistics 4.0 aims to enhance operational capabilities through autonomous decisions and intelligence. However, adopting MR technologies in the logistics industry, especially for small and medium enterprises, faces challenges such as high costs and the need for large datasets. A framework combining blockchain and MR technology is proposed to overcome these barriers. The framework leverages the multi-attribute fuzzy ABC classification method to optimise inventory management in space missions. It offers benefits such as improved visualisation, interaction capabilities, and precise inventory classification, enhancing operational efficiency and accuracy. Challenges related to developing robust MR hardware and software for space conditions and managing the computational complexity of space inventory classification are acknowledged. This framework allows for revolutionising inventory management, enabling efficient and reliable operations in mission-critical space logistics scenarios. We also acknowledge the challenges of implementing MR and fuzzy ABC classification, such as developing robust MR hardware and software for space conditions and the increased computational complexity of space inventory classification. This chapter highlights how the adoption barriers to MR-based logistics 4.0 solutions can be resolved and eliminated, resulting in enhanced business competitiveness in the future market.

Keywords: logistics 4.0, blockchain, metaverse and mixed reality (MR), space management

1 Introduction

The metaverse of MR and augmented reality (AR) technologies have surfaced as ground-breaking tools with significant capacity to optimise and improve inventory management within the distinctive and demanding milieu of space missions (Speicher et al., 2019). By providing immersive and interactive experiences, these cutting-edge technologies have the potential to fundamentally transform the procedures through which inventory is classified, monitored, and managed in the context of space exploration initiatives.

Proficient inventory management is pivotal in the success of space missions, where the immediate availability and optimal utilisation of mission-critical components are paramount (Williams and Tokar, 2008). However, conventional inventory management systems often fall short when confronted with the dynamic, multifaceted, and uniquely rigorous challenges of space missions. Such challenges include adapting to continually evolving mission requirements, managing constrained storage space and weight allowances, mitigating lengthy procurement lead times and infrequent resupply opportunities, and navigating intricate interdependencies among spacecraft components (Song et al., 2020).

This chapter presents an innovative inventory classification system that synergistically combines multi-attribute fuzzy ABC classification and blockchain with the immersive capabilities of MR technology to address these challenges. Blockchain technology is applied to establish a decentralised framework to consolidate industrial knowledge over the network, and thus, an appropriate set of decision criteria can be collectively determined. This novel combination aims to overcome the limitations inherent in traditional inventory management methods, thereby offering a more adaptive and efficient solution tailored to space missions. Integrating multi-attribute fuzzy ABC classification allows for a comprehensive evaluation of inventory items based on multiple criteria, facilitating optimal allocation of limited storage space and resources. Concurrently, MR technology enables inventory managers to visualise and interact with virtual inventory objects in real-time, thereby enhancing inventory tracking, identification, and decision-making processes.

The proposed system holds very great potential to enhance inventory management efficiency, curtail mission downtime, and significantly contribute to the overall triumph of space missions. In this chapter, we will discuss the underlying principles and methodologies of this innovative inventory classification system, discuss its advantages and potential applications in space missions, and underscore its value in addressing the unique challenges associated with inventory management in space exploration.

2 Related Work

2.1 Classification and Management

Inventory classification systems are widely used to categorise and prioritise inventory items based on their importance and value. One notable approach is fuzzy ABC classification, which combines the advantages of fuzzy logic and the ABC analysis technique (Zadeh, 1965; Liu, 2010). Fuzzy ABC classification allows for a more nuanced and flexible classification of inventory items by considering multiple criteria simultaneously (Puente et al., 2002). Fuzzy ABC classification involves assigning inventory items to different categories (A, B, or C) based on their fuzzy membership values, representing the degree of their belongingness to each category. This approach considers multiple attributes such as demand variability, criticality, lead time, and scarcity to determine the appropriate classification for each item. By incorporating fuzzy logic (Serrano-Guerrero et al., 2021), which allows for the representation of uncertainty and imprecision, fuzzy ABC classification provides a more accurate and adaptable classification method than traditional deterministic approaches. The benefits of fuzzy ABC classification in inventory management are noteworthy. Firstly, it enables a more granular and dynamic classification of inventory items, allowing for better resource allocation and decision-making. The fuzzy membership values provide a continuous representation of an item's importance, facilitating more precise inventory control strategies. Secondly, fuzzy ABC classification considers multiple criteria simultaneously, capturing the complexity and interdependencies of inventory items. This enhances the robustness of the classification system and enables a more comprehensive evaluation of inventory items. Thirdly, the flexibility of fuzzy logic allows for easy adaptation to changing business conditions and mission requirements, making it well-suited for dynamic environments like space missions. However, there are certain limitations to consider when employing fuzzy ABC classification. Firstly, determining appropriate membership functions and selecting criteria and their weights require careful consideration and expert knowledge. Improper choices may lead to biased classifications or suboptimal decision outcomes. Secondly, computational complexity increases with the number of criteria and inventory items, potentially impacting real-time decision-making in large-scale inventory systems. Therefore, efficient algorithms and computational techniques are necessary to handle the computational load effectively. The applicability of fuzzy ABC classification in space missions is evident. Given the unique challenges of space exploration, such as limited resources, dynamic environments, and complex interdependencies among components, fuzzy ABC classification can help optimise inventory management. It also facilitates adaptive allocation of storage space, efficient resupply strategies, and accurate inventory forecasting, all of which are critical for successful space missions.

Traditional inventory management systems often face challenges when applied to space missions due to several factors (Ufua et al., 2022; Khokhar, 2023):

Dynamic Nature of Space Missions: Space missions are characterised by evolving mission objectives, changing requirements, and unforeseen contingencies. Traditional inventory management systems, typically designed for static and predictable environments, struggle to adapt to the dynamic nature of space missions. These systems often lack the flexibility and responsiveness to manage inventory effectively in such complex and uncertain scenarios.

Limited Storage Space and Weight Constraints: Spacecrafts have strict storage space and weight capacity limitations. Every component carried onboard must be carefully selected and optimised to ensure efficient use of resources. Traditional inventory management systems may not adequately address these constraints, leading to suboptimal allocation of storage space and weight, which can impact mission efficiency and compromise the ability to accommodate new components or adapt to changing requirements.

Long Lead Times and Limited Resupply Opportunities: Space missions operate in remote and often challenging environments, with limited opportunities for resupply. Obtaining replacement components or restocking inventory may involve significant lead times, making it critical to have accurate inventory forecasts and efficient replenishment strategies. Traditional systems relying solely on historical demand patterns or deterministic models may not account for a space mission's unique challenges and uncertainties, leading to inadequate inventory levels or delays in acquiring critical components.

Complex Component Interdependencies: Spacecraft assemblies comprise numerous interdependent components, where one component's availability and functionality can impact the performance of others. Traditional inventory management systems that treat components in isolation may fail to capture these interdependencies, resulting in suboptimal inventory allocation and potential disruptions during critical operations.

More recently, the application of blockchain technology in inventory management and classification has vast potential to revolutionise conventional supply chains, facilitate information sharing, and optimise decision-making processes. Zheng et al. (2021) explore the use of blockchain technology in a three-level spacecraft supply chain. The research focuses on risk decision-making problems encountered by various participants, including a spacecraft builder, supplier, and logistics service integrator. The Stackelberg game is applied under three decision-making scenarios: decentralised, partially centralised, and fully centralised. The study found that the optimal order quantity for the spacecraft builder and the supplier's degree of blockchain application varied with the spacecraft builder's risk coefficient.

Interestingly, the overall profit of the supply chain differed across the decision-making scenarios. It is suggested that the deployment of blockchain technology can be customised based on specific risk coefficients and the desired level of centralisation in decision-making, thereby enhancing the efficiency of the supply chain. Wang et al. (2022) investigate vendor managed inventory (VMI), focusing on achieving supply chain coordination in an asymmetric information environment. The research proposes a commitment penalty contract to enhance the performance of a VMI supply chain. This contract can reveal the secured information of the manufacturer and can coordinate the supply chain under bilateral asymmetric information. This approach essentially leverages the transparency and immutability of blockchain to mitigate information asymmetry, thereby improving the overall efficiency of the supply chain. Li (2023) presents a structural framework for blockchain-based supply chains and outlines five significant changes that blockchain can bring: establishing a common platform, enabling end-to-end information sharing and traceability, providing real-time updates, facilitating speedy and efficient asset transfers, and automating contracts. The major breakthrough is the transformation from the tiered structure of a traditional supply chain to a decentralised common platform in a blockchain-based supply chain. This transformation shortens the length of supply chain tiers, eliminating problems associated with multi-tier supply chain management. Moreover, a blockchain-based supply chain is both time- and cost-efficient and reduces the cost and risk associated with supply chain partners. These changes make supply chains smarter and more efficient.

2.2 Mixed Reality for Inventory and Logistics Management

To mitigate these supply chain problems, integrating mixed reality (MR) technology and the multi-attribute fuzzy ABC classification method, as proposed by Yung et al. (2021), can significantly enhance inventory management on space missions. The multi-attribute fuzzy ABC classification method considers multiple attributes, including weight, volume, and criticality, to comprehensively and precisely classify inventory items. Incorporating MR technology into this classification system provides astronauts with enhanced visualisation and interaction capabilities with the classified inventory (Tsang et al., 2022). The study by Yung et al. (2021) offers a valuable approach to developing a multi-attribute fuzzy ABC classification method specifically tailored for space mission inventory classification. This methodology addresses the constraints of traditional inventory management systems by considering an array of attributes and employing fuzzy logic to manage uncertainties. By amalgamating this classification method with MR technology, space agencies may potentially augment inventory management's efficiency, accuracy, and safety. MR technology can be harnessed to create a virtual environment where inventory items are represented in 3D, arranged based on their classification, and prioritised according to the fuzzy ABC method (Lang et al., 2019; Baroroh and Chu, 2022). Astronauts can navigate this virtual space and interact with inventory items in a more intuitive and immersive fashion, thereby improving the identification and management of critical inventory. Moreover, MR can offer training and simulation capabilities, enabling astronauts to practice inventory management tasks within realistic virtual environments, thereby reducing errors in real-world scenarios. However, the implementation of MR in space exploration and inventory management does present its own set of challenges. Ensuring the reliability and accuracy of MR hardware and software under the harsh conditions of space, including radiation, extreme temperatures, and microgravity environments, is paramount. Furthermore, integrating MR features into existing inventory management systems may necessitate the development of new software or modifications to existing ones (Marino et al., 2021).

The deployment of MR technology in space exploration holds the promise of numerous potential benefits, notably, as introduced above, the enhancement of inventory management. MR amalgamates the features of virtual and augmented reality to generate immersive and interactive experiences, facilitating users in visualising and interacting with digital content within their real-world environments (Çöltekin et al., 2020). Within the context of space missions, MR can augment inventory management processes, thereby contributing to more efficient operational procedures. One potential application of MR in space exploration pertains to the visualisation and simulation of inventory systems (Berman and Pollack, 2021). MR technology can fabricate virtual representations of inventory storage areas and furnish real-time data on each inventory item's location, quantity, and status. This capability enables astronauts and mission controllers to garner a comprehensive understanding of the inventory status, facilitating accurate inventory tracking and retrieval. Moreover, MR technology can bolster remote collaboration and training for inventory management. Astronauts and ground personnel can utilise MR headsets to share live video feeds, 3D models, and annotations, thereby enabling real-time communication and guidance (Rokhsaritalemi et al., 2020). This capability is particularly valuable during spacewalks or when astronauts require assistance identifying and handling specific inventory items. Another potential advantage of employing MR in inventory management is the ability to overlay digital information onto physical objects. Utilising MR interfaces, astronauts can receive real-time inventory updates, warnings, or instructions directly within their field of view, obviating the need to consult separate displays or manuals. This streamlined access to information has the potential to improve efficiency, reduce errors, and enhance situational awareness during inventory-related tasks (Rejeb et al., 2020). However, implementing MR in space exploration and inventory management also introduces its own challenges. A significant challenge is the development of robust and reliable MR hardware and software capable of withstanding the harsh conditions of space. Additionally, ensuring the accuracy and reliability of the virtual representations and tracking systems is a critical factor for the successful implementation of MR in inventory management.

2.3 Use of the Metaverse

Despite significant progress in metaverse with MR technology and fuzzy ABC classification for logistics management, there remains a substantial research gap. Most notably, there is a lack of empirical studies evaluating the effectiveness of integrating MR technology with fuzzy ABC classification in real-world space missions. While the theory and potential advantages are well-discussed, the impact of this combined approach on improving inventory management efficiency, accuracy, and adaptability under the unique conditions of space missions is yet to be fully understood. Additionally, research has not sufficiently addressed the challenges and potential solutions for implementing this integrated approach. For instance, developing robust and reliable MR hardware and software that can withstand the harsh conditions of space is a significant challenge that needs further exploration.

Similarly, ensuring the accuracy and reliability of the virtual representations and tracking systems, and determining and adjusting appropriate fuzzy membership functions and criteria weights are critical issues requiring more detailed investigation. Furthermore, there is a need for research on efficient algorithms and computational techniques to handle the increased computational complexity associated with the application of fuzzy ABC classification in large-scale inventory systems. This is particularly important for enabling real-time decision-making in dynamic and unpredictable space mission environments. Finally, there is a lack of comprehensive user studies evaluating the usability and user acceptance of MR interfaces and a fuzzy ABC classification approach. Understanding the user experience and addressing potential usability issues are crucial for successfully deploying and adopting these technologies in space missions.

3 Using a Blockchain-Enabled MR-Based Space Logistics System

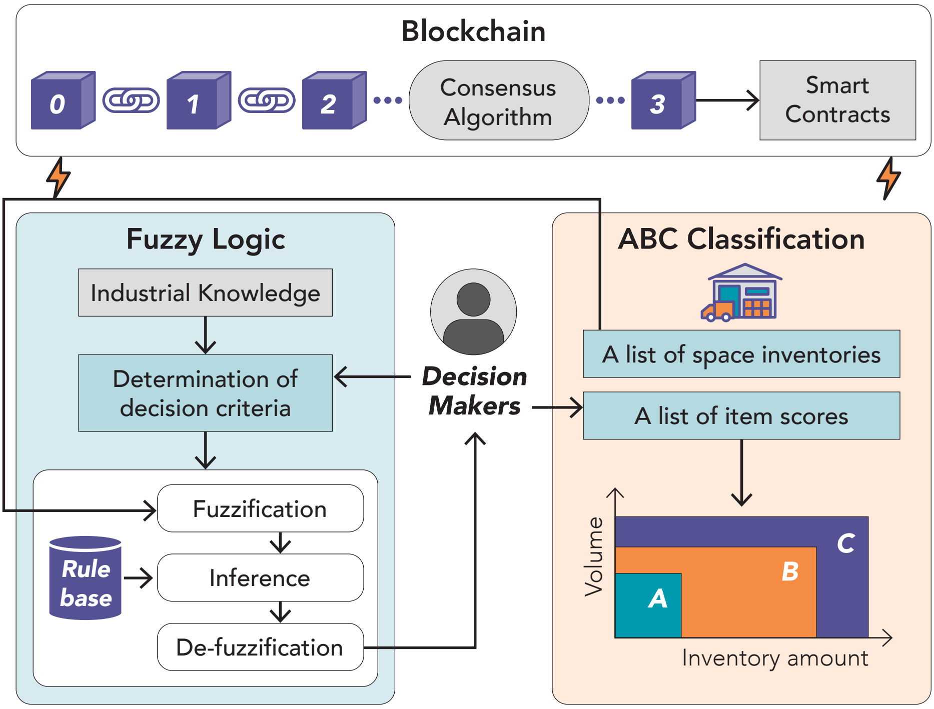

Figure 1. Architecture of the Fuzzy ABC Classification for Inventory Management

The proposed inventory classification system combines the multi-attribute fuzzy ABC classification method with MR technology to enhance inventory management in space missions, as shown in Figure 1. This system aims to overcome the limitations of traditional inventory management systems by considering multiple attributes and providing an immersive and intuitive interface for astronauts. In the proposed system framework, blockchain technology is applied over the system network to automate knowledge consolidation among decision-makers. The decision criteria for the inventory classification can thus be determined upon reaching the consensus of decision-makers over the network.

Subsequently, the multi-attribute fuzzy ABC classification method considers various attributes, such as weight, volume, and criticality, to comprehensively classify inventory items. This classification approach enables a more accurate and granular inventory categorisation, allowing for better prioritisation and allocation of resources based on their importance and characteristics. MR technology is utilised to implement this classification system. MR creates a virtual environment where inventory items are displayed in three dimensions, organised based on their classification. Astronauts can navigate this virtual space using MR devices, such as headsets or handheld devices, and interact with the inventory items in a highly immersive and intuitive manner. This setup enables astronauts to visualise and manipulate the inventory items as if they were physically present, enhancing their ability to identify, locate, and manage them effectively. When wearing AR/MR glasses, astronauts can observe their surroundings while simultaneously viewing virtual information related to the ABC classification of inventory items. The glasses provide real-time overlays, allowing astronauts to see each item's classification category (A, B, or C) directly within their field of view. This visual representation empowers users to quickly identify and locate high-priority items (Category A) or items requiring attention (Category C), streamlining their inventory management tasks.

Furthermore, the AR/MR glasses enable natural and intuitive interactions with the inventory items. Astronauts can use gestures, voice commands, or handheld controllers to select, move, and manipulate items virtually. This direct and tactile interaction enhances the user experience, enabling seamless navigation through the virtual inventory space and facilitating efficient item retrieval based on their classification. Integrating the ABC classification method with AR/MR glasses allows for real-time updates and synchronisation with the inventory. Any changes or updates to the classification or inventory data are instantly reflected in the virtual environment, ensuring that the information presented through the glasses remains accurate and up-to-date. MR technology offers significant advantages for virtual inventory management in space missions, providing astronauts with an immersive and interactive platform to visualise, organise, and manipulate inventory items.

In the virtual environment, inventory items can be displayed in three dimensions, allowing astronauts to view them from different angles and perspectives. This spatial representation enhances their understanding of the inventory layout and facilitates efficient navigation and identification of specific items. Additionally, using MR devices enables natural and intuitive interactions with the virtual inventory.

Moreover, MR can provide real-time information and overlays directly within the virtual environment, such as for item descriptions, status indicators, or alerts. This contextual information enhances situational awareness and decision-making, allowing astronauts to make informed choices regarding inventory utilisation, maintenance, and replenishment. However, implementing MR for virtual inventory management in space missions poses challenges. As noted above, ensuring the reliability and accuracy of MR hardware and software in extreme space conditions, requires careful design and testing. Moreover, integrating MR features with existing inventory management systems may necessitate the development of new software interfaces and data synchronisation mechanisms.

4 The Metaverse Development

Implementing the proposed system by using AR/MR glasses to interact with inventory using the ABC classification method has demonstrated promising results in classifying and prioritising inventory items in space missions. The study's findings suggest that implementing the proposed system, which utilises AR/MR glasses in combination with the ABC classification method for inventory interaction, has shown promising results in space missions. A key outcome was the accurate classification and prioritisation of inventory items. The system employed a multi-attribute fuzzy ABC classification method, effectively categorising inventory items based on importance, weight, volume, and criticality (Chen, Li, & Zhou, 2020) and integrating fuzzy logic accommodated uncertainties and imprecisions in inventory data, enhancing classification accuracy. Astronauts could swiftly identify high-priority (Category A) and attention-requiring items (Category C) through real-time overlays within their field of view provided by the AR/MR glasses.

To implement the fuzzy logic for the ABC classification, five essential factors are considered as the system input, namely (i) product price value (V_1), (ii) lead time (V_2), (iii) sustainability (V_3), (iv) manufacturing method (V_4), and (v) number of available suppliers (V_5). Therefore, the purchase index (*PI*) of the space instruments and parts can be estimated as the system output. Some inference samples are illustrated in Table 1.

Table 1. Results from the Proposed Solution

#		Purchase Index	Classification
1	Encoder receiver	0.86	A
2	Driver IC	0.82	B
3	Oscillator	0.48	C
4	Sieve	0.16	C
5	Inlet cover	0.15	C

Furthermore, the use of AR/MR glasses improved inventory management efficiency. The glasses offered an immersive interface for astronauts to interact with the inventory, facilitating an enhanced understanding of the inventory layout through three-dimensional visualisation. The ability to virtually navigate and manipulate inventory items and intuitive interactions like gestures and voice commands streamlined the inventory management process. The result was a noticeable reduction in the time and effort required to locate and retrieve specific items. Finally, the AR/MR glasses significantly enhanced situational awareness. Astronauts had access to real-time overlays and contextual information within their field of view, enabling a comprehensive understanding of the inventory environment. Item descriptions, status indicators, and alerts were visible, facilitating informed decision-making regarding inventory utilisation, maintenance, and replenishment. This facilitation will lead to improvements in overall mission efficiency and effectiveness.

The proposed integration of AR/MR glasses with the ABC classification method for inventory management in space missions presents several compelling advantages over traditional systems. Firstly, the immersive and intuitive interface provided by the AR/MR glasses enhances astronauts' interaction with the inventory. The glasses enable three-dimensional visualisation and inventory item manipulation, bolstering spatial understanding and efficient navigation within the virtual environment. This intuitive interface reduces astronauts' cognitive load, allowing them to concentrate on critical tasks and make faster and more informed decisions regarding inventory management. Secondly, the system offers real-time updates and synchronisation with the actual inventory, a significant advantage over traditional methods. Changes or updates to inventory data or classification are instantly reflected in the virtual environment viewed through the AR/MR glasses. This real-time synchronisation ensures the presented information remains accurate and up-to-date, eliminating potential outdated or inconsistent data issues common in traditional systems. This feature bolsters the reliability and effectiveness of the inventory management process, allowing astronauts to make informed decisions based on the most current information. Thirdly, using AR/MR glasses significantly enhances efficiency and productivity in inventory management tasks. By providing a comprehensive overview of the inventory, the system enables quicker identification and retrieval of items. The intuitive interactions and real-time overlays reduce the time and effort required to locate and prioritise inventory items, freeing the astronauts to focus on other critical mission tasks. This improved efficiency and productivity can lead to optimised resource utilisation and enhanced overall mission performance.

Despite the significant advantages of the proposed system, it is crucial to acknowledge its limitations and potential challenges. Technological constraints pose one such challenge. The system's successful implementation hinges on having reliable and robust AR/MR glasses capable of withstanding the extreme conditions of space missions. The hardware and software components must undergo rigorous testing and validation for space environments to guarantee performance and durability. Moreover, integrating the proposed system with existing inventory management systems might necessitate the creation of new software interfaces and data synchronisation mechanisms, thereby introducing technical complexities.

Furthermore, adopting novel technology like AR/MR glasses calls for proper training and adaptation by astronauts. Familiarising users with the new interface, gestures, and voice commands might necessitate extra training and practice. Astronauts must acquire proficiency in using the AR/MR glasses to interact seamlessly with the inventory items. However, it is expected that the benefits will outweigh the initial learning curve regarding efficiency and productivity once users become accustomed to the system.

5 Discussion

The findings of this study have several implications for space exploration and the development of inventory management systems on space missions. Additionally, recommendations for future research and system improvements can further enhance the efficiency and effectiveness of inventory management in space. Implementing the use of AR/MR glasses coupled with the ABC classification method presents significant implications for space exploration missions. Accurate classification and prioritisation of inventory items enable astronauts to identify high-priority items and focus on critical tasks quickly. This streamlined approach to inventory management improves overall mission efficiency and reduces the risk of errors or delays in locating and retrieving necessary items. As a result, the proposed system can contribute to the success of extended-duration space missions, where efficient resource utilisation is crucial.

Furthermore, the enhanced situational awareness provided by the AR/MR glasses empowers astronauts with real-time information, alerts, and status indicators. This increased awareness allows for better decision-making regarding inventory utilisation, maintenance, and replenishment, ultimately improving space operations' overall safety and effectiveness.

To further improve inventory management systems in space missions, several areas warrant future research and development:

Integration with Robotics: Exploring the integration of AR/MR glasses with robotic systems could enhance inventory management efficiency. Collaborative efforts between astronauts and robotic assistants could automate certain inventory-related tasks, such as item retrieval and replenishment, thereby reducing the workload of astronauts and ensuring more accurate and timely inventory updates (Makhataeva and Varol, 2020).

Advanced Sensing Technologies: Investigating advanced sensing technologies, such as radio frequency identification and computer vision, could enable real-time tracking and monitoring of inventory items. Integrating such technologies with AR/MR glasses could provide astronauts with instant and accurate information about the location and status of each item, further improving inventory management efficiency (Park et al., 2019).

User Experience and Training: Conducting user experience studies and providing comprehensive training programs for astronauts could help optimise the adoption and utilisation of AR/MR glasses for inventory management. Identifying potential challenges, refining the user interface, and ensuring ease of use could maximise the system's benefits and minimise any potential learning curve (Kaplan et al., 2021).

Long-Term Sustainability: Considering the long-term sustainability of inventory management systems is crucial. Research should focus on developing lightweight, reliable, and resilient hardware and software solutions that can withstand the harsh conditions of space, such as radiation, heat and microgravity, over extended durations (Becerra et al., 2021).

Integrating AR/MR glasses with the ABC classification method offers significant implications for space exploration. The findings highlight the potential for improved inventory management efficiency, enhanced situational awareness, and optimised resource utilisation. Future research and development recommendations emphasise integrating robotics, advanced sensing technologies, user experience and training, and long-term sustainability. By advancing inventory management systems, space missions can benefit from streamlined operations, reduced risks, and improved overall mission performance.

6 Conclusion

In conclusion, this study underscores the potential of integrating metaverse AR/MR glasses with the ABC classification method for inventory management in space missions. The findings suggest that this approach can significantly enhance the accuracy in classifying and prioritising inventory items, augment efficiency in item retrieval, and bolster situational awareness for astronauts. Providing real-time overlays and contextual information through AR/MR glasses empowers astronauts to make informed decisions and optimise resource utilisation during space exploration. The implications of these findings for space exploration are considerable. Efficient inventory management is pivotal for the success of space missions, particularly in extended-duration missions where resources are scarce. The proposed system could potentially streamline inventory management tasks, minimise human error, and amplify overall mission efficiency. The enhanced situational awareness and decision-making capabilities provided by the AR/MR glasses could further bolster the safety and effectiveness of space operations. Future research should focus on integrating the proposed system with robotics, investigating advanced sensing technologies, improving the user experience through dedicated training programmes, and addressing the long-term sustainability of inventory management systems in space. These prospective research domains hold the potential to optimise further inventory management processes, automation, real-time tracking, and user proficiency. In essence, the fusion of metaverse AR/MR glasses with the ABC classification method holds considerable promise for revolutionising inventory management in space missions. By harnessing the advantages of augmented and mixed reality technologies, astronauts can efficiently manage inventory items, allocate resources effectively, and make informed decisions in real-time. These advances contribute significantly to the overall success of space exploration missions and pave the way for improved efficiency, safety, and mission performance in future endeavours.

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Chapter 8

Metaverse-Driven Space Scene Image Synthesis

Abstract

The emergence of the metaverse has ushered in a new era of exploration beyond the boundaries of our planet, redefining the way we interact with and understand the cosmos. This chapter further describes the transformative landscape of the Space Metaverse, where the seamless integration of electronic systems and cutting-edge artificial intelligence (AI) technology drives innovative applications in space exploration. Through an interdisciplinary lens, we explore the convergence of electronic systems and AI, shedding light on their contributions to spacecraft design, communication, navigation, and autonomous operations. By analysing case studies and drawing insights from existing literature, we unravel the potential of the Space Metaverse to revolutionise space exploration and open new frontiers of discovery. Additionally, we examine the challenges, opportunities, and ethical considerations associated with this paradigm shift. As we chart

a course through this evolving frontier, this study aims to inspire further research and innovation at the intersection of electronic systems, AI technology, and the boundless expanse of outer space.

Keywords: metaverse, planet, cosmos, electronic systems, artificial intelligence (AI), space exploration, spacecraft design, communication, navigation, autonomous operations, outer space

1 Introduction

1.1 Background and Motivation

In recent years, the convergence of cutting-edge technologies has given rise to the concept of the metaverse, a virtual shared space created by the convergence of physical and digital reality. This dynamic and immersive environment has spurred numerous applications across various industries, from entertainment and gaming to education and commerce. One intriguing avenue of exploration within the metaverse paradigm is the generation of realistic and captivating space scene images, harnessing the power of artificial intelligence (AI) and computer graphics.

Space scene imagery has long captured the human imagination, offering glimpses into the vast and awe-inspiring cosmos. Traditionally, the creation of such imagery has relied on labour-intensive manual processes, limiting the scalability and diversity of generated content. The emergence of AI-driven techniques has revolutionised this domain by enabling the automated generation of space scenes that exhibit a remarkable level of realism and artistic expression. The integration of the metaverse concept with space scene image generation presents a novel and exciting research direction. By leveraging the immersive capabilities and interactive nature of the metaverse, researchers have the opportunity to create a new breed of space scene images that not only simulate astronomical phenomena but also engage users on a deeper level. This fusion opens doors to applications that span interactive storytelling, virtual tourism, and educational simulations, among others.

Key challenges in this research domain include developing advanced AI algorithms capable of synthesising visually stunning and scientifically accurate space scenes, incorporating real-time interactivity to enable user exploration and manipulation, and addressing the ethical implications of creating and sharing AI-generated content within the metaverse. Additionally, the integration of real-world astronomical data, such as the positions and properties of celestial bodies, adds a layer of complexity and authenticity to the generated scenes. Researchers in this field draw from a rich interdisciplinary landscape, blending expertise in computer graphics, artificial intelligence, astrophysics, human-computer interaction, and metaverse technologies. As advances continue to unfold in AI research, computational power and metaverse platforms, the potential for groundbreaking contributions to both scientific understanding and artistic expression within the realm of metaverse-based space scene image generation becomes increasingly tangible.

In summary, the research background outlined above highlights the intersection of the metaverse and space scene image generation as a captivating and transformative area of exploration. As the metaverse ecosystem evolves and matures, the potential to create immersive, interactive, and visually stunning cosmic landscapes holds promise for reshaping the way we experience and engage with the wonders of the universe.

1.2 Main Contribution of This Work

This research presents a novel concept that integrates metaverse technologies with the state-of-the-art image synthesis algorithms to create visually captivating space scenes that can be experienced interactively within the metaverse environment. The study pioneers the accurate simulation of complex astronomical phenomena, such as supernovae, nebulae formation, and gravitational lensing within the metaverse, contributing to public engagement and education in astronomy.

The research empowers users to manipulate variables, change viewpoints, and observe dynamic cosmic events in real-time, fostering a deeper understanding of celestial mechanics. The integration of metaverse-based space scenes offers a unique platform for immersive storytelling, where users can become protagonists in captivating cosmic adventures, blending scientific facts with imaginative storytelling to enhance engagement and learning. The fusion of real-world astronomical data with AI-generated content achieves a higher level of authenticity, catering to both scientific accuracy and artistic expression.

The metaverse-based approach facilitates collaborative exploration, allowing users from diverse backgrounds to interact in a shared virtual space, fostering interdisciplinary collaboration among astronomers, artists, educators, and enthusiasts. The research establishes a set of validation techniques and visual fidelity metrics to ensure the quality and accuracy of the generated space scenes. Beyond academia, this work extends into the public domain, offering a novel platform for outreach and engagement, promoting science literacy, encouraging curiosity, and inspiring the next generation of space enthusiasts. This chapter encompasses groundbreaking advances in the fusion of metaverse technologies and space scene image generation, spanning technical innovation, interdisciplinary collaboration, ethical considerations, and public engagement, collectively reshaping the way we perceive, explore, and communicate the marvels of the cosmos.

2 Literature Review

In the context of a literature review, we can categorise our research into the following directions: Metaverse-Related Scene Synthesis, Advances in 3D Scene Synthesis, GAN Scene Synthesis, and Diffusion Model Scene Synthesis.

The comparison table below provides an overview of the main categories and their key aspects in each of the reviewed sections. It comprises an overview of the main aspects of each literature review section, highlighting the focus, notable research papers, and key contributions. It also suggests the transformative potential of each section. Table 1 can be further customised and expanded to include additional details or specific findings from each section if needed.

Table 1. Summary of Related Work

Aspect	Metaverse-Related Scene Synthesis	Advances in 3D Scene Synthesis	GAN Scene Synthesis	Diffusion Model Scene Synthesis
Notable Research Papers	Lee, L. H. et al. (2021), Misa, A. et al. (2022), Valaskova, K. et al. (2022), Perkins, J. (2022), Newell, M. (2022), Holt, S. (2022), Gao, Z. & Braud, T. C. (2023), Mogavi, R. H. et al. (2023)	Chang, A., Savva, M., & Manning, C. D. (2014), Chang, A. et al. (2015), Siddiqui, Y. et al. (2021), Gu, J. et al. (2021), Jeong, J. et al. (2022), Schwarz, K. et al. (2020), Yi, H. et al. (2023), Zhang, J. et al. (2023)	Reed et al. (2016), StackGAN (2017), StackGAN++ (2018), Li et al. (2019), Wan et al. (2019), Zhu et al. (2019)	Esser et al. (2021), Gu et al. (2022), Rombach et al. (2022), Wang et al. (2022), Fan et al. (2023), Liu et al. (2023)

Aspect	Metaverse-Related Scene Synthesis	Advances in 3D Scene Synthesis	GAN Scene Synthesis	Diffusion Model Scene Synthesis
Key Contributions	Various metaverse applications in the fields of art, the workplace, retail, education, and cultural heritage preservation)	Innovative 3D scene synthesis methodologies	Bridging text-to-image in GANs, hierarchical GANs, multi-modal synthesis across domains	Controlled image generation through diffusion process, semantic guidance for realistic images
Transformative Potential	Multifaceted and transformative impact across metaverse domains	Advances in text-driven, style-based, and semantic image synthesis	Transformation of textual descriptions into photo-realistic images	Controlled and high-quality image, synthesis with semantic guidance

2.1 Metaverse-Related Scene Synthesis

The synthesis of immersive scenes within the metaverse has become a captivating realm of research, encompassing computational arts, workplace dynamics, retail experiences, and more. This literature review presents a comprehensive analysis of prominent works exploring 3D scene synthesis within the metaverse landscape, uncovering methodologies, challenges, and innovative contributions.

Lee, L. H. et al. (2021): This survey investigates the fusion of computational arts and the metaverse, highlighting the synergy between artistic creativity and digital technologies. It explores how creators leverage the capabilities of the metaverse to synthesise captivating and interactive scenes, reshaping the landscape of artistic expression. Misa, A. et al. (2022): This study extends the impact of the metaverse to workplace dynamics, utilising immersive 3D virtual reality to synthesise scenes for analysing engagement metrics and predictive behaviours. Such insights provide valuable data for optimising human resource management and productivity.

Valaskova, K. et al. (2022): In the realm of retail, this research explores the synthesis of immersive retail environments enhanced by visual analytics and object recognition algorithms. The integration of these technologies enriches customer experiences, paving the way for innovative retail strategies. Perkins, J. (2022): Investigating extended reality, this study investigates the fusion of object recognition algorithms, virtual retail strategies, and simulation modelling within the metaverse. This synthesis transforms consumer engagement and potentially reshapes the future of commerce.

Newell, M. (2022): Focusing on the economic landscape, this research investigates the influence of the metaverse on spatial cognition and context awareness. The integration of virtual modelling and data mining technologies enhances economic activities within the metaverse ecosystem. Holt, S. (2022): In the realm of space exploration, this work explores how the metaverse can contribute to astronaut well-being, educational outreach, and public engagement. The integration of mixed reality technologies offers novel approaches to space science and education.

Gao, Z. & Braud, T. C. (2023) addresses cultural heritage preservation, showcasing how the metaverse can breathe new life into digitised museum archives. By transforming historical artifacts into interactive metaverse exhibits, the study enriches the museum experience and enhances archival accessibility. Mogavi, R. H. et al. (2023): "Envisioning an Inclusive Metaverse: Student Perspectives on Accessible and Empowering Metaverse-Enabled Learning.": This research investigates the educational aspects of the metaverse, focusing on inclusivity and empowerment through metaverse-enabled learning environments. The synthesis of immersive scenes offers diverse and accessible educational experiences.

In summary, the reviewed literature underscores the multifaceted and transformative potential of scene synthesis within the metaverse context. From artistic expression and workplace analytics to retail engagement, education, and cultural heritage, the synthesis of immersive scenes is reshaping how we interact, learn, work, and extend across a wide spectrum of applications.

2.2 Advances in 3D Scene Synthesis

The realm of 3D scene synthesis has witnessed remarkable advances driven by innovative methodologies and cutting-edge technologies. This literature review explores seminal contributions in the field, highlighting significant studies that have revolutionised text-driven, style-based, and semantic image synthesis, as well as database-driven scene reconstruction.

Chang, A., Savva, M., & Manning, C. D. (2014): In this foundational work, the authors bridge the gap between natural language and visual representation by introducing a model that acquires spatial knowledge to synthesise 3D scenes from textual descriptions. The incorporation of spatial reasoning enhances the fidelity of generated scenes.

Chang, A. et al. (2015): The authors introduce rich lexical grounding to text-to-scene synthesis. This approach leverages detailed lexical information to enhance the realism and coherence of generated scenes, resulting in more contextually accurate visualisations. Siddiqui, Y. et al. (2021): This study proposes a database-driven approach to 3D scene reconstruction. By utilising a repository of existing scenes, the authors demonstrate the effectiveness of a retrieval-based technique for generating complex 3D scenes, showcasing its potential in enhancing scene synthesis.

Gu, J. et al. (2021) introduces Stylenerf, a novel style-based

3D-aware generator that enables high-resolution image synthesis. By incorporating style information, the authors demonstrate the ability to produce visually appealing and coherent 3D scenes with a focus on artistic and stylistic elements. Jeong, J. et al. (2022) explores the realm of semantic image synthesis for 3D scene painting. By incorporating semantic information, the authors enable the generation of complex scenes with detailed object interactions, paving the way for more nuanced and contextually rich scene visualisations.

Schwarz, K. et al. (2020) introduces generative radiance fields, a technique that leverages volumetric representations to synthesise 3D-aware images. This approach enables the generation of intricate scenes with high levels of detail and realism, thus enhancing the quality of scene synthesis. Yi, H. et al. (2023) presents a human-aware 3D scene generation model. By incorporating human-centric attributes and interactions, the study advances the field by generating scenes that consider human presence, behaviour, and engagement, thereby enhancing the realism and applicability of generated scenes.

Zhang, J. et al. (2023) introduces Text2NeRF, a text-driven approach to 3D scene generation using neural radiance fields. Combining text-based descriptions with radiance fields, the authors achieve high-fidelity scene synthesis, enabling the creation of immersive and visually compelling 3D environments.

In conclusion, these studies explore various facets of 3D scene synthesis, encompassing techniques such as spatial knowledge learning, text-driven generation, database reconstruction, style-based and semantic image synthesis, and human-aware scene generation. The advances showcase the cutting-edge methodologies employed in the synthesis of intricate and lifelike 3D scenes within the metaverse. Collectively they demonstrate the rapid evolution of 3D scene synthesis, showcasing advancements in text-to-scene generation, style-based synthesis, semantic image painting, and human-aware scene modelling. These contributions not only enhance the quality and realism of synthesised scenes but also open avenues for innovative applications in various domains, including art, design, entertainment, and beyond.

2.3 GAN Scene Synthesis

Generative adversarial networks (GANs) have revolutionised the field of computer vision and image synthesis, enabling the creation of realistic scenes from textual descriptions and pushing the boundaries of creative content generation. This review examines key contributions in GAN-based scene synthesis, highlighting advances in text-to-image conversion, hierarchical generation, and multi-modal synthesis.

Reed et al. (2016) presented a pioneering work on generative adversarial text-to-image synthesis, demonstrating the potential of GANs to bridge the gap between textual descriptions and photo-realistic images. Their approach laid the foundation for subsequent research in translating semantic information into compelling visual content. Building on this foundation, Zhang et al. introduced StackGAN (2017) and its enhanced version, StackGAN++ (2018) introduced stacked GAN architectures for text-to-image synthesis, achieving remarkable improvements in image quality and semantic consistency (Zhang et al., 2017). StackGAN++ further elevated image synthesis quality and resolution, showcasing the capacity of stacked GANs to generate highly realistic scenes.

Li et al. (2019) extended GAN scene synthesis into an object-driven paradigm, incorporating adversarial training for text-to-image conversion. This approach emphasised contextually meaningful object-level details, enhancing the realism and semantic accuracy of generated images. Wan et al. (2019) expanded the horizon of GAN scene synthesis to audio, presenting an approach to convert audio signals into scene images. This multi-modal synthesis demonstrated GANs' adaptability to diverse data types, showcasing their potential for cross-modal content generation. Zhu et al. (2019) extended GAN-based synthesis with dynamic memory GAN, integrating dynamic memory mechanisms to enhance scene generation by capturing long-range dependencies in textual description.

In conclusion, the reviewed works collectively underscore the transformative impact of GANs in scene synthesis. From text-to-image translation to hierarchical generation and multi-modal synthesis, these studies showcase the versatility and creative potential of GANs in producing visually rich and contextually coherent scenes.

2.4 Diffusion Model Scene Synthesis

In recent years, the field of computer vision and image synthesis has been significantly advanced by the development and application of diffusion models. These models offer a novel approach to generating high-quality images through a diffusion process that allows for the controlled transformation of noise into coherent visual content. This literature review explores the key contributions and advances in diffusion model scene synthesis.

Esser et al. (2021) introduced Imagebart, a bidirectional context model that leverages multinomial diffusion for autoregressive image synthesis. Their work demonstrates the potential of diffusion models in generating high-quality images by capturing bidirectional dependencies in image data. The incorporation of multinomial diffusion provides a novel approach to preserving both local and global image structures, contributing to the fidelity of the synthesised images. Taking diffusion models into the realm of text-to-image synthesis, Gu et al. (2022) presented a vector-quantised diffusion model. This research showcases the versatility of diffusion models in bridging the gap between textual descriptions and image generation. By enabling the synthesis of images from textual input, this work opens new avenues for content creation and creative applications.

In the context of high-resolution image synthesis, Rombach et al. (2022) introduced latent diffusion models. Their research explores the synthesis of images with enhanced detail and resolution, addressing challenges in producing realistic high-resolution images. By leveraging latent variables in the diffusion process, this work contributes to the advancement of image synthesis quality and fidelity.

Wang et al. (2022) proposed semantic image synthesis via diffusion models, further expanding the capabilities of diffusion-based techniques. This research focuses on incorporating semantic information into the diffusion process, enabling the generation of images with desired visual content and semantics. By combining semantic guidance with diffusion-based synthesis, this work offers new possibilities for controlling image synthesis outcomes. The exploration of complex scene image synthesis is advanced by Fan et al. (2023), who introduced Frido, a feature pyramid diffusion model. Their work highlights the importance of multi-scale information in capturing scene complexity and producing coherent images. This contribution underscores the potential of diffusion models to address challenges in generating intricate and detailed scene images.

Incorporating semantic guidance for enhanced control, Liu et al. (2023) introduced an approach to image synthesis with semantic diffusion guidance. By leveraging semantic information, this research offers increased control over the diffusion process, leading to more interpretable and customisable image synthesis outcomes.

In conclusion, the advancement of diffusion model scene synthesis has greatly enriched the field of computer vision and image generation. From bidirectional context modelling to text-to-image synthesis and high-resolution image generation, diffusion models have demonstrated their versatility and potential in capturing complex visual information. As seen in the highlighted research papers, these models continue to evolve and offer innovative solutions for producing high-quality, realistic, and semantically meaningful images.

3 Fundamentals and Concepts

3.1 Scene Generation for the Metaverse

Scene generation for the metaverse is a multidisciplinary endeavor that combines computer graphics, AI, and VR to create immersive and diverse virtual environments within the interconnected digital universe. Understanding the foundational concepts of scene generation provides insights into how these virtual worlds are designed, populated, and brought to life, enriching the experiences of metaverse users. The following are some such concepts:

1. Virtual Environments: Virtual environments are digital spaces that simulate real-world or imaginative settings. They encompass various elements, including landscapes, architecture, objects, and atmospheric conditions.
2. Procedural Generation: Procedural generation involves using algorithms to create content, such as landscapes, textures, and structures, based on predefined rules and parameters. This technique enhances scalability and diversity in scene creation.

3. Assets and Resources: Assets are digital components that populate virtual scenes, such as 3D models, textures, animations, and sound effects. Libraries of assets contribute to scene richness and complexity.
4. Spatial Representation: Spatial representation involves defining the layout, dimensions, and coordinates of objects within a virtual scene. Techniques like Cartesian coordinates and transformations enable accurate placement and navigation.
5. Physics Simulation: Physics engines simulate realistic interactions between objects, including gravity, collisions, and dynamics. These simulations enhance the authenticity of virtual scenes.
6. Lighting and Rendering: Lighting models and rendering techniques simulate how light interacts with surfaces, creating shadows, reflections, and ambient effects. Realistic rendering contributes to visual immersion.
7. User Interaction: User interactivity adds depth to scenes. Elements like interactive objects, user-triggered events, and responsive environments engage users within the virtual space.
8. Aesthetics and Design Principles: Aesthetics encompass design principles, colour theory, composition, and visual hierarchy that guide the creation of visually appealing and coherent scenes.
9. Immersive Technologies: Immersive technologies, such as VR and AR, enhance scene generation by providing users with interactive and sensory-rich experiences.
10. Metaverse Integration: Scene generation contributes to the metaverse by providing diverse spaces for users to explore, interact, and collaborate. Seamless integration

with other metaverse components enhances the overall user experience.

An understanding of these concepts provides the foundation for designing and generating scenes that enrich the metaverse experience. By combining creativity, technology, and user engagement, scene generation contributes to building vibrant and captivating virtual worlds that reflect real-world elements, imaginative narratives, and collaborative opportunities.

3.2 3D Image Generation

3D image generation is a process that creates three-dimensional visual representations of objects, scenes, or environments. It is a crucial aspect of computer graphics, simulation, design, and various industries where realistic and immersive visualisations are essential. Understanding the foundational concepts of 3D image generation provides insights into how complex virtual worlds and lifelike simulations are crafted. The following are some such concepts:

1. Spatial Representation: In a 3D environment, objects are described using spatial coordinates (x, y, z) that determine their position, size, and orientation. These coordinates are used to create the geometry of objects and scenes.
2. Geometry: Geometry involves defining the shape and structure of objects through vertices (points), edges (lines connecting vertices), and faces (surfaces bounded by edges). Mathematical algorithms transform basic shapes into intricate forms.
3. Rendering: Rendering simulates how light interacts with objects to produce realistic images. Techniques such as shading, ray tracing, and rasterisation calculate how light is absorbed, reflected, and refracted, resulting in accurate

colour and shadow effects.

4. Texture Mapping: Texture mapping applies images (textures) onto 3D surfaces to enhance realism. This process involves mapping 2D textures onto 3D geometry, making objects appear detailed and textured.
5. Illumination and Lighting: Lighting models simulate the behaviour of light sources, creating highlights, shadows, and shading effects. Various lighting models (ambient, diffuse, specular) contribute to the perception of depth and material properties.
6. Camera Projection: A virtual camera captures the 3D scene from a specific viewpoint, projecting it onto a 2D plane. This process involves determining what is visible in the final image and accounting for perspective and depth.
7. Transformation: Transformations manipulate objects in 3D space. Translation, rotation, and scaling operations alter an object's position, orientation, and size.
8. Real-time vs. Offline Rendering: Real-time rendering focuses on generating images quickly and is often used in video games and interactive applications. Offline rendering emphasises image quality, can take longer, and is usually used in film production and visual effects.
9. Ray Tracing: Ray tracing is a rendering technique that simulates the behaviour of light rays as they interact with objects in a scene. It produces highly realistic images by tracing rays of light from the camera to the objects and simulating their interactions.
10. GPU Acceleration: Graphics processing units (GPUs) accelerate 3D image generation by performing parallel computations. GPUs are optimised for tasks like rendering and shading, enabling real-time visualisations.

An understanding of these concepts forms the foundation for creating 3D images and virtual environments. By combining geometry, rendering techniques, and visual effects, 3D image generation empowers designers, artists, and engineers to bring imaginative worlds to life and solve complex real-world challenges.

3.3 VAE Image Generation

Variational autoencoders (VAEs) are a type of generative model used for image generation and other generative tasks. VAEs are based on probabilistic modelling and aim to learn the underlying distribution of data.

The core equation for VAEs involves encoding and decoding, as well as a probabilistic approach to generating data. The objective of a VAE can be expressed as maximising the evidence lower bound (*ELBO*), which is equivalent to minimising the reconstruction error while encouraging the latent space to follow a specific distribution (typically a Gaussian). The *ELBO* is defined as:

$$ELBO = E[\log P(X|z)] - KL(q(z|X) \,||\, P(z)) \tag{1}$$

Where:

X represents the observed data, such as an image.

z represents the latent variable (the encoded representation).

$P(X|z)$ is the likelihood of generating observed data X given the latent variable z.

$q(z|X)$ is the approximate posterior distribution over the latent variable z given the observed data X.

$P(z)$ is the prior distribution over the latent variable z.

KL represents the Kullback-Leibler (KL) divergence between the approximate posterior and the prior.

The objective is to maximise the *ELBO*. In practice, this involves minimising the negative *ELBO* (*NELBO*):

$$NELBO = -ELBO \tag{2}$$

The *NELBO* consists of two terms: Reconstruction Loss: The first term, $E[\log P(X|z)]$, measures how well the VAE can reconstruct the input data X from the latent variable z. It encourages the decoder (generative network) to produce data that is similar to the input. Regularisation Term (*KL* Divergence): The second term, $KL(q(z|X) \| P(z))$, enforces a regularisation on the latent space. It encourages the approximate posterior ($q(z|X)$) to be close to the prior ($P(z)$), effectively controlling the structure of the latent space.

The combination of these terms results in a VAE that learns to generate data by encoding them into a lower-dimensional latent space, sampling from that space, and then decoding the samples back into data space. This probabilistic framework allows VAEs to generate diverse data samples by sampling from the latent space while ensuring that the generated samples follow a specific distribution.

In practice, the encoder and decoder networks in a VAE are parameterised by neural networks, and optimisation techniques, such as stochastic gradient descent, are used to train the model by minimising the *NELBO*.

3.4 GAN Image Generation

Generative adversarial networks (GANs) have revolutionised the field of AI and image generation. GANs are a class of deep learning models that excel in generating new realistic data by learning from existing examples. Understanding the foundational concepts of GANs provides insights into how these networks work and their significance in various applications, including art, design, and data augmentation.

The core idea behind GANs is a game-theoretic framework involving two neural networks: a generator (*G*) and a discriminator (*D*). The generator aims to produce fake images that are indistinguishable from real images, while the discriminator aims to differentiate between real and fake images. This is the fundamental equation for GANs:

In objective function, the objective function for GANs can be expressed as a minimax game between the generator and the discriminator:

$$min\_G \ max\_D \ V(D, G) = E[log(D(x))] + E[log(1 - D(G(z)))] \quad (3)$$

Where:

G represents the generator network.

D represents the discriminator network.

x is a real image from the dataset.

z is a random noise vector sampled from a prior distribution (e.g., Gaussian).

The objective function consists of two parts: Discriminator Loss (maximise): The discriminator aims to maximise its ability to correctly classify real images as real ($log(D(x))$) and fake images generated by the generator as fake ($log(1 - D(G(z)))$). Generator Loss (minimise): The generator aims to minimise the likelihood that the discriminator can distinguish its generated images as fake. It tries to maximise $log(1 - D(G(z)))$ to generate images that are similar to real ones.

During training, *G* and *D* are updated iteratively. The discriminator provides feedback to the generator, which then adjusts its parameters to produce more convincing fake images. The generator and discriminator engage in a game of one-upmanship, with the generator improving its ability to generate realistic images while the discriminator becomes better at distinguishing real from fake.

The GAN training process continues until either convergence is reached, or a predefined number of iterations are completed. At convergence, the generator ideally produces images that are visually indistinguishable from real ones.

It is important to note that variations of GANs, such as conditional GANs (cGANs) and Wasserstein GANs (WGANs), have different objective functions and loss functions tailored to specific tasks and requirements.

Understanding these concepts illuminates the power of GANs in generating realistic and diverse data, fostering creativity, and advancing various fields by enabling novel applications and insights. GANs' ability to learn from data distributions and create new content has reshaped the landscape of artificial intelligence and computer graphics.

3.5 Diffusion Model for Image Generation

Diffusion model image generation involves simulating the process of diffusion to create visual representations of how particles or substances spread and interact in a given environment. This approach combines principles from physics and computer graphics to generate dynamic and visually compelling images that showcase diffusion phenomena.

The diffusion model for image generation is a probabilistic generative model that models the process of iteratively adding noise to an image to generate samples from a target distribution. The core equation of the diffusion model is as follows:

In forward diffusion equation, at each step t, an image x_t is generated from the previous step x_{t-1} by adding noise proportional to a decreasing noise level σ_t:

$$x_t = x_{t-1} + \sigma_t * \eta_t \quad (4)$$

Where:

x_t represents the image at step *t*.

x_{t-1} is the image at the previous step *t-1*.

σ_t is the standard deviation of the noise at step *t*, which decreases over time.

η_t is white Gaussian noise sampled independently at each pixel.

The key concept in the diffusion model is that the noise level σ_t decreases over time, starting from a high value and gradually approaching zero. This process allows the model to generate increasingly coherent and sharp images over multiple steps.

In inverse diffusion equation, to sample from the target distribution, an inverse diffusion equation is used. Given a final target image x_0 (typically sampled from a simple distribution like Gaussian), you can iteratively reverse the diffusion process to generate an image at step *t*:

$$x_{t-1} = x_t - \sigma_t * \eta_t \quad (5)$$

Starting from x_0, you iteratively sample x_{t-1} at each step to generate the final image x_t. The key challenge in using the diffusion model for image generation is determining an appropriate schedule for decreasing the noise levels σ_t and selecting suitable noise distributions η_t to ensure convergence to the target distribution. Various techniques and modifications have been proposed to optimise and stabilise this process for practical image generation tasks.

3.6 CLIP Model

The CLIP (Contrastive Language-Image Pre-training) model is a sophisticated deep learning architecture designed to create a shared embedding space for both images and text, enabling comparisons between the two modalities. The core idea behind CLIP is to learn representations of images and text such that they can be effectively matched or contrasted. This is accomplished by utilising a contrastive loss function to minimise the difference between similar image-text pairs and maximise the difference between dissimilar pairs.

The equation representing the similarity score between an image embedding vector I and a text embedding vector T in CLIP's shared space can be defined as:

$$S(I, T) = I \bullet T \tag{6}$$

In this equation, "•" signifies the dot product operation between the image and text embeddings. The computed similarity score quantifies the proximity of the image and text embeddings in the shared space, where higher scores indicate a stronger correspondence between the image and the text description.

It is important to note that CLIP's actual architecture is far more intricate, involving deep neural networks with numerous layers and intricate mechanisms for generating these embeddings. This equation serves as a simplified representation of the concept of measuring similarity in the shared space and does not encompass the full extent of the model's complexity. For a comprehensive understanding of CLIP, including its architecture and training process, reference to OpenAI sources can be made.

4 Methodology and System Architecture

4.1 Research Methodology

Problem Formulation:	Clearly define the problem of scene image generation
	Specify the scope, objectives, and goals of the project
	Identify the target application or use case for the generated scene images
Data Acquisition and Preprocessing:	Determine the sources of data, which could include real-world images, 3D models, or other relevant datasets
	Collect and curate the data, ensuring they are representative of the scenes you want to generate
	Preprocess the data by resizing, cropping, normalising, and augmenting them as needed
Feature Extraction and Scene Representation:	Extract relevant features from the data, such as objects, textures, colours, and spatial relationships
	Choose an appropriate representation for scenes, which could be based on semantic segmentation masks, feature vectors, or other forms of scene encoding
Model Selection:	Select a suitable scene image generation model
	Consider the model's architecture, scalability, and compatibility with your data
Data Splitting:	Split your dataset into training, validation, and test sets
	Ensure that the data distribution across sets is representative and that there is no data leakage
Model Training:	Train the selected model on the training data
	Define appropriate loss functions that encourage the model to generate realistic and semantically meaningful scene images
	Use an optimiser and learning rate schedule to efficiently converge the model
Validation and Hyperparameter Tuning:	Evaluate the model's performance on the validation set using relevant evaluation metrics (e.g., PSNR, SSIM, FID)
	Fine-tune hyperparameters based on validation results to improve model performance
Testing and Evaluation:	Assess the model's performance on the test dataset to ensure its generalisation capabilities
	Compare the generated scene images against ground truth or reference images
	Perform both quantitative and qualitative evaluations

Figure 1. Research Flow for Space Scene Image Synthesis

In the pursuit of robust and effective scene image generation, a systematic research methodology is imperative to guide the process. This methodology serves as the backbone of the project design, ensuring clarity, precision, and successful outcomes. The methodology commences with an essential step in problem formulation. This stage involves a meticulous definition of the problem at hand, setting the stage for a comprehensive understanding. Concurrently, the scope, objectives, and goals of the project are meticulously specified, laying the foundation for the project's overarching purpose. Moreover, the identification of the target application or use case for the generated scene images crystallises the project's practical utility and relevance.

Subsequently, data acquisition and preprocessing come to the fore. The sources of data are determined, with a potential repertoire ranging from real-world images to 3D models and other pertinent datasets. The collected data undergo a rigorous curation process, ensuring that they are a faithful representation of the scenes earmarked for generation. The data are further subjected to preprocessing, encompassing activities such as resizing, cropping, normalisation, and augmentation, tailored to the specific project requirements. Moving forward, feature extraction and scene representation play a pivotal role. Relevant features, spanning objects, textures, colours, and spatial relationships, are extracted from the data, infusing them with meaningful information. The choice of an appropriate representation for scenes follows suit, which could manifest as semantic segmentation masks, feature vectors, or alternative forms of scene encoding.

In tandem with these preparatory stages, model selection emerges as a critical juncture. The methodology underscores the selection of a suitable scene image generation model, offering a spectrum of choices, including variational autoencoders (VAEs), GANs, Conditional GANs, and Transformer-based models such as VQ-VAE-2 and DALL-E. The model selection process is strengthened by considerations of architectural suitability, scalability, and compatibility with the available data. Data splitting is introduced as a pivotal practice to mitigate data-related pitfalls. The dataset is judiciously partitioned into training, validation, and test sets, ensuring representative data distribution and shielding against data leakage. Model training, a cornerstone of the methodology, follows this segmentation. The selected model is meticulously trained on the training data, with a paramount focus on defining loss functions that incentivise the generation of realistic and semantically meaningful scene images. Additionally, an optimiser and learning rate schedule are deployed to efficiently guide the model towards convergence.

Validation and hyperparameter tuning stand as crucial checkpoints within the methodology. The model's performance is rigorously evaluated on the validation set, employing pertinent evaluation metrics such as PSNR, SSIM, and FID. Fine-tuning of hyperparameters is undertaken based on these validation results, orchestrating enhancements in model performance. Finally, the methodology culminates in testing and evaluation. This phase entails a comprehensive assessment of the model's performance on the test dataset, ultimately validating its generalisation capabilities. Notably, the generated scene images are meticulously juxtaposed against ground truth or reference images, facilitating a dual-pronged evaluation approach that encompasses both quantitative and qualitative dimensions.

4.2 Main Architecture

In Figure 2, we present the architecture for space scene image synthesis, showcasing two distinct approaches for generating space scene images. Each approach leverages a combination of text and image data to create immersive and visually captivating scenes from the cosmos. The architectural elements employed in these methods are designed to bring space scenes to life with varying levels of complexity.

(a) Simple Image Generation with Text Only: In this first approach (Figure 2a), we focus on the fundamentals of generating space scenes using textual descriptions as the primary input. The main components of this architecture include a text encoder and an image decoder. The process begins with a textual prompt provided by the user, which serves as a description of the desired space scene. This text is then passed through the text encoder, which translates the text into a form that can be used by the image decoder. The decoder, in turn, generates the corresponding space scene based on the encoded textual input. This straightforward approach is ideal for creating space scenes based solely on textual descriptions, enabling users to conjure up cosmic vistas with ease.

(b) Advanced Image Generation with Text and Image: In the second approach (Figure 2b), we enhance the image generation process by incorporating both textual descriptions and images as input. The main components of this architecture consist of a text encoder, image encoder, image decoder, and a CLIP Model. This approach is ideal for users who seek a more comprehensive and detailed representation of space scenes, complete with intricate elements such as spaceships.

The process begins with a textual prompt, similar to the first approach, and an image representing the desired space scene or spaceship. The textual description and image are both processed through their respective encoders. The Text Encoder captures the essence of the textual input, while the Image Encoder extracts relevant information from the image. These encoded representations are then fused to provide a comprehensive understanding of the desired scene. The fused representation is passed to the Image Decoder, which creates a visually appealing space scene that incorporates the specific details provided in the text and image input.

In this advanced approach, the inclusion of the CLIP Model further refines the image generation process. The CLIP Model aids in understanding the context and relevance of the textual and visual inputs, ensuring that the generated space scenes are not only visually accurate but also semantically meaningful.

Figure 2 illustrates the versatility of the presented architecture, catering to a range of user preferences, from simple text-only space scene generation to more sophisticated image and text-based synthesis that includes complex elements like spaceships. These two approaches offer a glimpse into the evolving landscape of space scene image synthesis, where technology combines the power of language and imagery to unlock the infinite wonders of the cosmos.

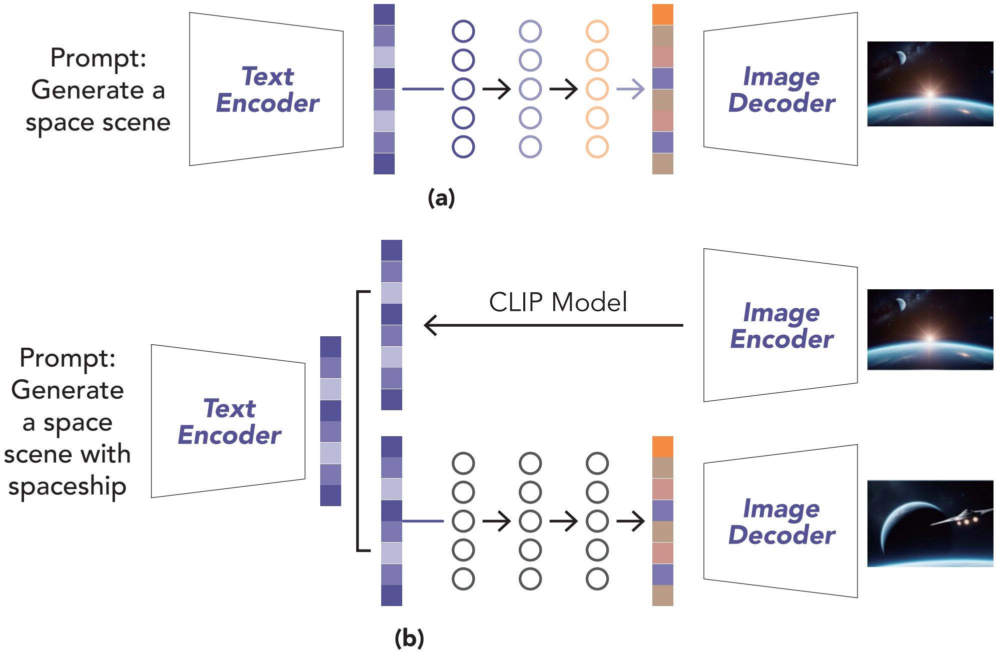


Figure 2. Architecture for Space Scene Image Synthesis, (a) Simple Image Generation with Text Only, (b) Advanced Image Generation with Text and Image

5 Comparison Study

5.1 Deep Learning Models for Image Scene Generation

Table 2. Comparison of Deep Learning Models for Image Scene Generation

Model	Strengths	Weaknesses	Typical Use Cases
Variational Autoencoders (VAEs)	- Probabilistic representations - Diversity in generated images	- Possibility of less realistic images compared to GANs	Image inpainting, data compression
Generative Adversarial Networks (GANs)	- Highly realistic images - Fine details and coherence	- Challenging training process - Mode collapse	General image generation, super-resolution
Flow-Based Models (e.g., Glow, RealNVP)	- Tractable complex distribution modelling - Invertible mappings	- Computationally expensive training - Careful design required	Density estimation, data generation
Transformer-based Models (e.g., DALL-E, CLIP)	- Combine language understanding and image generation - Context-aware and creative	- Computationally expensive - Large data requirements	Text-to-image synthesis, creative scene generation

Table 2 outlines a comparison of different deep learning models used for image scene generation, such as VAEs, GANs, flow-based models, and transformer-based models.

VAEs are valued for their probabilistic representations, enabling them to capture data uncertainty effectively. They stand out in generating diverse images by sampling from the learned distributions. However, VAEs may produce images that are slightly less realistic when compared to GANs, as their primary focus is on data distribution modelling rather than directly mimicking data.

On the other hand, GANs excel in creating highly realistic images, paying attention to fine details and ensuring scene coherency. Despite this strength, GANs can be challenging to train and may suffer from mode collapse, where they repetitively generate similar images.

Transformer-based models, exemplified by DALL-E and CLIP, combine language understanding and image generation, making them proficient in producing images from textual descriptions while maintaining context-awareness. However, they are computationally intensive and demand substantial training data, complicating the fine-tuning process.

Flow-based models like Glow and RealNVP provide a tractable approach to model intricate data distributions and offer invertible mappings. However, training them can be computationally demanding and requires careful design of flow transformations.

5.2 Free Diffusion Model Websites

Table 3. Free Diffusion Model Websites for Image Scene Synthesis

Criteria	https://stablediffusion.huggingface.co/	https://stablediffusionweb.com/
Link Type	Online tool for "Stable Diffusion"	Website focusing on "Stable Diffusion"
Target Audience	General users	Developers and researchers
Content Focus	Provides an in-browser tool for user interaction and image generation using "Stable Diffusion"	Acts as a central resource hub for "Stable Diffusion" and potentially related tools and resources
Technical Complexity	User-friendly and accessible for general users	Likely includes more technical content, suitable for developers and researchers
Information Delivery	Provides direct, in-browser, hands-on experiences	Likely offers information and resources for exploration, with less emphasis on direct interaction

Image Quality	Medium quality images	High-quality images, implying superior image results
Speed	Offers fast processing and interactions, allowing quick results generation	Tends to be slower, potentially due to high-quality images or complex functionalities

Table 3 offers a comprehensive comparison between two websites dedicated to providing resources related to the "Free Diffusion Model" for image scene synthesis. The evaluation is based on several key criteria:

Link Type: the first website, https://stablediffusion.huggingface.co/, functions as an online tool, enabling users to directly engage with and employ the "Stable Diffusion" model through a web-based interface. In contrast, the second website, https://stablediffusionweb.com/, is categorised as a dedicated platform for "Stable Diffusion", hinting at its potential to offer not only information on "Stable Diffusion" but also additional technologies and resources.

Target Audience: https://stablediffusion.huggingface.co/ is designed with general users in mind, emphasising accessibility and user-friendliness for individuals lacking specific technical expertise. On the other hand, https://stablediffusionweb.com/ caters primarily to developers and researchers, implying a more technical and specialised user base.

Regarding Content Focus: the first website is centered around providing a direct in-browser tool, empowering users to actively experiment with "Stable Diffusion" technology. It places a strong emphasis on enabling users to create images and engage in hands-on experimentation. Conversely, the second website serves as a central hub for "Stable Diffusion", signifying its potential to offer a comprehensive resource center. This may encompass not only information in relation to "Stable Diffusion" but also related tools and resources.

Technical Complexity: the first website, https://stablediffusion.huggingface.co/, is intentionally user-friendly and accessible, implying a lower degree of technical complexity. In contrast, https://stablediffusionweb.com/ is expected to include more technical content, making it suitable for developers and researchers who may require in-depth technical information.

Information Delivery: the first website provides direct, in-browser, hands-on experiences, indicating active user engagement with the technology. Conversely, the second is likely to offer information and resources for users to explore, suggesting a more informational and less interactive experience.

Image Quality: the first website provides images of medium quality, while the second website offers images of high quality, implying superior image results.

Speed: https://stablediffusion.huggingface.co/ offers fast processing and interactions, enabling users to generate results quickly. Conversely, the second website tends to be slower in terms of processing, which may be attributed to the inclusion of high-quality images or more complex functionalities.

In summary, this table serves as a detailed reference for understanding the distinctions between the two websites, highlighting their divergent purposes, target audiences, content emphases, technical intricacies, and other pertinent aspects concerning the "Free Diffusion Model" for image scene synthesis.

5.3 Commercial Websites for Image Synthesis

Table 4. Commercial Websites for Image Synthesis

Feature/ Aspect	Midjourney	DALL-E 2
Company/ Team	Midjourney	OpenAI

Model Architecture	Based on a combination of CLIP and VQGAN models	Derived from the CLIP, GLIDE and GPT models
Application Areas	Image generation, creative text generation, creative editing tasks, etc.	Image generation, creative text generation, creative editing tasks, etc.
Text Input Length Limit	No specific limit, but recommended not to exceed 175 characters (approximately 30 words)	No specific limit, but recommended not to exceed 175 characters (approximately 30 words)
Output Image Resolution	Adjustable, up to a maximum of 1024x1024 pixels (depends on the model and hardware configuration)	Adjustable, up to a maximum of 1024x1024 pixels (depends on the model and hardware configuration)
Training Data Source and Size	Large text-image datasets (such as COCO, WikiArt, etc.), image search results, online visual media, etc. Data volume not explicitly disclosed.	Trained on millions of images, massive dataset size
Image Generation Evaluation Method	Human subjective assessment (via platforms like Amazon Mechanical Turk), no specific quantitative evaluation metrics. Compared to other models: New version of Midjourney has higher mean subjective ratings and lower rating variance.	Human subjective assessment (via platforms like Amazon Mechanical Turk), no specific quantitative evaluation metrics. Compared to other models: DALL-E 2 is more mature and has a wider range of applications.
Multi-language/ Multi-style Support	Does not support multiple languages/styles and requires high-performance GPUs to run.	Does not support multiple languages/styles, requires high-performance GPUs to run, and additional functionality requires the use of an OpenAI API key.
Platforms and Costs	Runs entirely on the Discord platform, allowing users to generate images by inputting text in specific channels. Limited free compute time, additional features require payment.	DALL-E 2 requires the use of an OpenAI API key and offers interaction and image editing through various platforms like Playground, Codex Sandbox, Canva, etc. Additional features also require payment.
Image Generation Speed	Performs well, capable of producing a large number of high-resolution images quickly.	Relatively slower in terms of generation speed

Style Features	Supports various styles, including photos, illustrations, comics, etc., and can generate diverse image styles. Style features are less prominent than those in DALL-E2	Style features are relatively prominent, capable of producing more realistic, natural, and detailed image styles.
Accessibility	Operates on the Discord platform, with users able to generate images by inputting text in specific channels. Low entry barrier but limited accessibility	Requires the use of an OpenAI API key, offers interaction and image editing through various platforms like Playground, Codex Sandbox, Canva, etc. Higher entry barrier but better accessibility than Midjourney
User Involvement and Feedback	Users can participate in testing new versions of the model on the Discord platform, but user involvement is limited, and feedback may not be very timely.	Does not provide a feature for users to participate in testing new versions of the model, but users can exchange their experiences in the community, and feedback is relatively timely.

Table 4 provides a detailed comparison between two commercial websites, Midjourney and DALL-E 2, focusing on image synthesis. Midjourney, developed by the Midjourney company, is based on a unique combination of CLIP and VQGAN models. On the other hand, DALL-E 2, created by OpenAI, is derived from a fusion of CLIP, GLIDE, and GPT models, showcasing a different architectural approach. Both platforms cater to a range of applications, including image generation, creative text generation, and creative editing tasks, among others. While there is no specific limit on text input length, it is recommended to stay within approximately 175 characters or 30 words for both. Users can adjust the output image resolution, with a maximum of 1024x1024 pixels, dependent on the model and hardware configuration.

In terms of training data, Midjourney employs large text-image datasets like COCO and WikiArt, supplemented by image search results and online visual media, though the exact data volume is not explicitly disclosed. In contrast, DALL-E 2 boasts training on millions of images, signifying a massive dataset size.

Image generation quality is assessed through human subjective evaluation, typically via platforms like Amazon Mechanical Turk, without specific quantitative metrics. In comparisons with other models, the new version of Midjourney demonstrates higher mean subjective ratings and lower rating variance, while DALL-E 2 exhibits maturity and broader applications.

Both platforms require high-performance GPUs and do not support multiple languages/styles. Midjourney operates solely on the Discord platform, offering text-to-image generation with limited free compute time, requiring payments for additional features. DALL-E 2 necessitates an OpenAI API key for access and extends its interaction and image editing capabilities to various platforms, such as Playground, Codex Sandbox, Canva, and more, with added features also available through payments. In terms of image generation speed, Midjourney excels, producing a substantial number of high-resolution images rapidly, whereas DALL-E 2 is relatively slower.

Stylistically, Midjourney supports various image styles, including photos, illustrations, comics, and more, though its style features are less pronounced. In contrast, DALL-E 2 has more prominent style features, capable of generating more realistic, natural, and detailed image styles.

Accessibility-wise, Midjourney operates on Discord, offering relatively low entry barriers but limited accessibility. On the other hand, DALL-E 2 requires an OpenAI API key, with interaction and image editing available on multiple platforms, resulting in a higher entry barrier but improved accessibility.

User involvement differs, with Midjourney allowing users to participate in testing new versions on Discord, albeit with limited involvement and potentially delayed feedback. DALL-E 2 lacks a dedicated feature for users to test new versions but provides a community platform for users to exchange experiences, with feedback being relatively timely.

5.4 Applications for Space Scene Image Synthesis

Image scene generation holds significant importance in the realm of space exploration and satellite missions, offering a multitude of valuable applications. In the context of space, it serves several critical applications as illustrated in Table 5.

Table 5. Applications for Space Scene Image Synthesis

Space Application	Description	Benefits	Challenges
Simulating Space Environments	Creating realistic simulations of extraterrestrial landscapes, space stations, and spacewalk scenarios	- Aids astronaut training - Facilitates spacecraft system testing	Requires accurate representation and realism
Training Astronauts	Preparing astronauts for spacewalks, and lunar and Martian missions by exposing them to simulated environments	- Familiarises astronauts with mission conditions	Requires high-fidelity simulations
Mission Planning	Generating detailed visual representations of target locations for selecting landing sites and planning routes	- Assists in hazard assessment - Enhances mission planning	Requires accurate terrain and geological data
Testing Instruments and Cameras	Simulating images and data that instruments will capture in space to validate and calibrate equipment	- Ensures reliability of scientific instruments	Requires accurate modelling of instrument behaviour
Planetary Exploration	Creating synthetic scenes to visualise terrain, geological features, and potential scientific targets	- Aids in data interpretation and mission decision-making.	Requires knowledge of target bodies and features
Spacecraft Testing	Simulating spacecraft surroundings for sensor testing, navigation verification, and autonomous system testing	- Validates spacecraft systems - Refines autonomous navigation	Requires accurate modelling of sensor behaviour
Mission Simulation	Generating mission simulations for practising procedures and testing software algorithms in controlled settings	- Enhances mission preparedness - Validates software systems	Requires comprehensive mission scenario modelling

Telescope Calibration	Using synthetic starfields and galaxies for calibration purposes in space-based telescopes	- Ensures accurate astronomical observations	Requires precise knowledge of celestial objects
Educational Outreach	Creating engaging content for public and educational outreach programmes to explain space phenomena and missions	- Enhances public understanding of space science	Requires user-friendly interfaces and visuals
AR and VR	Employing scene generation for immersive experiences, allowing users to explore and interact with simulated space environments	- Enhances science communication and education	Requires AR/VR hardware and software development
Data Augmentation	Using synthetic scenes to augment real-space imagery datasets for machine learning and data analysis applications	- Improves model robustness and diversity	Requires accurate modelling of real-world conditions
Autonomous Navigation	Simulating terrain and obstacles to test and refine autonomous navigation algorithms for spacecraft and rovers	- Enhances spacecraft and rover navigation capabilities	Requires realistic representation of navigational challenges
Mars Sample Return	Employing scene generation to simulate the handling and analysis of Martian soil and rock samples for mission preparation	- Ensures success of Mars sample return missions	Requires accurate representation of Martian soil and rock

One of the primary applications for space scene image synthesis is the simulation of diverse space environments, including the surfaces of celestial bodies like planets, moons, and asteroids. These synthetic scenes serve as indispensable tools for training astronauts, conducting spacecraft systems testing, and mission planning. Furthermore, image scene generation aids in astronaut training by providing realistic depictions of extraterrestrial landscapes and space station settings. This immersive training experience allows astronauts to become familiar with the conditions they might encounter during spacewalks and missions to lunar or Martian surfaces.

In the realm of mission planning, this technology offers detailed visual representations of target locations on celestial bodies, supporting activities such as selecting landing sites, planning rover routes, and evaluating potential hazards. Before launching instruments and cameras into space, researchers can utilise scene generation to simulate the images and data these tools will capture. This pre-launch testing process is invaluable for validating and calibrating equipment.

When it comes to planetary exploration, generating synthetic scenes proves instrumental in helping mission planners and scientists visualise and analyse terrain, geological features, and scientific objectives on planets, moons, and asteroids. For spacecraft development and testing, image scene generation can simulate what the spacecraft's sensors will observe in space. This is particularly useful for sensor testing, navigation system verification, and the development of autonomous control systems.

Mission simulations benefit from image scene generation, enabling space agencies and research institutions to rehearse procedures and test software algorithms under controlled conditions.

Space-based telescopes, including renowned ones like the Hubble Space Telescope, rely on scene generation to create synthetic starfields and galaxies for calibration purposes, ensuring the precision of astronomical observations. In terms of educational outreach, scene generation aids in creating captivating content that educates the public and students about space phenomena, celestial bodies, and spacecraft missions. AR and VR technologies leverage scene generation to craft immersive experiences, allowing astronauts, scientists, and the general public to explore and interact with simulated space environments.

In machine learning applications related to space data analysis, synthetic scenes serve as valuable data augmentation tools, enhancing the robustness and diversity of models trained on real-space imagery datasets. Autonomous navigation systems for spacecraft and rovers can refine their algorithms by using scene generation to simulate potential terrains and obstacles. In preparation for the Mars sample return mission, image scene generation proves crucial for simulating the handling and analysis of Martian soil and rock samples, helping to ensure the mission's success.

Image scene generation plays a vital role in multiple aspects of space exploration, ranging from astronaut training to scientific research, mission planning, and public outreach. Each application comes with its unique benefits and challenges, emphasising the versatility and significance of this technology in space-related endeavours.

6 Image Synthesis Experiment for Space Scenes

6.1 Prompting for Popular Space Scenes

The popular space scene and the prompts used for generating a diverse set of images that vividly portray the diffusion model is illustrated in Table 7, emphasising the intricate details and scientific significance of a wide range of celestial objects and astronomical events. The diffusion model is employed to produce these images with exceptional clarity and realism.

Table 6. Prompt Description for Space Scene Image Synthesis

Astronomical Object / Phenomenon	Prompt Description
Solar System Planets	Various planets in our solar system, including Mars, Jupiter, Saturn and Venus, showcasing unique features and moons in orbit
Space Missions	Scenes from historic space missions, including the Apollo moon landings, Mars rovers, and the Voyager probes, highlighting the spirit of exploration and discovery
International Space Station (ISS)	Images featuring the ISS orbiting Earth, showcasing humanity's presence in space and the remarkable engineering of space stations
Astronomical Instruments	Concluding with a showcase of telescopes and observatories, including radio telescopes and interferometers, emphasising their pivotal role in advancing astronomical knowledge
Spaceship	Generate an image of a futuristic spaceship in a cosmic setting, highlighting its sleek design and advanced technology

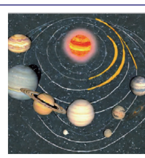
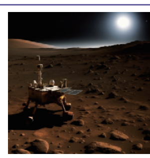
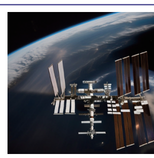
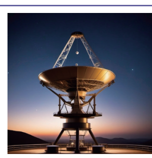
Generating these images with precision and artistry, enables viewers to appreciate both the aesthetic beauty and the scientific significance of these celestial objects and cosmic events.

6.2 Image Synthesis Experiment for Popular Space Scene

Table 7 provides an overview of an image synthesis experiment focused on popular space scene-related categories. The experiment involves two platforms, namely, "https://huggingface.co/spaces/stabilityai/stable-diffusion" and "https://stablediffusionweb.com/#demo," each evaluated based on their capabilities in generating images related to various astronomical objects and phenomena. The categories explored in this experiment include solar system planets, space missions, the International Space Station (ISS), astronomical instruments, and spaceships.

The two platforms are assessed based on their ability to produce images and visual representations related to these space-related objects. The goal of this experiment is to compare and evaluate the image synthesis capabilities of the platforms in the context of popular space scenes and subjects. The specific outcomes of this experiment, such as the quality and accuracy of generated images, can provide insights into the suitability of these platforms for creating visual content related to space exploration and astronomy.

Table 7. Image Synthesis Experiment for Popular Space Scene

Astronomical Object / Phenomenon	https://huggingface.co/spaces/stabilityai/stable-diffusion	https://stablediffusionweb.com/#demo
Solar System Planets		
Space Missions		
International Space Station		
Astronomical Instruments		
Spaceship		

7 Case Study

7.1 Designing a Space Station on Mars

Creating a design for a space station on Mars involves numerous considerations for habitation, sustainability, and functionality. Below is a conceptual design for a Mars space station, as illustrated in Figure 3:

1. Name: Mars Habitat Alpha

2. Location: Ideally situated near the equator for favorable temperature conditions and near resources like water ice.

3. Design Overview:

   1. Modular Architecture: Mars Habitat Alpha is designed in modular sections that can be transported from Earth and assembled on Mars. Modularity allows for flexibility in expansion and maintenance.
   2. Life Support Systems: The habitat features advanced life support systems that recycle air and water, providing a sustainable environment for crew members. These systems use Martian resources when available.
   3. Radiation Protection: Given the thin atmosphere and higher radiation levels on Mars, the habitat incorporates thick radiation shielding and underground components to protect inhabitants.
   4. Energy Generation: Solar panels and advanced nuclear power systems provide a dependable energy supply. Energy storage is crucial to survive the planet's frequent dust storms.
   5. Agricultural Area: A dedicated greenhouse area utilises

hydroponics and LED lighting to grow crops, reducing reliance on supplies from Earth.

6. Research and Lab Facilities: The habitat includes research and lab modules for scientific experiments, Mars geology studies, and resource utilisation research.
7. Crew Quarters: Comfortable living quarters provide crew members with private sleeping areas, shared recreational spaces, and facilities for communication with Earth.
8. Resource Utilisation: The habitat prioritises in-situ resource utilisation by extracting water from Martian ice, producing oxygen, and utilising Martian soil for construction.
9. Surface Mobility: Rover garages and landing pads facilitate exploration and transportation on the Martian surface.
10. Communication: High-frequency radio equipment ensures reliable communication with Earth and other Mars missions.
11. Redundancy: Backup systems and resources are available to handle emergencies and ensure crew safety.

4. Sustainability and Expansion:

Mars Habitat Alpha is intended to be a stepping stone for future Martian colonies. Its modular design allows for expansion as more missions arrive on Mars. It is built with the aim of sustainability and self-sufficiency, reducing the need for continual resupply missions from Earth.

5. Mission Objectives:

1. Conduct scientific research on the geology, climate, and potential for life on Mars.
2. Test technologies for future Martian colonisation efforts.
3. Provide a safe and habitable environment for astronauts

working on Mars.

4. Serve as a base for exploration and resource utilisation.

This conceptual design represents a starting point for developing a sustainable and functional space station on Mars, taking into account the unique challenges and opportunities presented by the Red Planet.

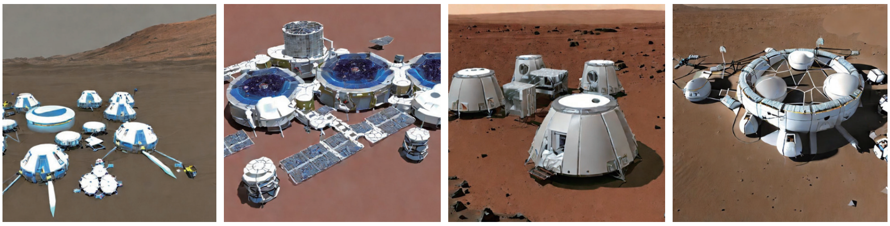


Figure 3. Image Synthesis for Habitat on Mars

7.2 Designing a Space Rover for Exploration on Mars

Designing a space rover for Mars is a complex task that involves considerations with regard to mobility, scientific exploration, communication, and survival in a harsh environment. Below is a conceptual design for a Mars rover, as illustrated in Figure 4:

1. Name: Mars Exploration Rover (MER) - Model X1

2. Design Overview:

    1. Size and Mobility: The MER-X1 rover is a mid-sized rover, approximately four meters in length, equipped with six large, rugged wheels for enhanced mobility. Each wheel can articulate independently for navigating challenging Martian terrain.

    2. Power Source: Solar panels cover the rover's top surface to harness energy from the Martian sun. Battery storage allows for continued operation during Martian nights and dust storms.

3. Communication: The rover is equipped with high-frequency communication systems for reliable data transmission between Mars and Earth. It can autonomously adjust communication parameters to optimise data transfer efficiency.

4. Scientific Instruments: MER-X1 is equipped with a suite of scientific instruments, including a multispectral camera, a spectrometer for mineral analysis, a sample collection arm with a drill, and a microscopic imager for close-up sample examination.

5. Sample Analysis: The rover can collect soil and rock samples, analysing them onboard for signs of past or present life, chemical composition, and geologic history. Samples can also be sealed for future return missions.

6. Navigation and Autonomy: Advanced navigation systems, including LiDAR and computer vision, enable autonomous navigation and obstacle avoidance. The rover can plan and execute its routes, adjusting for unexpected obstacles.

7. Durability: The rover's chassis is designed to withstand the extreme temperatures, dust storms, and radiation on Mars. It has a sealed, dust-resistant body to protect its internal components.

8. Communication Array: A retractable communication mast allows for effective signal reception and transmission. It can be raised to maintain a continuous link with orbiting spacecraft.

9. Payload Bay: A payload bay located at the rear of the rover can carry scientific instruments, additional equipment, or payloads for specific missions or experiments.

10. Remote Operation: The rover can be remotely operated from Earth for precise tasks and sample collection, but it

also has autonomous capabilities for extended missions when direct control is not feasible.

3. Mission Objectives:

   1. Explore Martian terrain, including valleys, craters, and rocky outcrops, to study the geology and search for signs of past or present life.
   2. Collect and analyse samples of Martian soil and rocks to understand the planet's history and potential habitability.
   3. Study Martian weather patterns, atmospheric conditions, and seasonal changes.
   4. Support future human exploration efforts by scouting potential landing sites and resources.

The MER-X1 rover is a versatile and robust exploration vehicle designed to advance our understanding of Mars and pave the way for future manned missions to the Red Planet.

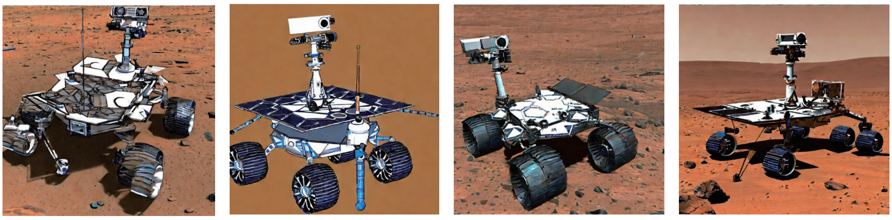


Figure 4. Image Synthesis for the Space Rover

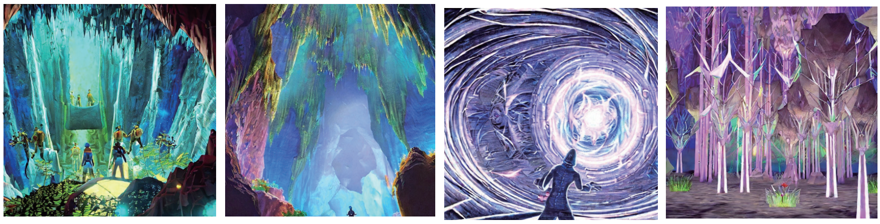
7.3 Space Fiction Image Synthesis

This subsection features the prompts and the captivating generated images for the space fiction titled *Chronicles of Xylothia: The Enigmatic World*. This imaginative piece of artwork was brought to life through the creative power of AI, and it vividly illustrates the otherworldly landscapes, alien creatures, and mysterious phenomena that populate the enigmatic world of Xylothia.

In this space fiction tale, readers will embark on a thrilling journey to a distant and uncharted planet known as Xylothia. The images convey a sense of wonder and intrigue, depicting a landscape bathed in the soft glow of an alien sun. Exotic flora and fauna inhabit this surreal environment, with their otherworldly forms hinting at the boundless diversity of life on Xylothia.

The generated image serves as a visual gateway to the narrative's rich tapestry of adventures, secrets, and discoveries that await within the pages of the *Chronicles of Xylothia*. It invites readers to immerse themselves in the mysteries of this alien realm, where the boundaries of science and imagination blur, and the possibilities of the universe seem endless.

As explorers from different corners of the galaxy venture to Xylothia, they are drawn into a web of intrigue and discovery. They seek for various reasons – some for the promise of god-like power, others for the pursuit of scientific knowledge, and a few simply to uncover the enigma of Xylothia. *The narrative* unfolds as a tale of wonder, adventure, and the boundless potential of human spirit in the face of the extraordinary. It invites readers to journey to a planet where reality is a canvas waiting to be painted with the strokes of imagination, where the impossible becomes the everyday, and where the line between science and magic blurs into something truly extraordinary.



(a) **(b)** **(c)** **(d)**

Figure 5. (a) Scene 1 - The Descent into the Crystal Caves, (b) Scene 2 -The Nexus of All Realities, (c) Scene 3 - The Bioluminescent Regatta, (d) Scene 4 - The Ethereal Crystal Forest at Night

1. Scene 1 - The Descent into the Crystal Caves

As the explorers venture deeper into Xylothia, they arrive at the entrance of the planet's famous crystal caves in Figure 5(a). The moment they step inside, they are enveloped in a breathtaking world of bioluminescent wonders. The caves are filled with delicate, glowing flora, and the walls shimmer with vibrant, ever-changing colours. In this scene, readers experience the initial sense of awe and intrigue that the crystal caves evoke, setting the stage for their journey into the heart of Xylothia.

2. Scene 2 - The Nexus of All Realities

The explorers finally reach the fabled Nexus of All Realities in Figure 5(b), a chamber deep within Xylothia where the very fabric of space and time seems to unravel. The scene is surreal, with walls adorned with shimmering crystals that seem to contain the secrets of the universe. In the center of the chamber, a swirling vortex of energy hovers, promising unimaginable power and knowledge. This pivotal moment drives the plot as the characters grapple with the moral and ethical implications of harnessing the power of the Nexus.

3. Scene 3 - The Bioluminescent Regatta

In the underground rivers of Xylothia's crystal caves, the explorers encounter a remarkable event known as the Bioluminescent Regatta in Figure 5(c). This scene unfolds as the explorers witness a captivating procession of translucent, aquatic creatures that emit radiant patterns and melodious tunes. The Regatta is a rare and enchanting spectacle, showcasing the interconnectedness of life on Xylothia and the planet's harmonious relationship with its inhabitants.

4. Scene 4 - The Ethereal Crystal Forest at Night

At night, the crystal forest takes on a different kind of enchantment in Figure 5(d). The explorers find themselves surrounded by towering crystal trees that emit a soft, otherworldly glow. Ethereal creatures, with wings resembling delicate prisms, fill the air. This scene is a moment of tranquility and reflection, allowing the characters to contemplate the beauty and mysteries of Xylothia under the starlit sky. It deepens their connection to the planet and its enigmatic wonders.

8 Discussion

The discussion for this chapter revolves around the intersection of emerging metaverse technologies and space scene image synthesis. This innovative approach brings together two distinct domains to create immersive, interactive, and educational experiences. Here are some key points for the discussion:

Q: **What is the primary focus of the discussion on "Metaverse-Driven Space Scene Image Synthesis"?**

A: The primary focus of the discussion is to explore the convergence of metaverse technologies and space scene image synthesis. This interdisciplinary approach aims to provide immersive experiences and educational opportunities in the realm of space exploration.

Q: **How can integrating metaverse technologies enhance space scene image synthesis for educational purposes?**

A: Integrating metaverse technologies enhances educational experiences by allowing users to immerse themselves in simulated space environments. VR and AR offer interactive platforms for users to explore celestial bodies, fostering a deeper understanding of space science.

***Q:* What potential does metaverse-driven space scene image synthesis hold for public engagement in space exploration and astronomy?**

A: Metaverse-driven space scene image synthesis has the potential to engage the public by providing captivating and interactive experiences. Users can virtually explore celestial phenomena, igniting interest in space and promoting a greater appreciation of astronomy and space missions.

***Q:* How can this technology benefit scientific visualisation and research in the field of space science?**

A: This technology can significantly benefit scientific visualisation by enabling researchers to visualise and analyse complex astronomical data in immersive ways. It can aid in understanding space phenomena, planetary geology, and atmospheric conditions, enhancing collaboration and research outcomes.

***Q:* What are some challenges and limitations associated with integrating metaverse technologies into space scene image synthesis?**

A: Challenges include ensuring data accuracy, addressing ethical considerations related to creating synthetic space scenes, and overcoming technical limitations. This includes hardware requirements, data privacy concerns, and potential biases in simulated representations.

***Q:* How can metaverse-driven space scene image synthesis be made accessible and inclusive for a diverse audience?**

A: Ensuring accessibility involves considering individuals with disabilities, optimising user interfaces, and providing multiple modes of interaction. It is essential to prioritise inclusive design, incorporating features that cater to a wide range of abilities and needs.

Q: **What ethical considerations are paramount in the development and deployment of metaverse-driven space scene image synthesis?**

A: Ethical considerations include data privacy, informed consent, and the responsible use of technology. Developers must be mindful of potential biases in synthesised scenes and ensure that the technology respects individual rights and cultural sensitivities, fostering a responsible and inclusive virtual space exploration experience.

We can see that "Metaverse-Driven Space Scene Image Synthesis" is at the forefront of technological innovation, education, and scientific research. It offers a unique opportunity to bridge the gap between the virtual and the astronomical, making space exploration more accessible and engaging for everyone.

9 Future Prospects

As this innovative intersection of metaverse technologies and space exploration continues to evolve, the future prospects for this work are promising. Here are some anticipated future prospects:

1. Advanced Immersive Experiences: Future developments in metaverse-driven space scene image synthesis will likely lead to even more immersive and realistic experiences. Enhanced graphics, spatial audio, and haptic feedback will create a heightened sense of presence for users exploring

space environments.

2. Expanded Educational Applications: Educational institutions, from primary schools to universities, will increasingly adopt metaverse-driven space scene image synthesis as a core teaching tool. Virtual field trips to distant planets and galaxies will become standard, enabling students to grasp complex astronomical concepts with ease.

3. Virtual Space Tourism: Metaverse platforms may offer virtual space tourism experiences, allowing users to visit iconic space destinations like the Moon, Mars, and beyond. These experiences could simulate the feeling of being an astronaut, complete with simulated spacewalks and moonwalks.

4. Integration with Space Missions: Space agencies may incorporate metaverse-driven space scene image synthesis into actual space missions. Astronauts could use VR or AR devices to interact with simulated environments that mirror their mission objectives, enhancing training and mission planning.

5. Scientific Visualisation Breakthroughs: Scientists and researchers will continue to benefit from this technology for scientific visualisation and data analysis. Advanced AI algorithms and simulations will provide new insights into cosmic phenomena and planetary exploration.

6. Global Collaboration: International space agencies and organisations will collaborate on metaverse-driven projects, fostering global cooperation in space exploration. This could lead to shared virtual spaces for research, learning, and cross-cultural exchange.

7. Space Art and Creativity: Artists and creatives will use

metaverse-driven space scene image synthesis as a canvas for space-inspired art, films, and experiences. This fusion of art and science will further inspire and captivate audiences.

8. Digital Archives of Space History: Future prospects include the creation of extensive digital archives of space history, documenting space missions, astronomical discoveries, and the evolution of our understanding of the cosmos. These archives will be accessible to researchers and the general public.

9. AI-Enhanced Simulations: AI will play a significant role in creating realistic space simulations. AI-driven agents may populate these virtual worlds, providing dynamic and responsive interactions with users.

10. Ethical Frameworks and Standards: The development of ethical frameworks and standards for metaverse-driven space scene image synthesis will become increasingly important. These would include guidelines for data privacy, content creation, and the responsible use of technology.

11. Commercial Ventures: Private companies may enter the metaverse-driven space scene image synthesis market, offering unique experiences, services, and applications. This could lead to a burgeoning metaverse space industry.

12. Scientific Citizenry: Metaverse-driven experiences will foster a more scientifically literate and engaged citizenry. People of all ages will have the opportunity to participate in citizen science projects and contribute to real space research.

The future of this work holds tremendous potential for transforming how we engage with and understand space. This technology is poised to inspire, educate, and deepen our connection to the cosmos while fostering collaboration and innovation across diverse fields.

10 Conclusion

In conclusion, this work represents a groundbreaking fusion of metaverse technologies and space exploration that holds immense promise for the future. This innovative approach offers a gateway to immersive, educational, and scientifically enriching experiences that can captivate the imagination of people across the globe. As we navigate the metaverse, we discover not only virtual space landscapes but also a profound connection to the mysteries of the universe. It has the power to inspire the next generation of space enthusiasts, empower scientists and researchers, and engage the public in a shared journey through the cosmos. However, with this transformative technology also come important ethical considerations. Striking the balance between responsible use, data privacy, and inclusivity will be pivotal as we chart the course forward.

The future prospects of this research are challenging, offering advanced immersive experiences, expanded educational applications, and the potential to reshape how we understand and explore space. As we embark on this cosmic metaverse adventure, we find ourselves at the intersection of innovation, education, and human curiosity—a place where the boundaries of reality and imagination blur, and the cosmos becomes more accessible to all.

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Chapter 9

Exploring the Space Metaverse: Applications of Electronic Systems and Artificial Intelligence Technology

Abstract

The emergence of the metaverse has ushered in a new era of exploration and imagination beyond the boundaries of our planet, redefining the ways we interact with and understand the cosmos. This chapter further describes the transformative landscape of the Space Metaverse, where the seamless integration of electronic systems and cutting-edge artificial intelligence (AI) technology drives innovative applications in space exploration. Through an interdisciplinary lens, we explore the convergence of electronic systems and AI, shedding light on their contributions to spacecraft design, communication, navigation, and autonomous operations. By analysing case studies and drawing insights from existing literature, we unravel the potential of the Space Metaverse, also known as Space Verse, to revolutionise space exploration and open new frontiers of discovery. Additionally, we examine the challenges, opportunities, and ethical considerations associated with this

paradigm shift. As we chart a course through this evolving frontier, this study aims to inspire further research and innovation at the intersection of electronic systems, AI technology, and the boundless expanse of outer space.

Keywords: metaverse, Space Metaverse, planet, cosmos, electronic systems, artificial intelligence (AI), space exploration, spacecraft design, communication, navigation, autonomous operations, outer space

1 Introduction

1.1 Fundamentals and Concepts

The emergence of the metaverse has sparked a profound revolution across diverse industries, introducing immersive digital landscapes that mirror the physical realm. Among the resulting groundbreaking applications lies the awe-inspiring Space Metaverse, a domain where electronic systems and AI technology synergise to propel the frontiers of space exploration, research, and innovation to unprecedented heights. Within this case study, we embark on a journey to explore the multifaceted applications of electronic systems and technology within the expanse of the Space Metaverse, unveiling their profound impact on cosmic endeavours and their instrumental role in shaping the trajectory of interstellar discovery.

The Space Metaverse stands as a dynamic nexus, uniting the brightest minds of scientists, engineers, and enthusiasts within a virtual crucible where simulation, analysis, and visionary creation unfold in the realm of space exploration. Through the integration of cutting-edge tools such as virtual reality (VR), augmented reality (AR), AI, and sophisticated data analytics, this digital realm serves as a canvas for simulating cosmic landscapes, scrutinising celestial bodies, and crafting innovative spacecraft and technologies that transcend our earthly boundaries. In doing so, the Space Metaverse becomes a conduit that amplifies our comprehension of the universe and accelerates exploration beyond the confines of our planet.

Bolstered by the rapid strides in electronic systems and cutting-edge technology, a new era of exploration has dawned, beckoning us beyond terrestrial confines. At its core, this era embodies the profound concept of the "Space Metaverse", an audacious concept that envisions the seamless fusion of these technological marvels into the very fabric of outer space exploration. In the vanguard of transformation, the Space Metaverse galvanises a profound shift in how we engage with, interpret, and harness the enigmatic potential that the cosmos holds. As we embark on this narrative, we unveil a trajectory that propels humanity into a future where the boundaries of the imaginable are continually stretched and where the infinite wonders of the cosmos become increasingly accessible through the harmonious marriage of electronic ingenuity and celestial curiosity.

1.2 Main Contribution of This Work

The primary contribution of this exploration into the "Space Metaverse: Applications of Electronic Systems and Artificial Intelligence Technology" lies in its comprehensive analysis and illumination of how electronic systems and AI technology are revolutionising and expanding the frontiers of outer space exploration. By investigating this burgeoning field, this study sheds light on several significant contributions:

(i). In-depth Understanding of Space Integration: The research provides a thorough understanding of the seamless integration of electronic systems and advanced technology within the realm of outer space exploration. It elucidates the principles, methodologies, and challenges associated with harmonising these technologies to create a cohesive, coherent, and effective framework for exploring the cosmos.

(ii). Diverse Applications: Through detailed system design and case studies, the study unveils the wide-ranging applications arising from the convergence of electronic systems and AI technology in space. It highlights how electronic systems and AI facilitate satellite communication, navigation, remote sensing, data acquisition, and autonomous operations, while also enabling the deployment and management of robotic explorers on celestial bodies.

(iii). Challenges and Solutions: The study confronts the challenges that emerge when integrating electronic systems and technology into the cosmic environment. It addresses issues such as radiation exposure, thermal management, communication latency, and the complexities of operating in extreme conditions. Furthermore, the research presents innovative solutions and strategies that mitigate these challenges, ensuring the reliability and longevity of space missions.

(iv). Pathways to Future Exploration: By extrapolating current trends and emerging developments, the study offers insights into the future trajectory of space exploration. It envisions how the continued evolution of electronic systems and technology will enable ambitious missions to distant planets, asteroids, and even interstellar space, while also fostering the potential for human presence beyond Earth.

In essence, this work makes a substantial contribution by unveiling the transformative role of electronic systems and advanced technology in reshaping our understanding of the cosmos, advancing scientific knowledge, and paving the way for the next era of space exploration.

2 Literature Review

In the context of literature review, we can categorise our research into the following three directions: VR and AR in Space Exploration, Exploring the Metaverse Across Disciplines, and Electronic Systems and AI in Space Exploration.

2.1 Virtual Reality and Augmented Reality in Space Exploration

VR and AR technologies have emerged as transformative tools in space exploration, revolutionising astronaut training, extravehicular activities, navigation, and medical interventions. A collection of studies reveals the multifaceted applications of VR and AR in various aspects of space missions.

Holt (2022) discusses the potential uses of VR, AR, and Mixed Reality (MR) for astronaut mental health. She suggests that these technologies could be used to create immersive environments that reduce stress, provide social interaction, and promote relaxation. For example, VR could be used to simulate natural environments, such as forests or beaches, which have been shown to have a calming effect on people. AR could be used to project images of loved ones or friends onto the walls of a spacecraft, providing a sense of connection and companionship, while MR could be used to create interactive games and simulations that help astronauts relax and de-stress. Becker et al. (2023) explore the use of AR for human operations on the Moon. They conducted a study in which astronauts used an AR headset to perform tasks in a virtual environment that simulated the lunar surface. The results of the study showed that AR can be a valuable tool for astronauts, as it can help them visualise tasks, identify hazards, and make better decisions. Ebnali et al. (2022) describe the development of AR-coach, a system that uses AR to provide real-time clinical guidance to astronauts during medical emergencies. AR-coach is designed to be used in conjunction with a telemedicine system and can be used to provide astronauts with instructions on how to perform CPR, treat wounds, and manage other medical conditions. Bonilla Fominaya et al. (2022) present MoonBuddy, a voice-based AR user interface that supports astronauts during extravehicular activities (EVAs). MoonBuddy uses a combination of AR and voice recognition to provide astronauts with information about their surroundings, such as the location of hazards, the status of their equipment, and the steps required to complete a task. Miller et al. (2021) describe the development of an AR interface to aid astronauts in EVAs. The interface projects information onto the visor of an astronaut's helmet, such as the location of nearby objects, their equipment status, and what is needed to complete a task. The interface also includes a voice recognition system that allows astronauts hands-free control. Ahner-McHaffie et al. (2023) describe the development of an AR lunar surface navigation system which uses a combination of AR and GPS to provide astronauts with real-time navigation information, that includes their current location, the distance to their destination, and the best route to take. The system also includes a voice recognition system for hands-free control. Pinedo et al. (2019) describe the development of an AR system for human space operations. The system uses a combination of AR and haptic feedback to provide astronauts with a realistic experience of performing tasks in space. It has been used to train astronauts on a variety of tasks, including EVAs, docking procedures, and spacecraft maintenance. Karasinski et al. (2021) discuss the design of procedure execution tools with emerging technologies for future astronauts. They argue that VR and AR can be used to create interactive and immersive tools that can help astronauts to learn and execute procedures more effectively. They also suggest that these technologies can be used to provide astronauts with real-time feedback and support during critical operations.

These studies demonstrate the potential of VR and AR to improve astronaut mental health and support space exploration. As these technologies continue to develop, they are likely to play an increasingly important role in the future of space travel. In addition to the studies noted above, there are a number of other ongoing research projects that are exploring the use of VR and AR for astronaut mental health and space exploration. While the use of VR and AR is still in its early stages, the potential benefits of these technologies are significant. As these technologies continue to develop, they are likely to play an increasingly important role in the future of space travel.

2.2 Exploring the Metaverse across Disciplines

The concept of the metaverse, a virtual shared space that encompasses augmented and virtual reality, has gained significant attention across various fields due to its potential to transform industries and human experiences. Researchers from diverse domains have contributed to the understanding of the metaverse, its applications, challenges, and implications.

Wang et al. (2022) present a comprehensive survey exploring the foundational concepts, security concerns, and privacy issues surrounding the metaverse, and shedding light on the intricate balance between immersive experiences and safeguarding user data. Ning et al. (2023) provide an extensive overview of the state-of-the-art technologies, applications, and challenges in the metaverse. Their survey covers a wide range of topics, including VR, AR, MR, and the integration of the metaverse with the Internet of Things (IoT), offering insights into the current landscape and future directions. In the context of metasocieties within the metaverse, Wang et al. (2022) delve into metaeconomics and metamanagement for metaenterprises and metacities. Their work examines the potential of economic and managerial frameworks that emerge within the metaverse, offering insights into the novel dynamics and structures that may shape future digital societies. Kye et al. (2021) explore the educational applications of the metaverse and discuss its possibilities and limitations. Their study emphasises the potential of the metaverse for enhancing educational experiences, promoting interactive learning, and providing immersive environments for students. Xu et al. (2022) examine realising the edge-enabled metaverse by discussing visions, enabling technologies, and challenges. The authors explore the technical aspects of enabling seamless interactions and connectivity within the metaverse, highlighting the role of edge computing. Almarzouqi et al. (2022) investigate the use of metaverse systems to use metaverse systems in medical education using a hybrid SEM-ML learning approach. Their study contributes to understanding user behaviour and preferences in utilising metaverse platforms for educational purposes. Hollensen et al. (2022) explore the metaverse as a new marketing universe, discussing its implications for business strategy, highlighting how the metaverse presents opportunities for innovative marketing approaches and engagement with consumers. Gursoy et al. (2022) focus on the hospitality and tourism industry's engagement with the metaverse. Their overview of current trends and future research directions highlights the potential applications of the metaverse in enhancing guest experiences and industry operations.

Collectively, these studies contribute to a multidisciplinary understanding of the metaverse, encompassing its technological foundations, societal implications, and its applications in education, marketing, and various industries, as well as the challenges and opportunities it presents for future research and innovation.

2.3 Electronic Systems and Artificial Intelligence in Space Exploration

The integration of electronic systems and AI has revolutionised space exploration, offering enhanced capabilities, autonomous decision-making, and innovative solutions. A compilation of studies showcases the diverse applications of electronic systems and AI in various facets of space missions.

Carbone et al. (2023) investigate the voltage stability of spacecraft electric power systems for deep space exploration. Their study highlights the crucial role of electronic systems in ensuring reliable and stable power distribution within spacecraft, essential for prolonged missions in remote regions of space. Brinkmann et al. (2019) discuss the intersection of space robotic systems and AI within the context of the European Space Technology Roadmap, highlighting the synergistic potential of AI-driven robotics in enabling complex missions and addressing challenges posed by the space environment. Furano et al. (2020) explore the utilisation of AI on the edge in space systems, emphasising challenges and opportunities. Their study underscores the potential of AI to enhance on-board data processing, decision-making, and adaptability, particularly in resource-constrained space environments. Russo and Lax (2022) present a comprehensive survey of the use of AI for space missions. Their study provides insights into AI techniques, applications, and advances that enable more efficient mission planning, navigation, and data analysis. Legal, ethical, and technological considerations surrounding AI and space technologies are addressed by Soroka and Kurkova (2019). They highlight the complex interplay between AI applications, regulations, and ethical concerns in the context of space exploration. Martin and Freeland (2021) examine the legal challenges arising from the advent of AI in space activities, and explore the legal implications of AI-driven missions, autonomy, liability, and the evolving regulatory landscape. She et al. (2021) introduce a quantum-interference artificial neural network for space manipulator control. Their study showcases the potential of AI-enhanced control systems, leveraging quantum principles to optimise space operations. Sanders et al. (2023) highlight the role of AI in supporting biological research and self-driving labs in deep space. They emphasise how AI-driven automation enhances research efficiency, data analysis, and decision-making, enabling innovative scientific discoveries.

Taken together, these studies underscore the pivotal role of electronic systems and AI in space exploration, spanning voltage stability, robotic systems, edge computing, navigation, legal considerations, quantum-inspired control, and advanced research support. The fusion of electronic systems and AI technologies holds immense potential to transform the landscape of space missions, enabling autonomous, efficient, and innovative approaches to exploring the cosmos.

3 Methodology

3.1 Research Methodology

The methodology for "Exploring the Space Metaverse: Applications of Electronic Systems and Technology" involves a structured approach to investigating the seamless integration of electronic systems and cutting-edge technology in outer space exploration. This research aims to uncover the diverse applications, challenges, and opportunities that arise from the Space Metaverse. Figure 1 shows a methodology for conducting this study:

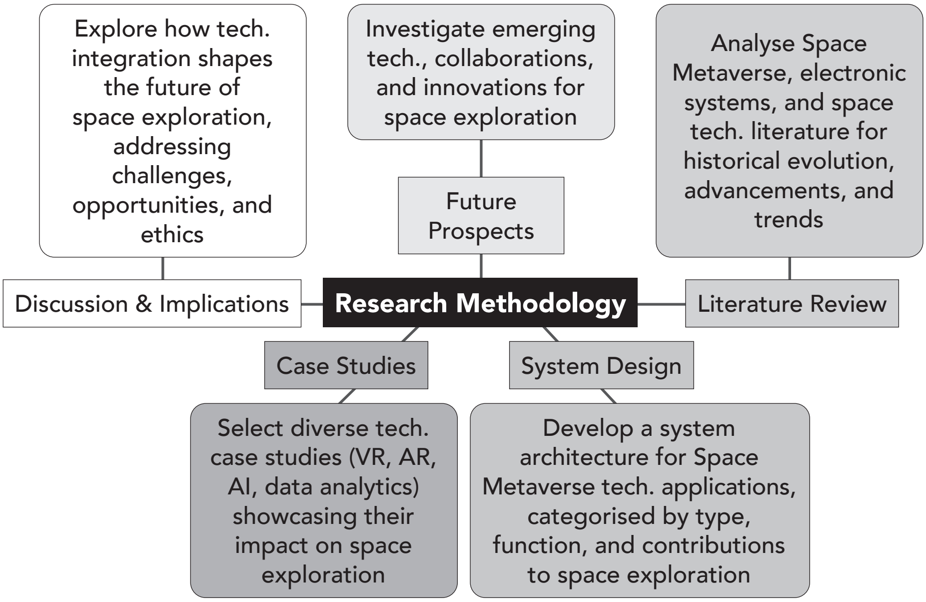


Figure 1. Research Methodology

1. Literature Review: Conduct an extensive review of existing literature related to the Space Metaverse, electronic systems, and advanced technology applications in space exploration. Gather insights into the historical evolution, technological advancements, and emerging trends in this interdisciplinary field.

2. System Design: Synthesise the findings from related work and comparative analysis to develop a comprehensive system illustrating the applications of electronic systems and technology in the Space Metaverse. Organise the systems into categories based on technology types, their functions, and their contributions to space exploration.

3. Case Studies Selection: Identify relevant case studies that exemplify the applications of electronic systems and technology in the Space Metaverse. Select cases that showcase a diverse range of technologies, such as VR, AR, AI, data analytics, and their impact on space exploration, research, and innovation.
4. Discussion and Implications: Engage in a critical discussion of the implications of the study findings. Examine how the integration of electronic systems and advanced technology shapes the future of space exploration, research, and innovation. Highlight potential challenges, opportunities, and ethical considerations.
5. Future Prospects: Explore potential avenues for further research and development in the field of electronic systems and the Space Metaverse. Discuss emerging technologies, interdisciplinary collaborations, and innovative approaches that could enhance our capabilities in exploring outer space.

By following this methodology, the research on "Exploring the Space Metaverse: Applications of Electronic Systems and Technology" aims to provide a comprehensive understanding of how electronic systems and cutting-edge technology are shaping the landscape of outer space exploration and expanding our knowledge of the cosmic realm.

3.2 Architecture of Space Metaverse

"Space Metaverse architecture" describes a conceptual framework or structure for integrating various technologies and systems related to space exploration and space applications. Space Metaverse is a digital representation or simulation of the space environment. Figure 2 illustrates different components or domains within this architecture.

Software Systems: These refer to the software components and systems used in space exploration, including mission control software, data processing, and other software applications. These include "Avionics Systems and Spacecraft" and "Communication and Navigation Systems".

Artificial Intelligence Technologies: AI technologies can be employed in various aspects of space exploration, including for autonomous decision-making, data analysis, and robotics, and extending to a "Robotic Exploration and Autonomous Algorithm" and an "Artificial Intelligence Algorithm".

Physical Electronic Systems: These are the physical electronic components used in the Space Metaverse for integration of systems.

Physical Sensors: Sensors are used to collect data about the physical environment and are crucial for navigation and scientific measurements in space.

Space Applications: These encompass various practical applications of space technology, from Earth observation to scientific research, including "Space Exploration", "Mission Planning", "Space Robot Interaction", and " Navigation".

Physical Environment and Equipment: This includes the actual conditions and equipment encountered in space, including microgravity, radiation, and specialised tools and machinery.

The concept of "Space Human and Robot Interaction" is a comprehensive framework that envisions the integration of physical and digital elements to facilitate Space Metaverse exploration, leveraging technologies like AI, robotics, and advanced software systems. It seems to emphasise the interconnectedness and interdependence of various components and technologies.

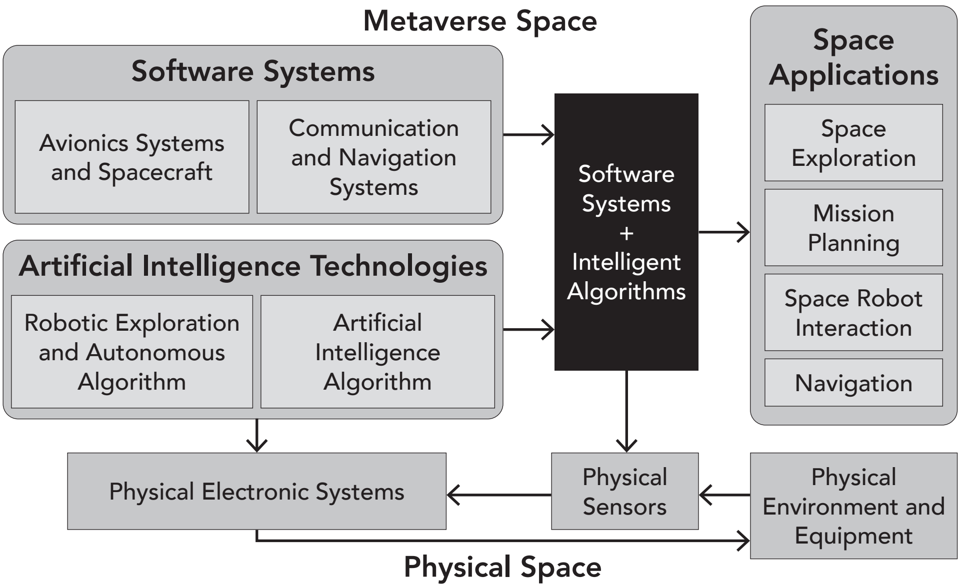


Figure 2. Research in the Space Metaverse

3.3 Metaverse Design

In this section, we examine the design methodologies of several significant systems, including of the Avionics Systems and Spacecraft, Communication and Navigation Systems, Robotic Exploration and Autonomous Systems, as well as Artificial Intelligence Systems. Table 1 provides an overview of the design flow for each system, highlighting the key aspects and considerations involved in their development.

Table 1. Design Flow for Main Space System

System	Design Flow
Avionics Systems and Spacecraft	- Define mission objectives for clear goals - Determine system architecture - Specify detailed technical requirements - Integrate sensors and instruments - Design communication and power systems - Develop data handling and processing - Select onboard computing systems - Integrate altitude control and propulsion - Conduct integration and testing - Address environmental considerations - Establish mission operations and updates

Communication and Navigation Systems	- Develop communication protocols - Choose communication frequencies - Design navigation systems - Implement real-time data transfer - Address technical challenges - Optimise bandwidth usage
Robotic Exploration and Autonomous Systems	- Analyse challenges and opportunities - Integrate electronic systems for autonomous navigation - Develop smart sensors and instruments - Design AI-driven control mechanisms
Artificial Intelligence Systems	- Explore AI technologies for space exploration - Implement AI algorithms for spacecraft autonomy - Address legal, ethical, and technical challenges - Apply AI to human-robot interaction

The System Design Flow for Avionics Systems and Spacecraft involves a systematic approach to ensure the successful execution of a space mission, beginning with defining clear mission objectives. The process then moves to determine the system architecture, outlining the overall structure and organisation of the spacecraft's electronic systems. Following that, detailed technical requirements are specified, which serve as the blueprint for the development process. While sensors and instruments are integrated into the design, ensuring the spacecraft can collect necessary data, the design also includes communication and power systems, ensuring efficient data transfer and power supply.

Data handling and processing systems are developed to manage the information collected during the mission. Selection of onboard computing systems is a critical step in ensuring that the spacecraft's processing capabilities align with mission requirements. Altitude control and propulsion systems are integrated to manage the spacecraft's orientation and movement. The integration and testing phase are crucial to verify that all components work together seamlessly. Environmental considerations, such as temperature and radiation, are addressed to ensure the spacecraft's resilience in space. Finally, mission operations and updates are established, outlining how the spacecraft will be operated and maintained throughout its mission.

In Communication and Navigation Systems, the design flow involves developing communication protocols to enable effective data transfer between the spacecraft and mission control. This includes choosing appropriate communication frequencies and designing navigation systems to ensure accurate positioning and movement. Real-time data transfer mechanisms are implemented to enable timely data exchange. Technical challenges related to communication and navigation are addressed, and bandwidth usage is optimised to make the most efficient use of available resources.

For Robotic Exploration and Autonomous Systems, the process begins with an analysis of challenges and opportunities in the context of the particular mission. Electronic systems for autonomous navigation are integrated to enable spacecraft or robots to navigate and make decisions independently. Smart sensors and instruments are designed to collect relevant data, and AI-driven control mechanisms are developed to facilitate autonomous decision-making.

In the domain of Artificial Intelligence Systems, the design flow involves exploring AI technologies suitable for space exploration. AI algorithms are implemented to enable spacecraft autonomy, allowing the craft to analyse data, adapt to changing conditions, and make real-time decisions. Additionally, legal, ethical, and technical challenges related to AI in space are addressed, and AI is applied to enhance human-robot interaction, enabling effective collaboration between astronauts and AI-driven systems. This systematic approach ensures that electronic systems are carefully designed, integrated, and tested to meet mission objectives and challenges in space exploration.

3.3.1 Designing Avionics Systems and Spacecraft

Designing avionics systems for spacecraft involves creating the electronic systems and components that enable the spacecraft to operate, communicate, and navigate in space. These systems play a crucial role in ensuring the success of the mission by facilitating data collection, communication with Earth, and onboard control. Below is a step-by-step guide on how to design avionics systems within the broader context of spacecraft design:

Throughout the avionics design process, collaboration among various engineering disciplines, including electronics, communication, and control systems, is essential. Iterative design, prototyping, and simulations help refine the avionics systems to ensure they meet the mission requirements and operate reliably in the challenging space environment.

3.3.2 Designing Communication and Navigation Systems

Designing communication and navigation systems for the Space Metaverse, which requires that electronic systems and cutting-edge technology converge in outer space exploration, is a complex endeavour that involves ensuring seamless connectivity, precise positioning, and efficient data exchange across vast cosmic distances.

It also requires a comprehensive understanding of space environment dynamics, radio frequency engineering, software development, and mission operations. Collaboration among experts from various disciplines is crucial to ensure the seamless integration of these systems, enabling successful exploration and interaction within the cosmic landscape of the metaverse.

3.3.3 Designing Robotic Exploration and Autonomous Systems

Designing robotic exploration and autonomous systems involves creating intelligent and adaptable robots that can navigate, operate, and make decisions in the challenging and dynamic environment of outer space. These systems play a vital role in enabling efficient data collection, scientific research, and resource utilisation on celestial bodies. Designing robotic exploration and autonomous systems for the Space Metaverse requires expertise in robotics, software engineering, sensors, communication, and space environment dynamics. Collaborative efforts among multidisciplinary teams are essential to create intelligent and capable robots that can navigate and explore the cosmic terrain autonomously.

3.3.4 Designing Artificial Intelligence Systems

Designing AI systems for the Space Metaverse involves creating intelligent algorithms and systems that can analyse data, make decisions, and adapt to changing conditions in the dynamic and challenging environment of outer space. AI can enhance spacecraft autonomy, optimise mission operations, and enable more sophisticated exploration. Designing the AI systems needed requires a deep understanding of AI techniques, space environment dynamics, mission objectives, and spacecraft or robotic systems. Collaboration among AI experts, space scientists, engineers, and mission planners is crucial in order to create intelligent systems that can enhance exploration, discovery, and interaction within the cosmic landscape of the metaverse.

4 Applications of the Space Metaverse

Space Metaverse applications collectively contribute to advancing our understanding of space, improving space mission outcomes, and inspiring the next generation of space enthusiasts and scientists. Below is a brief explanation of the functions:

(i). Space Exploration: This application involves using electronic

systems and AI technologies to enhance space missions. It includes tasks such as designing spacecraft, optimising trajectories, conducting remote operations, and ensuring autonomous navigation. The goal is to explore celestial bodies, gather data, and expand our understanding of the universe.

(ii). Mission Planning: Electronic systems and AI aid in accurately simulating and planning space missions. They help optimise spacecraft trajectories, plan efficient routes, and predict mission outcomes. This application ensures that missions are well-coordinated, resource-efficient, and successful.

(iii). Space Robot Interaction: AI technologies enhance the interaction between humans and robots in space. This includes remote operation of robots, collaborative tasks, and ensuring the safety of astronauts and robotic systems during space missions.

(iv). Navigation: Electronic systems and AI aid in spacecraft navigation and orientation. AR guidance and AI-enhanced positioning systems help ensure accurate navigation, especially in complex environments such as planetary surfaces.

The exploration of the Space Metaverse reveals a range of promising applications with distinct advantages and corresponding challenges. Understanding the potential benefits and drawbacks of these applications is essential for making informed decisions in the realm of space exploration and technology development.

4.1 Metaverse Applications and Space Technology

In Table 2, the various applications of the Space Metaverse are systematically outlined, showcasing their diverse functions and potential contributions to space exploration. Each application represents a unique avenue for leveraging electronic systems and advanced technology to enhance our understanding of the cosmos. The Table effectively highlights the multidimensional nature of the Space Metaverse, demonstrating how it encompasses aspects such as simulation, communication, navigation, research, and education. This overview serves as a valuable reference for understanding the wide-ranging possibilities that the Space Metaverse offers.

Table 2. Space Metaverse Technology and Applications

Application	Virtual Reality and Augmented Reality	Exploring the Metaverse Across Disciplines	Electronic Systems and Artificial Intelligence
Space Exploration	Immersive training simulations for astronauts	Visualisation collaboration tools	AI-assisted spacecraft navigation and autonomy
Scientific Research	Virtual experiments and simulations	Cross-disciplinary data analysis	AI-driven data analysis for discoveries
Education and Outreach	Interactive educational experiences	Outreach to diverse audiences	AI-enhanced educational tools and content
Mission Planning	Realistic mission simulations	Collaborative planning and design	AI-optimised mission trajectories and logistics
Communication	Virtual meetings and telepresence	Metaverse-enabled conferences and events	AI-enhanced communication and data transfer
Human-Robot Interaction	Remote operation of robotic explorers	Seamless integration of robotic systems	AI-enabled human-robot cooperation and synergy
Navigation	AR-assisted navigation and orientation	Cross-disciplinary spatial understanding	AI-enhanced spacecraft positioning and orientation
Data Analysis	VR-based data visualisation and exploration	Multidisciplinary data fusion	AI-driven insights from complex data sets
Entertainment	Space-themed VR/AR experiences	Creative expression and immersive arts	AI-generated interactive narratives and content
Innovation	Prototyping and testing of new technologies	Collaborative innovation platforms	AI-powered technology ideation and development

4.2 Metaverse Applications and Their Challenges

Table 3 provides an analysis of the advantages and disadvantages associated with applications of the Space Metaverse. By juxtaposing the benefits and challenges of each application, the Table offers a holistic view of the potential advantages and drawbacks of integrating electronic systems and advanced technology in space exploration. The advantages underscore the transformative potential of the Space Metaverse, from immersive training to innovative design, while the disadvantages shed light on critical considerations such as technical limitations, reliability concerns, and equitable access. This balanced assessment is intended to equip stakeholders with an understanding of the opportunities and complexities involved in harnessing the Space Metaverse for space endeavours.

Table 3. Pros and Cons of Metaverse Applications

Application	Advantages	Disadvantages
Space Exploration	Immersive training; Realistic simulations	Limited physical experience; Costly hardware
Scientific Research	Virtual experiments; Data simulations	Limited physical data collection; Data accuracy
Education and Outreach	Engaging education; Broad outreach	Access limitations; Technical requirements
Mission Planning	Accurate simulations; Efficient planning	Complex software; Resource-intensity
Communication	Remote collaboration; Real-time data	Technical issues; Bandwidth limitations
Human-Robot Interaction	Remote operation; Enhanced safety	Delayed responses; Lack of tactile feedback
Navigation	AR guidance; Improved orientation	Reliance on technology; Technical malfunctions
Data Analysis	Visualisation of complex data; Efficient analysis	Data integration challenges; Interpretation bias
Entertainment	Immersive experiences; Creative content	Isolation from reality; Limited physical activity
Innovation	Rapid prototyping; Collaborative ideation	Technical learning curve; Intellectual property issues

The applications of the Space Metaverse hold immense potential to transform space exploration and research. While offering innovative solutions and novel experiences, these applications also introduce various challenges that necessitate careful consideration and proactive mitigation. Striking a balance between the advantages and disadvantages is crucial to harnessing the full capabilities of the Space Metaverse in advancing humanity's reach into the cosmos.

5 Electronic Systems and AI Technologies

5.1 Electronic Systems

Electronic Systems play a crucial role in the Space Metaverse, enabling various applications and technologies. The components of electronic systems are summarised in Table 4 to enable the integration of electronic systems in the Space Metaverse, supporting various applications and advancements in space exploration and technology. These electronic systems are the backbone of modern spacecraft, each serving a crucial role in ensuring spacecraft functionality, safety, and success. At the core of these systems are microprocessors and microcontrollers, acting as the "brains" that execute instructions and oversee various functions. Sensors and actuators collect environmental data and initiate actions based on those data, which is vital for spacecraft to respond to changing conditions and perform critical tasks like adjusting orientation.

Power management systems guarantee a stable power supply, often utilising solar panels and batteries, while communication modules enable data exchange between spacecraft and Earth, as well as between spacecraft themselves, using radio frequency communication. Data handling units process, store, and manage data collected from sensors and instruments, incorporating data compression and storage solutions for efficiency.

Navigation and control systems ensure precise spacecraft orientation and trajectory adjustments, maintaining the correct path during missions. Avionics software governs diverse spacecraft functions, including mission planning, data processing, and autonomous decision-making. Telemetry, tracking, and command systems continuously monitor and control spacecraft operations, facilitating tracking, telemetry data reception, and command transmission.

AI and machine learning modules apply advanced algorithms for data analysis, pattern recognition, autonomous decision-making, and mission optimisation. Safety and redundancy systems incorporate redundancy mechanisms to ensure system reliability, fault tolerance, and safe operations. Embedded systems, specialised and compact, carry out specific tasks within spacecraft components, such as onboard cameras or scientific instruments.

User interfaces and displays enable astronauts or operators to interact with electronic systems and monitor spacecraft status. Thermal control systems are vital for regulating temperature and preventing overheating or extreme cold that could harm electronic components. Software-defined radios adapt to different communication protocols and frequencies, ensuring flexible and efficient communication.

Circuit protection and radiation hardening safeguard electronic components from cosmic radiation and space-related hazards. Navigation sensors, including gyroscopes, accelerometers, star trackers, and GPS, ensure precise positioning and orientation. Communication antennas transmit and receive signals for communication with Earth and other spacecraft.

Software for simulation and testing allows the development and simulation of electronic system behaviour before deployment, aiding in design and testing. Health monitoring and diagnostics continuously watch over electronic components, providing diagnostics for timely maintenance. Finally, timekeeping and synchronisation systems maintain accurate timekeeping for synchronisation across various spacecraft systems and functions. These interconnected electronic systems collectively form the technological infrastructure that drives the success of spacecraft missions, from scientific exploration to communication and beyond.

Table 4. Component Analysis of Electronic Systems

Component	Function and Purpose	Advantages	Challenges
Microprocessors and Microcontrollers	Execute instructions and control functions	Efficient processing; Real-time control	Computational limitations; Radiation effects
Sensors and Actuators	Collect environmental data; Perform actions	Data collection; Precise control	Calibration; Environmental variability
Power Management Systems	Ensure stable power supply; Manage energy	Reliable operation; Sustainable power	Power efficiency; System complexity
Communication Modules	Exchange data with Earth and spacecraft	Data transfer; Remote communication	Signal interference; Limited bandwidth
Data Handling Units	Process, store and manage data from sensors	Data analysis; Efficient storage	Data integrity; Storage capacity
Navigation and Control Systems	Orient spacecraft; Adjust trajectory	Accurate navigation; Course correction	Sensor accuracy; Algorithm complexity
Avionics Software	Control and manage spacecraft functions	Mission flexibility; Autonomy	Software bugs; Algorithm complexity
Telemetry, Tracking, and Command Systems	Monitor, control and track spacecraft	Operational insights; Remote control	Signal loss; Communication delays

AI and Machine Learning Modules	Analyse data, make decisions, optimisation	Data insights; Autonomous capabilities	Training data; Interpretability
Safety and Redundancy Systems	Ensure reliability and fault tolerance	System resilience; Mission planning	Increased complexity; Weight and cost
Embedded Systems	Perform specific tasks within components	Space-saving; Task specialisation	Integration challenges; Limited flexibility
User Interfaces and Displays	Interact with systems; Monitor spacecraft	Astronaut interaction; Status monitoring	Usability; Display limitations
Thermal Control Systems	Regulate temperature for component protection	Prevention of overheating; Ensuring stability	Power consumption; Thermal balance
Software-Defined Radios	Adapt to different communication protocols	Communication versatility; Flexibility	Signal quality; Complexity
Circuit Protection and Radiation Hardening	Shield components from radiation	Component protection; System longevity	Design complexity; Weight and cost
Navigation Sensors	Ensure precise positioning and orientation	Accurate navigation; Spatial awareness	Calibration; Sensor failure
Communication Antennas	Transmit and receive signals for communication	Data transfer; Communication reliability	Signal interference; Directionality
Software for Simulation and Testing	Model system behaviour; Aid design	Design validation; Risk reduction	Simulation accuracy; Resource demand
Health Monitoring and Diagnostics	Continuous component health monitoring	Early issue detection; System longevity	Sensor accuracy; False alarms
Timekeeping and Synchronisation	Maintain accurate timekeeping	System synchronisation; Data coherence	Timing accuracy; Synchronisation methods

5.2 AI Technologies

AI technologies are playing an increasingly significant role in shaping the future of the Space Metaverse. In this section, some key AI technologies that are being utilised and developed for various applications within the space domain are introduced. Table 5 outlines the advantages and disadvantages of various AI technologies used in space exploration.

AI encompasses a diverse range of techniques and technologies that play a crucial role in advancing space exploration and mission success. Machine Learning (ML) enables spacecraft systems to learn from data, facilitating tasks like data analysis, anomaly detection, and predictive maintenance without explicit programming. Deep Learning, a subset of ML, leverages neural networks with multiple layers for intricate pattern recognition, image analysis, and natural language processing. One ML algorithm using Reinforcement Learning empowers autonomous spacecraft control, robotic exploration, and decision-making by training agents to make sequential decisions through interactions with their environment. Natural Language Processing (NLP) facilitates human-computer communication in space and aids in processing textual data. Computer Vision techniques analyse space mission images and videos, identifying objects and anomalies. AI-driven autonomy enables spacecraft and robots to make independent decisions and perform tasks without human intervention, thus enhancing adaptability. Predictive Analytics leverages historical data to forecast future events, optimising mission planning, resource allocation, and risk assessment. Cognitive Computing simulates human thought processes for complex problem-solving and data analysis.

Swarm Intelligence draws inspiration from collective behaviour in nature, enabling spacecraft formations, distributed sensing, and collaborative exploration. Genetic Algorithms mimic natural selection processes to optimise solutions for mission planning and system design. Fuzzy Logic handles imprecise data in uncertain environments, making decisions based on degrees of truth.

Quantum Computing, in its early stages, holds the potential to revolutionise complex calculations required for space missions, including trajectory optimisation and quantum system simulation. Multi-Agent Systems involve multiple autonomous agents collaborating to achieve shared goals, enhancing exploration and data collection. Explainable AI provides explanations for critical decisions, ensuring transparency and safety in space missions.

Swarm Robotics sees multiple robots employing AI algorithms to complete tasks, such as planetary surface exploration or structure construction. Evolutionary Algorithms, similar to genetic algorithms, evolve solutions over time to optimise spacecraft designs and mission planning. Semantic Reasoning allows AI systems to reason and make inferences based on semantic information, aiding in knowledge representation and decision support. These AI techniques collectively shape the future of space exploration, offering unprecedented capabilities for scientific discovery and technological innovation.

These AI technologies are collectively pushing the boundaries of space exploration, enabling innovative missions, efficient operations, and expanding our understanding of the cosmos in the Space Metaverse.

Table 5. A Summary of AI Technology

AI Technology	Advantages	Disadvantages
Machine Learning (ML)	Automated insights; Adaptability	Data dependency; Overfitting risk
Deep Learning	Complex pattern recognition; Enhanced image analysis; NLP capabilities	Data hunger; High computational complexity
Reinforcement Learning	Autonomous decision-making; Exploration in dynamic environments	Training complexity; Limited interpretability
Natural Language Processing (NLP)	Enhanced communication; Textual data processing capabilities	Language nuances; Ambiguity

Computer Vision	Image and video analysis; Object recognition; Anomaly detection	Data requirements; Computational complexity
Autonomous Systems	Independent operation; Adaptability	Decision uncertainty; Safety concerns
Predictive Analytics	Future event prediction; Mission planning optimisation	Data assumptions; Limited historical data
Cognitive Computing	Complex problem-solving; Decision-making support	Computational complexity; Interpretation challenges
Swarm Intelligence	Cooperative exploration; Efficient task execution	Algorithm complexity; Communication resources
Genetic Algorithms	Optimisation; Evolutionary design for space missions	Convergence challenges; Limited applicability
Fuzzy Logic	Uncertainty handling; Decision-making in vague environments	Complexity in rule formulation; Limited suitability
Quantum Computing	Complex calculations; Quantum system simulation	Early-stage development; Technical challenges
Multi-Agent Systems	Collaborative exploration; Enhanced data collection capabilities	Coordination complexity; Communication overhead
Explainable AI	Transparent decision-making; Safety in critical applications	Computational overhead; Interpretability trade-offs
Swarm Robotics	Cooperative task execution; Enhanced exploration capabilities	Communication complexity; Scalability limitations
Evolutionary Algorithms	Optimisation; Design evolution for spacecraft	Convergence challenges; Limited applicability
Semantic Reasoning	Semantics-based inferences; Decision support	Complexity in knowledge representation; Limited applicability

6 Two Space Metaverse Case Studies

In this section, we will present two case studies, namely "Designing a Lunar Exploration Rover" and "AI-Driven Satellite Constellation Management".

6.1 Case Study: Designing a Lunar Exploration Rover

As suggested above, the field of space exploration has been significantly transformed by the integration of advanced technologies, including VR, AR, and sophisticated simulations. This case study focuses on the application of these technologies in the context of spacecraft design and simulation. By leveraging these tools, space agencies and organisations have been able to revolutionise the way spacecraft are conceptualised, designed, and tested, leading to improved efficiency, reduced costs, and enhanced mission success rates.

Traditionally, spacecraft design has been a complex and iterative process involving physical prototypes, extensive testing, and considerable time and resources. With the advent of electronic systems and technology, the aerospace industry has transitioned towards virtual design and simulation methodologies. This shift has enabled engineers and designers to create, visualise, and assess spacecraft components and systems in a digital environment before the physical construction phase.

As shown in Figure 3, the case of designing a lunar exploration rover exemplifies the transformative impact of VR and AR technologies on spacecraft design and simulation. By leveraging these tools, space agencies can accelerate the design process, reduce costs, enhance collaboration, and ultimately develop spacecraft that are more capable and reliable. As electronic systems and technology continue to evolve, the future of spacecraft design and simulation holds immense potential for pushing the boundaries of space exploration and innovation.

In a remarkable feat, SpaceTech Innovations (STI), a leading space agency, tackled the challenge of developing a state-of-the-art lunar exploration rover for scientific experiments on the Moon's harsh terrain. Their mission was to create a rover capable of withstanding extreme temperatures, navigating rugged landscapes,

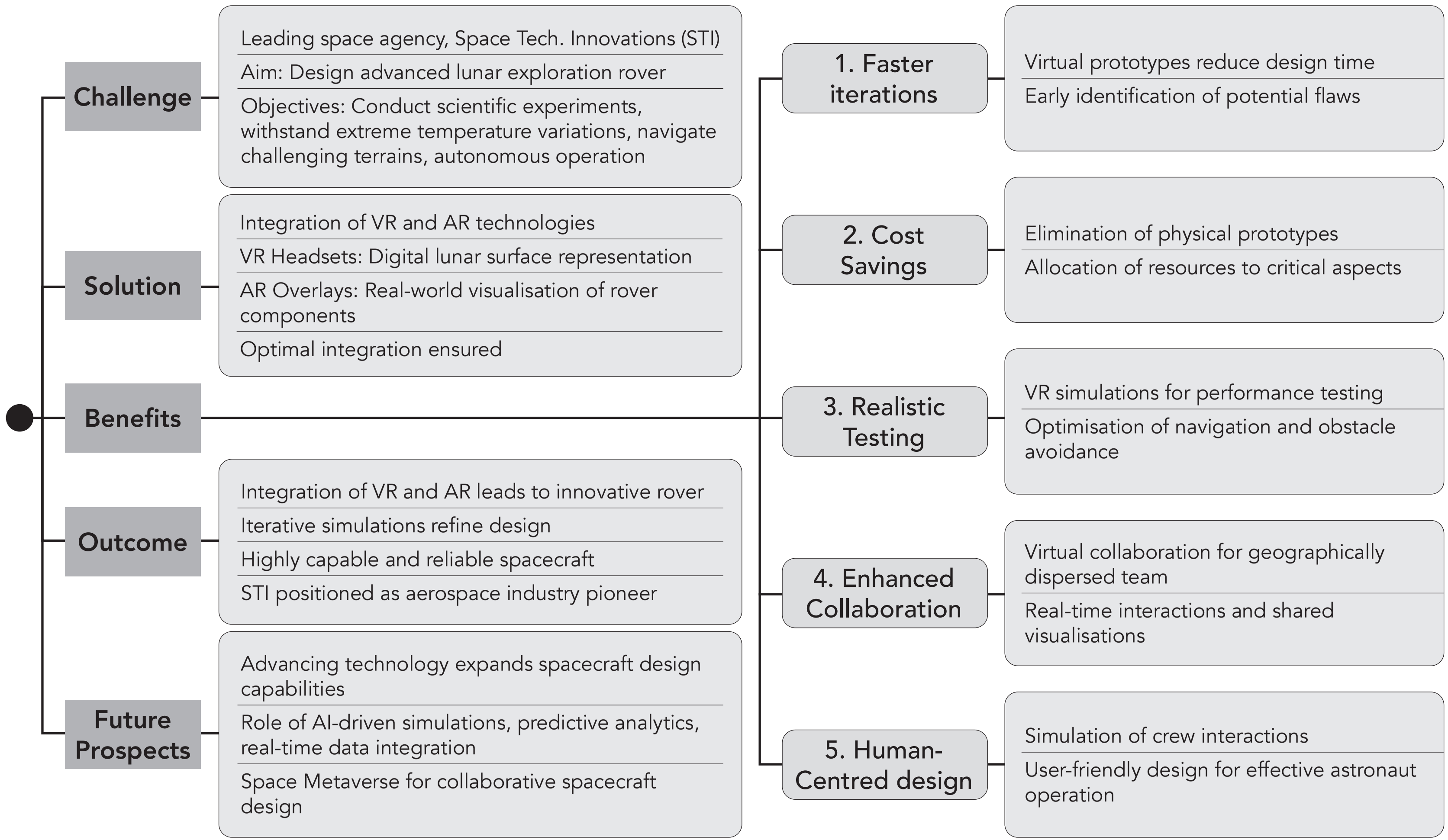


Figure 3. Mind Map for Case Study of Designing a Lunar Exploration Rover

and conducting complex experiments autonomously.

To meet this challenge, STI harnessed the power of VR and AR technologies. VR immersed the team in a lunar simulation, offering a vivid view of potential rover obstacles and complexities, while AR allowed them to seamlessly integrate rover components into real-world environments.

This innovative approach brought substantial benefits. It accelerated design iterations by creating virtual prototypes, leading to faster refinements and significant cost savings. Realistic VR simulations facilitated testing in lunar scenarios, refining navigation algorithms and obstacle avoidance. Collaborative AR-based design improved communication and decision-making among geographically dispersed teams. Crucially, human-centered design ensured astronaut-friendly controls. The outcome was extraordinary, STI developed an innovative lunar rover that met its mission objectives, solidifying its status as an aerospace pioneer.

Looking forward, spacecraft design and simulation will advance further with AI-driven simulations, predictive analytics, and real-time data integration. The Space Metaverse holds the potential to become a global collaborative platform for spacecraft design, fueling the future of space exploration and innovation.

6.2 Case Study: AI-Driven Satellite Constellation Management

The integration of AI systems into the Space Metaverse has opened new horizons for space exploration, communication, and research. This case study examines the intricate process of designing and implementing intelligent algorithms and systems that power the Space Metaverse, showcasing their vital role in shaping the future of space technology.

The Space Metaverse, a digital realm merging virtual and physical space, offers unprecedented opportunities for collaboration, data sharing, and exploration. AI, with its ability to analyse vast amounts of data, make predictions, and adapt to changing conditions, has emerged as a critical component in harnessing the potential of the Space Metaverse.

Designing AI systems for the Space Metaverse involves a unique blend of cutting-edge technology and space exploration. Figure 4 demonstrates how intelligent algorithms can transform space operations, optimise satellite constellations, and unlock new possibilities for space-based communication and exploration. As AI continues to evolve, its role in the Space Metaverse is set to expand, shaping the future of space technology and exploration.

NovaSat Dynamics, a pioneering space technology company, set out on a bold mission to efficiently manage a constellation of communication satellites orbiting Earth. Their challenge was to design an AI-driven system that could autonomously optimise satellite positioning, communication routing, and resource allocation for seamless global coverage with minimal signal interference.

Collaborating with AI experts and space engineers, the company developed SatAI, which harnesses machine learning algorithms to analyse real-time data from satellites, Earth's surface, and the space environment. SatAI predicts optimal satellite configurations considering user demand, orbital dynamics, and signal obstructions.

The innovative solution brought significant benefits, which include enhanced efficiency through real-time constellation adjustments, adaptability to changing conditions, data-driven decision-making, autonomous operation, and scalability. It has also revolutionised satellite constellation management, establishing

NovaSat Dynamics as a leader in satellite technology.

Looking forward, this case highlights the potential of AI in shaping the Space Metaverse, enabling complex tasks like autonomous space exploration, predictive maintenance, and intelligent resource allocation for interplanetary missions, ushering in a new era of space technology.

7 Discussion

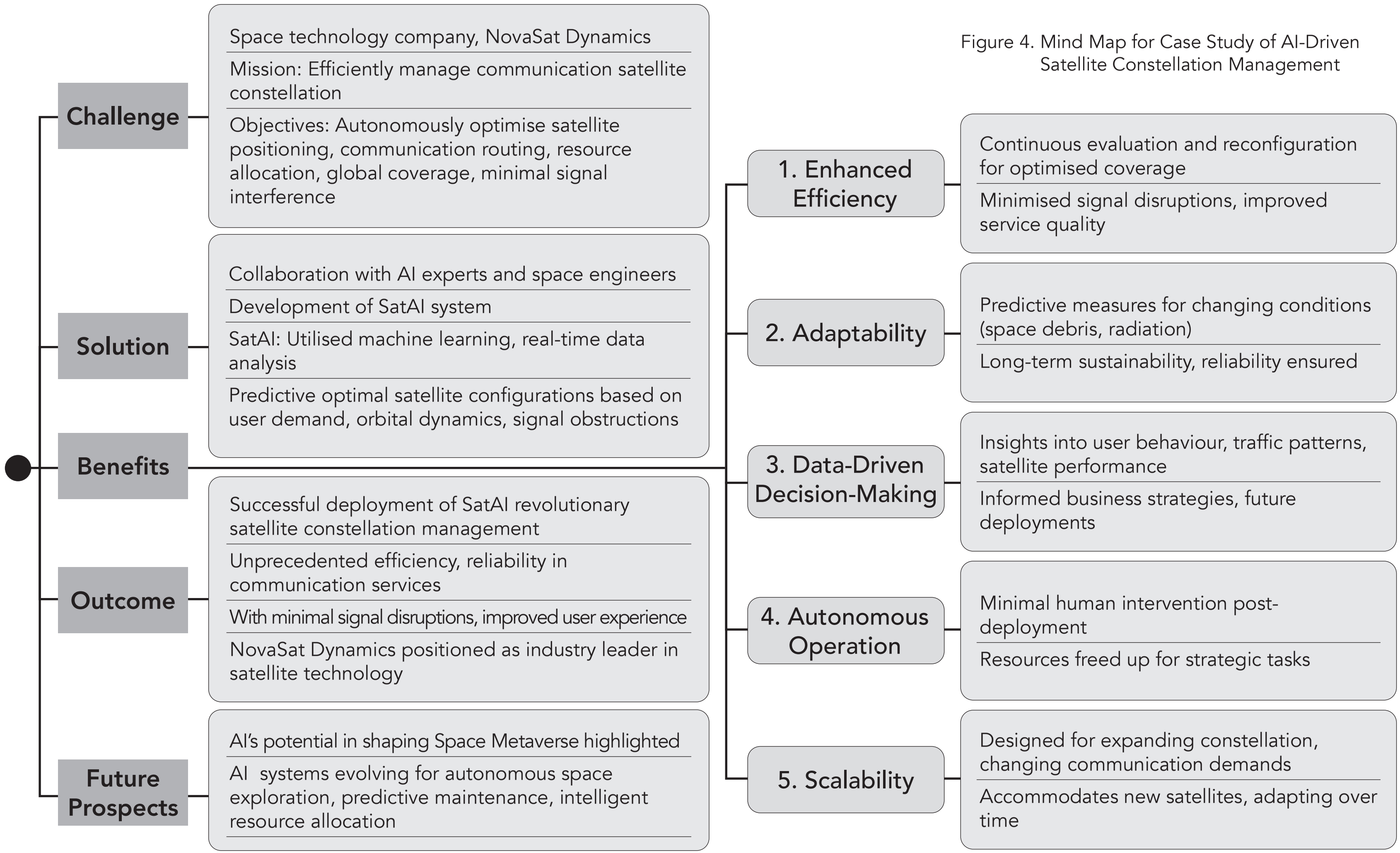
This section focuses first on Space Metaverse-related issues and then on the Space Metaverse and Industry 4.0, encompassing an in-depth exploration of the concept. We will analyse these issues and suggest solutions, while also examining the various potentials, challenges, and complexities of the revolutionary concept of Industry 4.0 for the Space Metaverse. We will explore the Industry 4.0 domains of space innovation, procedure utilisation, and human-technology collaboration.

7.1 Space Metaverse-Related issues

The exploration of the Space Metaverse through the applications of electronic systems and AI technology represents a paradigm shift in our approach to space exploration, research, and innovation. The integration of VR, AR, AI, and data analytics has opened up new dimensions of understanding of and interacting with the cosmos. This section discusses the key findings and implications of our study, highlighting the transformative potential of these technologies in shaping the future of interstellar exploration.

The Space Metaverse serves as a digital realm where

Figure 4. Mind Map for Case Study of AI-Driven Satellite Constellation Management



scientists, engineers, and enthusiasts can simulate, analyse, and innovate in the field of space exploration. VR and AR technologies enable immersive simulations of extraterrestrial environments, providing unprecedented opportunities for astronaut training and mission preparation. The advanced capabilities of AI and data analytics allow for the rapid processing and analysis of astronomical data, leading to accelerated discoveries and insights into celestial phenomena.

One of the central findings of our study is the accelerated pace of celestial research facilitated by electronic systems and technology. AI-powered algorithms can sift through vast datasets collected from telescopes and space probes, identifying patterns and anomalies that would be challenging for human researchers to detect. This not only expedites scientific discovery but also broadens our understanding of cosmic phenomena, from black holes and neutron stars to distant galaxies. Moreover, the integration of electronic systems has revolutionised spacecraft design and engineering within the Space Metaverse. Engineers can now create detailed virtual models of spacecraft components, test their functionality, and optimise their performance before physical prototypes are built. This iterative approach results in more robust and efficient spacecraft, ensuring the success of interstellar missions while minimising risks.

The ethical implications of the Space Metaverse cannot, however, be overlooked. As individuals engage with simulated celestial bodies in immersive environments, questions arise about responsible use of these digital spaces and potential consequences for natural cosmic processes. Striking a balance between exploration, preservation, and responsible stewardship of these virtual realms is essential to ensure the long-term sustainability of space-related activities.

Following are some issues for discussion.

1. **How do electronic systems and AI technology contribute to the Space Metaverse?**

   Electronic systems, including VR, AR, AI, and data analytics, play a pivotal role in the Space Metaverse. They enable realistic simulations of space environments, accelerate celestial research through data analysis, revolutionise spacecraft design, and enhance astronaut training. These technologies create a digital ecosystem where innovative ideas, simulations, and discoveries thrive.

2. **What are the implications of accelerated celestial research?**

   The accelerated pace of celestial research enabled by electronic systems leads to quicker discoveries of and deeper insights into the universe. AI-driven data analysis can uncover hidden patterns and cosmic phenomena that may have remained elusive. This rapid progress reshapes our understanding of the cosmos and paves the way for groundbreaking discoveries.

3. **How does the integration of electronic systems and AI impact spacecraft design?**

   Electronic systems facilitate detailed virtual modelling, testing, and optimisation of spacecraft components. This results in the creation of more efficient and durable spacecraft, minimising risks associated with space missions. The iterative design process ensures that interstellar exploration is driven by advanced technology and robust engineering.

4. **What ethical considerations arise in the Space Metaverse?**

   The immersive nature of the Space Metaverse raises ethical questions about responsible exploration and preservation. Engaging with simulated celestial bodies prompts discussions about the ethical implications of resource extraction, environmental impact, and potential disruption of natural cosmic processes.

5. How does the Space Metaverse contribute to public engagement and education?

The Space Metaverse has the potential to inspire and educate the public about space exploration. VR and AR experiences provide immersive journeys to distant galaxies, sparking interest in STEM fields and fostering a sense of wonder. This engagement encourages future generations to pursue careers in science, technology, engineering, and mathematics.

6. What role do interdisciplinary collaborations play in the Space Metaverse?

The integration of electronic systems encourages interdisciplinary collaborations among scientists, engineers, technologists, and artists. This convergence of expertise drives innovation, allowing different fields to contribute to the exploration of the cosmos. Interdisciplinary collaborations generate novel solutions and push the boundaries of space exploration capabilities.

In conclusion, the exploration of the Space Metaverse through the applications of electronic systems and technology signifies a transformative era in space exploration. The convergence of VR, AR, AI, and data analytics shapes our understanding of the cosmos, accelerates research, enhances spacecraft design, and inspires future generations. While ethical considerations and interdisciplinary collaborations present challenges, the potential for unlocking the mysteries of the universe and expanding human horizons is boundless. The Space Metaverse exemplifies the harmonious integration of technology and exploration, pointing the way towards a future where the cosmos is accessible and comprehensible as never before.

7.2 Space Metaverse and Industry 4.0

The Space Metaverse is a brand-new virtual universe that leverages cutting-edge VR technology, AI, and machine learning to take industrial manufacturing and space exploration to a whole new dimension. In this dimension, we can conduct experiments, design, and manufacturing more efficiently. In this virtual world, we can simulate various real-world conditions, including gravity, atmosphere, and lighting, which allows us to carry out a wide range of experiments and tests with greater accuracy and speed.

Figure 5(a) illustrates the concept of Industry 4.0 within the context of the Space Metaverse, showcasing the transformative impact of advanced digital technologies on space exploration and industrial processes. In the real world, Industry 4.0 has already begun to transform our lives and work. Industry 4.0 plays a significant role in the Space Metaverse, taking this transformation to new heights. By using AI and machine learning algorithms, we can achieve smarter and more automated manufacturing and workflows which not only increases our work efficiency but also reduces errors and costs.

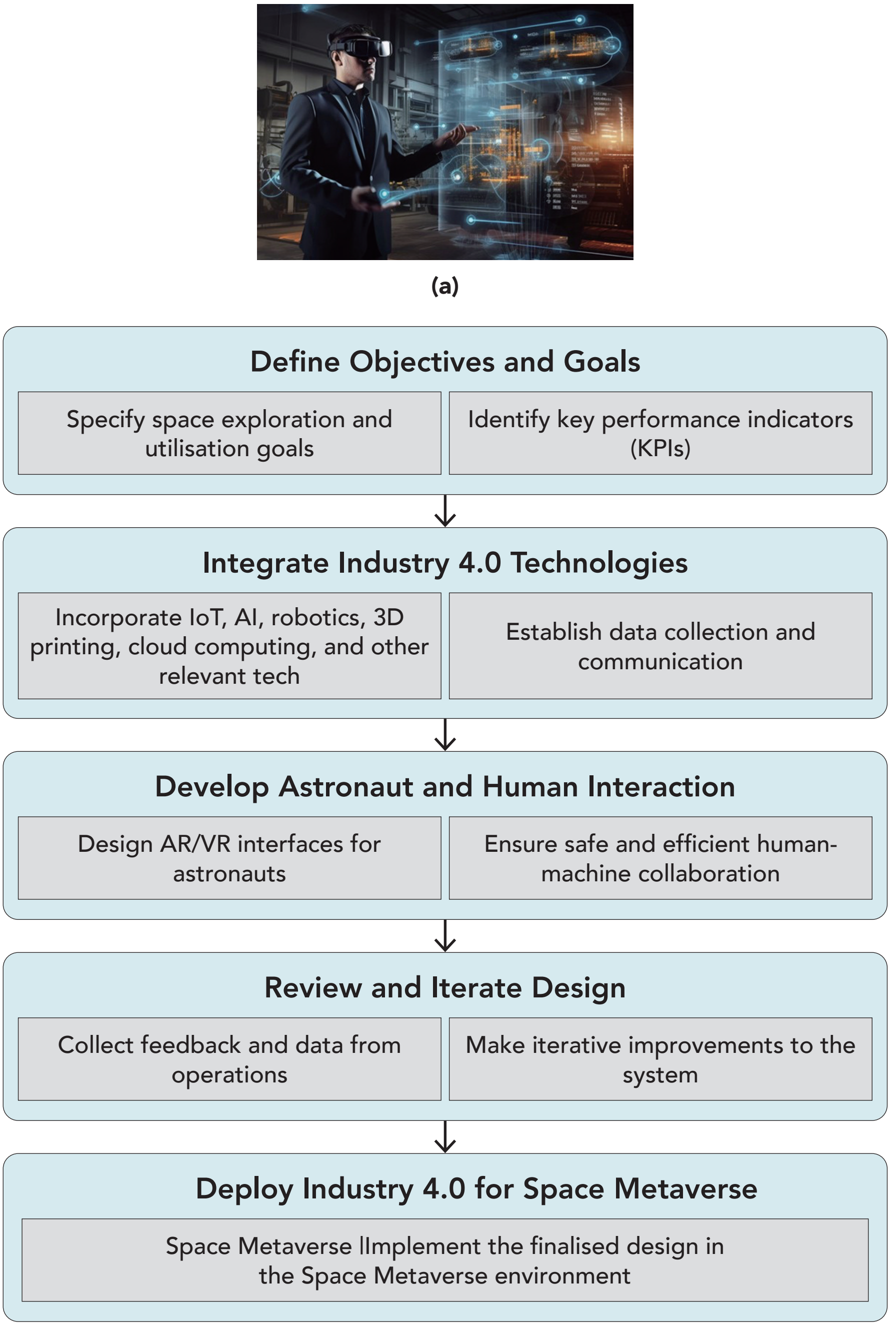
In the fusion of the Space Metaverse and Industry 4.0, we can see a bright new future beckoning to us. In this future, we can utilise VR technology to conduct experiments and manufacturing in simulated environments. At the same time, we can harness AI and machine learning algorithms to achieve more efficient workflows. This new way of working will enable us to better utilise resources, improve work efficiency, reduce costs, and reveal new paths for innovation.

Figure 5(b) outlines the sequential steps involved in designing and implementing "Industry 4.0 for the Space Metaverse", providing a structured approach for integrating advanced technologies into the mission of space exploration and utilisation.

The development of "Industry 4.0 for the Space Metaverse" is a multifaceted process that encompasses several crucial stages. Firstly, the endeavour commences with the crucial task of defining objectives and goals. This initial step entails setting precise and visionary targets for the space mission within the Space Metaverse, while concurrently identifying key performance indicators to measure progress and success.

Subsequently, the integration of Industry 4.0 technologies becomes paramount. Various cutting-edge technologies such as IoT, AI, robotics, and cloud computing are intricately woven into the fabric of the Space Metaverse. This integration serves to facilitate data collection and establish robust communication mechanisms, underpinning the efficient functioning of the entire system. Additionally, ensuring seamless interaction between astronauts and the technology-rich environment of the Space Metaverse is a pivotal aspect of the design, where the focus is on designing intuitive interfaces and interactions, prioritising safety and operational efficiency. Astronauts and other human personnel must be equipped with tools and systems that empower them to navigate and collaborate effectively within this advanced space ecosystem.

Throughout this intricate journey, a further critical phase involves constant evaluation and refinement. The review and iteration of the design process are fundamental, as they entail collecting feedback and valuable data from ongoing operations. The insights thereby derived drive iterative improvements, honing the system's capabilities and adaptability to real-world challenges. Ultimately, the culmination of these efforts leads to the deployment of "Industry 4.0 for the Space Metaverse". The finalised design, refined through iterative processes and meticulous planning, is then deployed within the Space Metaverse environment. This deployment marks the realisation of a vision where advanced Industry 4.0 technologies seamlessly blend with the mission of



(a)

(b)

Figure 5. The Concept of Industry 4.0 for the Space Metaverse

space exploration and utilisation, opening doors to a new era of possibilities in the cosmos.

In summary, the fusion of the Space Metaverse and Industry 4.0 opens up a completely new future for us. In this future, we can use VR technology, AI, and machine learning algorithms to achieve more efficient and intelligent ways of working. This new way of working will enable us to better utilise resources, improve work efficiency, reduce costs, and pave the way for innovation. Through this technology, we can simulate complex natural and societal phenomena, understand them, and find solutions to problems. In conclusion, the fusion of the Space Metaverse and Industry 4.0 reveals a future filled with endless possibilities and opportunities.

8 Conclusion and Future Prospects

Table 6. Summary of Future Prospects

Future Prospects	Description	Potential Impact
Enhanced Interstellar Exploration	Advanced VR and AR tech. for immersive cosmic experiences	Deeper insights, informed decision-making, higher engagement in space missions
Holistic Spacecraft Design and Testing	Sophisticated simulations for efficient spacecraft development	Reduced costs, shortened timelines, increased mission success rates
AI-Driven Space Exploration	AI integration for autonomous space exploration	Improved data analysis, adaptive spacecraft and rovers, real-time decision-making
Educational Transformation	Immersive and interactive learning experiences	Fostering STEM education, nurturing the next generation of space enthusiasts
Deepening Public Engagement	Virtual tours, interactive exhibits, and outreach	Generating public interest, bridging the gap between experts and the general public

The exploration of the Space Metaverse through the applications of electronic systems and AI technology opens up a realm of exciting future prospects that in turn hold the potential to redefine space exploration, scientific discovery, technological innovation, and human interaction with the cosmos. Table 6 highlights five future prospects and how they outline a trajectory toward a future where the Space Metaverse plays a pivotal role in advancing our understanding of the universe and shaping the course of interstellar exploration.

1. **Enhanced Interstellar Exploration:** The future of the Space Metaverse promises to revolutionise interstellar exploration by enabling unprecedented levels of immersion and realism. Advanced VR and AR technologies will transport researchers, scientists, and enthusiasts into virtual cosmic environments, allowing them to experience celestial phenomena first-hand. This immersive experience will lead to deeper insights, more informed decision-making, and a higher degree of engagement in space missions.
2. **Holistic Spacecraft Design and Testing:** As electronic systems and technology continue to advance, spacecraft design and testing will become more comprehensive and efficient within the Space Metaverse. Engineers will harness sophisticated simulations to model various scenarios, predict spacecraft behaviour, and optimise mission parameters. This approach will significantly reduce development costs, shorten timelines, and increase the success rate of space missions.
3. **AI-Driven Space Exploration:** The integration of AI into the Space Metaverse will pave the way for autonomous space exploration. AI algorithms will analyse massive datasets collected from virtual cosmic environments, identifying patterns, anomalies, and potential discoveries.

AI-driven spacecraft and rovers will navigate space autonomously, adapting to dynamic conditions and making real-time decisions.

4. **Educational Transformation:** The future Space Metaverse will transform education by providing immersive and interactive learning experiences. Students of all ages will have the opportunity to explore cosmic phenomena, conduct virtual experiments, and participate in simulated space missions. This will ignite a passion for science, technology, engineering, and mathematics (STEM) fields, nurturing the next generation of space pioneers.

5. **Deepening Public Engagement:** Future prospects for the Space Metaverse include heightened public engagement and outreach initiatives. Virtual tours, interactive exhibits, and educational programmes will captivate the public imagination, fostering a sense of wonder and curiosity about the cosmos. Increased engagement will bridge the gap between experts and the general public, generating support and enthusiasm for space exploration.

The future prospects of exploring the Space Metaverse through electronic systems and AI technology are boundless. This exciting trajectory promises to reshape the landscape of space exploration, redefine scientific methodologies, inspire technological innovation, and ignite a sense of awe and curiosity about the universe. As humanity continues to venture into the digital realm of the Space Metaverse, it will unlock new frontiers of knowledge, ushering in an era of unprecedented discovery and exploration that transcends the boundaries of our physical world.

In the grand tapestry of human exploration, the emergence of the Space Metaverse stands as a transformative chapter, where electronic systems and AI technology have converged to create a digital cosmos ripe for discovery, innovation, and awe-inspiring revelations. In this study, we have examined the boundless potential of the Space Metaverse, a realm where VR, AR, AI, and advanced data analytics converge to redefine our understanding of the universe.

The applications of electronic systems and AI technology within the Space Metaverse have ignited a paradigm shift in the way we approach space exploration. Our journey through this digital frontier reveals the power of immersive simulations that mirror celestial environments and enable us to simulate cosmic phenomena, design spacecraft, and unravel the mysteries of the cosmos. The fusion of human ingenuity and technological prowess within the Space Metaverse has paved the way for unprecedented scientific breakthroughs and groundbreaking discoveries. As we navigate the vast expanse of virtual space, we have witnessed the collaborative spirit that propels us forward. Researchers, engineers, and enthusiasts from across the globe have united within the digital confines of the Space Metaverse, transcending geographical barriers to collectively unravel the secrets of the universe. This collaborative synergy has not only accelerated the pace of scientific progress but also nurtured a sense of camaraderie and shared purpose that spans the cosmos.

The implications of our exploration reach far beyond the digital realm. The Space Metaverse has the power to transform space missions, spacecraft design, and interstellar exploration. It offers a glimpse into a future where AI-driven spacecraft autonomously navigate the cosmos, where immersive simulations redefine the boundaries of learning and education, and where our understanding of the universe is deepened in ways previously thought impossible. Yet, as we embrace the possibilities, we must also confront ethical considerations and challenges. The responsible stewardship of virtual cosmic environments and the preservation of their integrity become paramount as we journey deeper into the Space Metaverse. As our understanding of this realm grows, so too must our commitment to its sustainable management and ethical exploration.

In our final discussion, the exploration of the Space Metaverse through electronic systems and AI technology is seen as testament to humanity's insatiable curiosity and unyielding spirit of exploration, and to our ability to transcend the limits of the physical world and venture into the uncharted territories of the digital cosmos. We stand on the edge of a new era, one where the frontiers of space are no longer bound by distance but are accessible through the power of human ingenuity and technological innovation. The Space Metaverse beckons us to venture further, dream bigger, and embrace the infinite possibilities that lie before us.

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Chapter 10

The Space Metaverse in Entertainment and Lifestyle

Abstract

Previously, we have explored the Space Metaverse through the applications of Blockchain, Industry 4.0, AI, and electronic systems, which open up a paradigm of exciting prospects for future deep-space exploration, scientific discovery, technological innovation, and human interaction with the cosmos. In this chapter, we discuss the Space Metaverse in entertainment and lifestyle which is transforming education, healthcare, movies, music, gaming and culture, as well as playing a pivotal role in advancing our understanding of the universe and shaping the course of interstellar exploration and deep space. The Space Metaverse, which is also known as the Space Verse, is in the early stage of space research and development, and many new innovations are emerging from various countries leading the new space race.

1 Introduction

"We've got a ways to go," said Neal Stephenson when he discussed his metaverse vision with Chris Cox, the chief product officer at Meta, on January 18, 2023. Stephenson has worked for technology companies including rocket maker Blue Origin in recent years. "It's really just in the last couple of years that everything has come together," Stephenson commented further. He and Cox laid out an array of engineering breakthroughs needed to allow millions of people to move seamlessly through immersive virtual worlds displayed on head-mounted devices. Despite the burgeoning interest in the metaverse, there is a lack of discussion concerning the adoption intention of metaverse technology in the space environment within entertainment and lifestyle such as movies, game, music and education. While existing studies explore the potential of metaverse technology across various sectors, such as education, healthcare, music and gaming, a focused investigation into the opportunities and challenges specific to space explorations is lacking.

2 Metaverse, Entertainment and Lifestyles

2.1 Definition and Conceptualisation

The metaverse is a self-sustaining, temporal, and 3D immersive virtual shared space, fused by the physically persistent virtual space and virtually enhanced physical reality. It can be seen as a synthetic world of user-controlled incarnations, digital things, virtual environments, and other computer-generated elements, in which humans (represented by incarnations) can communicate, collaborate, and socialise with each other through any smart device using their virtual identities. The construction of the metaverse integrates the physical, human, and digital ternary worlds. The metaverse concept is not new in the context that science fiction writers and futurists have envisioned it for decades. Many of them have related their imaginations to deep space explorations to the Moon, Mars, and other planets.

2.2 Key Characteristics and Impacts of the Metaverse

As technology evolves, particularly in areas such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI), the Metaverse in the Space explorations are becoming more of a reality than a mere fantasy. The technologies involved can be generally classified as follows:

(i) Digital Twin Technology

Digital Twin (DT) technology plays a crucial role in reshaping the physical world into a virtual digital space and providing technical support for the construction of the metaverse, where the concept of the DT can be seen in the immediate sensing and communication between particles. When one particle is affected, another particle in a different location senses it and, at a certain point, the two particles achieve complete consistency, representing the alignment between the real and virtual worlds in the metaverse. Quantum entanglement can be viewed as a realisation of DTs and a manifestation of the metaverse.

In the Metaverse of Space exploration, it is essential to construct and study DT models which present both challenges and opportunities for future research and developments. Furthermore, DT technology is increasingly being combined with the extended reality (XR) paradigm, which encompasses VR, AR, and MR. XR allows for the manipulation of DTs and facilitates their direct interaction with the physical world, and vice versa. By integrating XR with DT technology, researchers and industry professionals in the space industry can create immersive and interactive experiences that bridge the gap between different planets in the metaverse.

(ii) Internet of Things Technology

We can see many IoT applications in satellites, ground stations communications, as well as Chinese and NASA space stations which rely on IoT sensors and actuators to navigate the spacecraft. However, overcoming remote sensing in outer galaxy is a major challenge. IoT can enable smarter communication environments by integrating technologies, improving energy and data transmission efficiency, optimising storage space, enhancing security, and enabling real-time control and analysis in future space exploration. IoT technology can be utilised for various purposes, such as monitoring the health and status of spacecraft, collecting data from sensors and instruments, managing communication networks, and facilitating autonomous operations. Integration of IoT with DT technology allows for real-time monitoring, analysis, and control of space systems, enabling efficient and intelligent decision-making, as well as machine-man interactions in deep-space exploration missions.

In summary, the implementation of metaverse technology to solve space problems involves a combination of DT, XR and IoT technologies. These interconnected approaches provide the foundation for creating virtual representations, immersive experiences, and smart communication environments, ultimately enhancing our understanding, exploration, and utilisation of Space. Figure 1 illustrates the world of immerse technologies for deep space explorations.

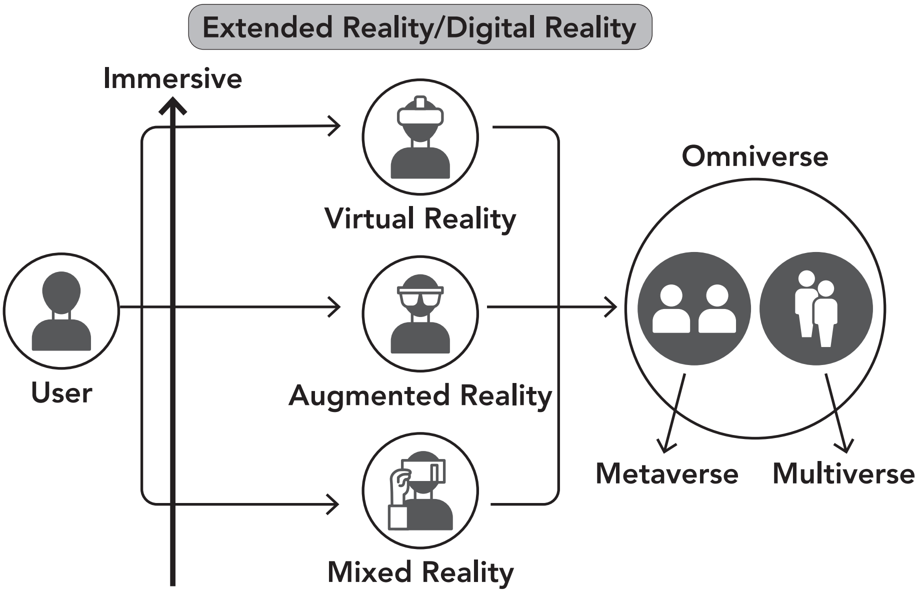


Figure 1. Immersive Technologies

The importance of the metaverse has been forecasted by many researchers and in numerous reports. Metaverse Statistics 2024 reported the following statistics in relation to metaverse games.

> The global number of metaverse users is predicted to exceed 1.4 billion by 2030, with user penetration growing three-fold and achieving 18% saturation.
>
> 17% of IT companies are investing or planning to invest in the metaverse.
>
> The metaverse gaming market is forecast to reach $13.84 billion in 2023 and grow to $710.21 billion by 2027.
>
> 36% of millennials and 31% of Gen Zers reported being very interested in attending a museum within the Metaverse.
>
> Over 77% of people expressed concern about the metaverse's harmful impact on society.

It is estimated that 25% of the population will spend at least an hour in the metaverse every day by 2026.

2.3 Movies Related to the Metaverse and Space

Movie entertainment related to deep space and future world are the most popular science fictions films which feature the metaverse. The following are some classic examples. *Ready Player One* (2018) describes a dystopian future where people escape their harsh reality by entering a virtual reality world called the OASIS. The story follows a young boy as he embarks on a quest within OASIS to find a hidden Easter egg left by its creator. *Tron* (1982) follows a computer programmer who is transported into a virtual world inside a computer where he must compete in deadly games in order to escape back to the real world. *The Matrix* trilogy (1999-2003) takes place in a dystopian future where humans are unknowingly trapped in a simulated world called the Matrix while their bodies are used as a power source by sentient machines. *Inception* (2010), though not explicitly about the metaverse, follows a group of skilled individuals who can enter people's dreams and manipulate them to extract information or implant ideas. *Minority Report* (2002) is a futuristic neo-noir film set in a society where crimes can be predicted and prevented using precognitive individuals known as "pre-cogs." A police officer becomes a fugitive after being accused of a future murder. The film examines themes of free-will and surveillance, as well as the implications of using advanced technology to predict and control human behaviour. *The Thirteenth Floor* (1999) focuses on a prime suspect in a murder which occurs in a virtual world replicating Los Angeles, leading to a mystery that blurs the lines between reality and simulation.

2.4 Gaming Related to the Metaverse and Space

The following are some classic games related to the metaverse. *No Man's Sky* (2016) allows players explore a virtually infinite universe, gather resources, trade, and engage in combat, while navigating diverse planets and ecosystems in this procedurally generated open-world game. *EVE Online* (2003) constructs a science fiction universe, where players pilot their spaceship, engage in trading, mining, and combat, and participate in a player-driven economy and politics in this immersive massively multiplayer online game. *Elite Dangerous* (2014) takes players to the stars in a realistic rendition of the Milky Way galaxy, where they pilot their spacecraft, engage in trading, mining, and exploration, and experience a deep and immersive space simulation. *Star Citizen* (in development) lets players embark on an ambitious space simulation adventure, piloting various spacecraft, engaging in combat, exploring planets, and interacting with other players in a highly detailed and persistent online universe.

All the above movies and games provide players with the opportunity to explore and interact within virtual universes, allowing for a sense of immersion and shared experiences, where players engage in various activities and interact with each other. They provide fun, entertainment, imagination, and education, enriching players' interests and imaginations, and motivating them to join in these space explorations.

2.5 Metaverse Concerts

Music is a component of the movies and games in the metaverse, where it can be an art or culture itself or can be part of the entertainment. The following are two interesting examples. Travis Scott's Fortnite Concert "Astronomical" (2020), taking place within the popular video game *Fortnite*, accommodated millions of viewers, at the time setting a record for the largest concurrent audience in a virtual event. Lil Nas X's Roblox Concert (2020) was held on the online gaming platform Roblox. "Marshmello's Fortnite Concert" (2019) was presented in the early era of the metaverse but millions of players attended the virtual show.

Today, metaverse concerts blur the lines between gaming, music, and live events which can be used to simulate an outer space environment, opening up new possibilities for artists to reach their fans and create immersive experiences that go beyond traditional live performances. An example of the latest such metaverse companies is Muxic (HK) Limited, the first Hong Kong technology company producing a DuoVerse (Muxic's patented metaverse concert technology: *www.muxic.io*). It is the first of its kind, providing a unique, immersive, and interactive experience for concert-goers around the world. By leveraging cutting-edge motion capture suits, Muxic enables artists, including Tyson Yoshi and Serrini, to perform live in both physical and virtual spaces simultaneously. This innovative fusion of physical and digital realities, or dual reality, is a groundbreaking disruption in the live entertainment industry. The technology's advanced server topology, a first in the metaverse space, allows it to host an unprecedented number of attendees without experiencing latency or lag, a common issue in large-scale virtual events. Furthermore, Muxic's AI-powered Non-Playable Characters (NPCs) enhance the concert experience by guiding users, providing an industry-first, AI-powered personalised concierge service. This metaverse solution allows for a high degree of customisation and interaction, including avatar customisation, live chat, animated emojis, and gamification elements like sponsored virtual gifts that can be redeemed in real life. These features not only enhance user engagement but also open up new avenues for innovation and entrepreneurship, sponsorship and advertising, redefining the business model for virtual events delivered in a space environment.

The ability to customise space avatars and interact with the performer and other attendees in real time provides an immersive, social experience that goes far beyond traditional live streaming. This metaverse technology offers considerable benefits for all stakeholders in deep space explorations. For artists, it provides a new avenue to reach out to global audiences without the constraints of geography. For concert-goers, it offers a unique, interactive experience that goes beyond passive viewing. For young entrepreneurs, organisers, and sponsors, it opens up new innovations to explore space business opportunities. Moreover, by making concerts accessible to anyone with an internet connection, the technology has significant social impact potential, democratising access to cultural events and experiences (*www.muxic.io*).

Figure 2. Avatars Created for Tyson Yoshi and Serrini for their "DuoVerse" Music Show in February 2023 (Image created by MUXIC)

Figure 3. This "DuoVerse" in February 2023 was first of its kind in the world. (Image created by MUXIC)

2.6 AI-Enhanced Personalised Information Display Panel

Among one of the products from Muxic is the AI-Enhanced Personalised Information Display Panel (AIKOL) which can be trained as a tailor-made concierge for specific fields and companies. It leverages natural language processing and AI technologies and hence is marketable in the metaverse in various ways. For example, the metaverse platform of Muxic can apply its AI-enhanced technology to AIKOL to deliver personalised and high-quality responses to user queries. This can be particularly useful in the metaverse, where users are looking for quick and relevant information. In the domain of entertainment, this technology can collaborate with content creators and production studios to create unique and engaging audio-visual experiences in the space environment. For example, it can provide voice-overs for virtual characters or create custom sound effects for immersive environments. In the field of education, it can create interactive and engaging learning experiences through voice-overs for educational videos or creating custom sound effects for immersive space simulations.

Figure 4. AIKOL can be presented in digital human avatar form, such as concierge and service support. (Image created by MUXIC)

The AIKOL architecture integrates with secure voice models, real-time streaming capabilities, and advanced features such as watermarking and auto-tuning, offering a wide range of space entertainment industry applications and opening up new possibilities in the metaverse for creative expression and audio manipulation. In the music and recording industry, the system's ability to change voices can be leveraged for creative musicians, singers, and producers who can use the system to experiment with different vocal styles, harmonies, and character voices. This technology can also apply in post-production, enabling adjustments to singers' voices for better matching with the desired musical genres and lyrics of a deep Space Metaverse.

Figure 5. In the Space Metaverse, with their voice trained by an AI voice change system, a popular personality can speak and sing in different languages. (Image created by MUXIC)

3 The Space Verse

Although the term "Space Verse" is not commonly used in the space industry, it can be broadly defined as deep space explorations in the metaverse. The concept of deep space is generally defined as the region beyond the Earth's atmosphere, where stars, planets, and other celestial bodies exist. Space is often divided into different regions based on their distance from the Earth, such as the low Earth orbit, geostationary orbit, and deep space. The history of space exploration dates back to the

20th century, when the Soviet Union launched the first artificial satellite, Sputnik 1, in 1957. Since then, several countries have launched satellites, probes, and manned missions to explore space. The space industry has evolved significantly over the years, with advancements in technology enabling more sophisticated space missions and operations such as satellite launches, Moon and Mars space exploration, space tourism, and space mining. The key components of the space industry include launch vehicles, satellites, spacecraft, and ground stations. The industry relies on advanced technologies such as 5G, big data, drones, quantum computing, and AI to support and improve space operations.

While avatars are more often employed in the metaverse, robots may play a more significant role in both the metaverse and Space Verse. In the metaverse, robots can be used to create immersive experiences and enhance user interactions. For example, chatbots and NPCs can be used to engage and interact with people in a virtual world. Additionally, AI-powered engines can be used to create accurate avatars that emulate physical and emotional characteristics like facial expressions and body language. In the Space Verse, robots can be used to perform tasks that are too dangerous or difficult for humans. For example, robots can be used to explore other planets and moons, mine resources, and build structures, as well as repair and maintain spacecraft and space stations. As the space industry continues to grow, it is likely that robots will play an increasingly important role in space exploration and operations. Similarly, as the metaverse continues to evolve, robots will likely become more prevalent in virtual worlds.

The space verse is still in its early stages, but there are already several platforms and technologies that are being developed. Some of the most popular platforms include Roblox, Second Life, and Decentraland, which allow users to create their own virtual worlds and interact with other users. In terms of technologies, VR, AR and AI are the most important being used to create the metaverse. VR allows users to immerse themselves in a virtual world, while AR overlays digital information onto the real world. AI can be used to create immersive experiences and enhance user interactions in the metaverse and Space Verse, personalise user experience based on their preferences, analyse data from space missions, and provide insights to scientists and researchers. In social media and education, AI is being used to create virtual communities where people can interact with each other for educational purposes, and to create virtual classrooms and other training environments.

4 Deep Space Explorations with Space Verse

Various countries are making use of metaverse technology to help space explorations. For example, NASA, SpaceX and Blue Origin have successfully launched their rockets and spacecrafts. On September 11, 2023, China's Ministry of Industry and Information Technology along with other four departments unveiled the ambitious Three-Year Action Plan for the Industrial Innovation and Development of the Metaverse (2023-2025). This document outlines China's visionary approach to metaverse industry development, with a focus on establishing "three to five industrial clusters" that revolve around emerging technologies. These clusters will serve as central hubs, driving innovation and governance structures within the realm of the next-generation internet, characterised by immersive three-dimensional spaces.

Previously, in November 2022, the Chinese government had released a plan for development of VR and related industries (thus, including the metaverse), setting a target of expanding the MR industry to RMB 350 billion (approximately US$47.8 billion) by 2026. China's metaverse market is poised to reach a staggering US$12.6 billion in 2023, with a projected compound annual growth rate of 31.93% between 2023 and 2030. The Space Verse has been intergated into many of their space technologies and industries such as simulations, training, as well as R&D. The following is an account of some of the achievements of China's space missions over the years.

China's first earth satellite was launched in the early 1970s. The China Manned Space Programme commenced in 1992 and has, since then, achieved much with notable breakthroughs in crucial technologies, establishment of its own manned spacecraft system, multiple successful flight missions, and development of expertise in areas such as rendezvous and docking, as well as extravehicular activities. In late 2022, the construction of the Tiangong Space Station was completed, symbolising realisation of the goals outlined in the "three-step" development strategy, transitioning towards the utilisation and further advancement stages.

4.1 Tiangong Space Station

Tiangong Space Station is China's first long-term space station, part of the Tiangong programme and the core of the "Third Step" of the China Manned Space Programme. The purpose and mission of Tiangong is to develop and gain experience in spacecraft rendezvous technology, permanent human operations in orbit, long-term autonomous space station flight, regenerative life-support technology, and autonomous cargo and fuel supply technology. It will also serve as the

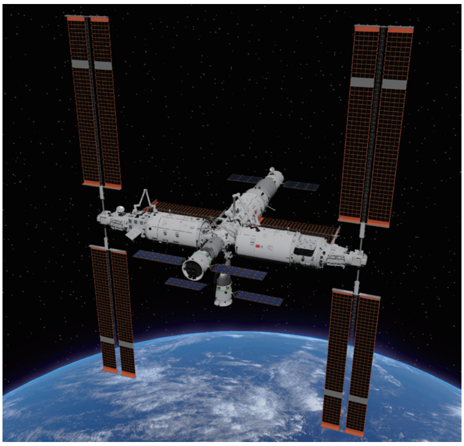


Figure 6. On November 2, 2023, China sent its youngest-ever crew to the Tiangong space station, with an average age of only 38 years old. After taking off from the Gobi Desert, they embarked on a six-month trip.

platform for the next-generation orbit transportation vehicles, large-scale scientific and practical applications in orbit, and technology for future deep space exploration.

4.2 Beidou Global Navigation Satellite System

Beidou Global Navigation Satellite System, independently developed by China System, entered operation in July 2020, thus becoming the third mature global satellite navigation system after GPS and GLONASS. It comprises the space segment, ground segment and user segment, being able to serve global positioning, navigation, and timing services. The system's construction and application span various fields including transportation, public safety, agriculture, fishery, meteorology, seismology, surveying and mapping, electricity, water conservancy, forestry, mining, oceanography, and aerospace.

4.3 Lunar Exploration Project

Lunar Exploration Project, also known as the Chang'e Programme, is China's ambitious endeavour to explore the Moon. It began with the launch of the Chang'e-1 lunar orbiter on October 24, 2007, marking China's first step in lunar exploration. Since then, the Programme has achieved several milestones, including the successful landing of the Chang'e-3 lander and rover on the Moon's surface in December 2013, making China the third country to accomplish a soft landing on the Moon. The Programme has continued to advance with subsequent missions, including the Chang'e-4 mission in January 2019, which achieved the first-ever landing on the far side of the Moon. Through the Lunar Exploration Project, China aims to deepen humanity's understanding of the Moon's geology, conduct scientific research, and pave the way for future lunar exploration and potential human missions.

Figure 7. In collaboration with CAST, PolyU developed and manufactured the "Surface Sampling and Packing System" for the Nation's Chang'e-5 mission, the world's first fully automated multi-point lunar surface sampling and packaging. The system automatically collected and packed approximately 1.5 kilograms of surface lunar soil samples and returned back to Earth.

Chang'e-5's journey in November 2020 went through a total of eleven flight stages from launch to the return module re-entry and recovery: launch and orbit insertion; Earth-Moon transfer; lunar approach and braking; lunar orbit flight; landing descent; lunar surface operation; lunar ascent; rendezvous, docking, and sample transfer; lunar orbit waiting; lunar-Earth transfer; and re-entry and recovery.

4.4 Tianwen-1 Mission

The Mars project also known as the Tianwen-1 mission, is the country's first independent mission to the Red Planet. Launched on July 23, 2020, Tianwen-1 successfully entered Mars' orbit on February 10, 2021. Tianwen-1 comprises an orbiter, a lander, and a rover, all working in tandem to conduct comprehensive scientific investigations of Mars. The rover, named Zhurong, touched down on May 15, 2021, making China the second country to achieve a successful landing and rover operation on Mars. The mission's aim was to study the morphology, geology, mineralogy, space environment, and soil and water-ice distribution of Mars.

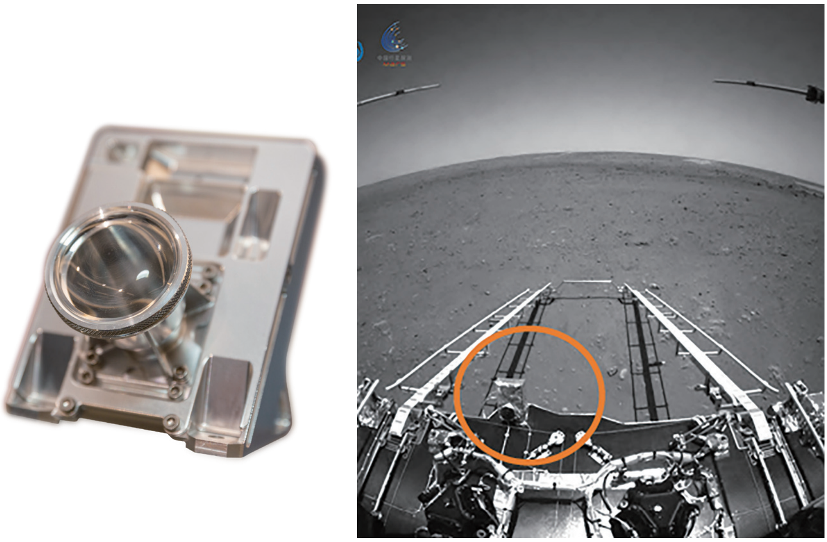


Figure 8. PolyU researchers contributed to the Nation's first Mars exploration project Tianwen-1 through developing the "Mars Landing Surveillance Camera (Mars Camera)". Located at the top of the Mars lander platform, the Mars Camera weighs only around 390g but is strong and durable. It has a wide field of vision with low image distortion, and can withstand extreme temperature variations, high radiation, mechanical impact and vibrations.

4.5 Chang'e-6

In June 2024, China's Chang'e-6 lunar probe returned from the far side of the Moon with precious lunar soil samples at the historically astonishing speed of 31 Mach. The Hong Kong Polytechnic University (PolyU) played a pivotal role in Chang'e-6's lunar mission, collaborating with the China Academy of Space Technology to contribute to the successful soil sampling using the PolyU "Surface Sampling and Packing System". Unlike previous methods of soil sampling involving drilling or manual excavation, this system is fully automated and multi-point, allowing accurate lunar surface sampling using robotic arms and computer vision systems. It includes two samplers for collecting loose and sticky lunar soil, along with high-temperature near-field cameras for precise sample capture, and a primary sealing and packaging system which ensured secure containment of the samples. The design and manufacturing of the system was led by Prof. K. L. Yung, PolyU Chair Professor, and his team, making use of the latest key space technologies involving metaverse simulation and experimentation in a harsh environment of high levels of radiation and high temperatures, as well as an unknown surface for the probe to land on and on which the Surface Sampling and Packing System needed to operate. PolyU's involvement has extended beyond Chang'e-6. The University also participated in the Chang'e-5 lunar sample return mission and the Tianwen-1 Mars exploration project

Chang'e-6 became the second probe to land on the far side of the Moon and the first to return samples from that area. The mission faced challenges due to restricted sampling timeframes and reliance on a relay satellite for communication. The Chang'e-6 lunar exploration mission marks a major breakthrough in China's space programme. It is not only China's first-ever soft landing and sample return from the lunar far side, but also a courageous attempt to explore unknown realms of the universe. This mission was of immense significance, aimed at deepening our understanding of the Moon and the solar system, and driving progress in space technology. Lunar soil is precious because it contains rich scientific information. Without an atmosphere or magnetic field, the lunar surface is directly exposed to cosmic rays and solar winds, preserving a wealth of records about solar activity, cosmic rays, and the Moon's own evolutionary history. These soil samples are invaluable for research into the Moon's origin, composition, and evolutionary processes, as well as the formation and evolution of the solar system. Moreover, lunar soil may contain elements and minerals that are rare and scarce on Earth, such as Helium-3, an ideal nuclear fusion fuel that could be crucial for solving future energy crises. Therefore, lunar soil is not only a treasure trove for scientific research, but also a potential source of future resources for human development.

5 Technologies and Infrastructure for the Space Verse

Various technologies and infrastructure are being developed to support deep space explorations described in previous sections. One of the most important technologies is reusable rockets, which can significantly reduce the cost of space travel. Other important technologies include 3D printing, which can be used to create structures and tools in space, and inflatable habitats, which can be deployed quickly and easily in space. Virtual and augmented reality experiences have the potential to enhance space exploration and habitation. For example, VR can be used to simulate spacewalks and other activities in space, while AR can be used to provide astronauts with real-time information about their surroundings. Metaverse can be used for VR experiences, including a virtual tour of the International Space Station.

As highlighted previously, emerging technologies such as AI, VR, and AR, together with spacecraft propulsion are shaping the future of the metaverse and Space Verse. AI is being used to create more realistic and intelligent virtual environments, while VR and AR are being used to create immersive experiences. The integration of physical and digital realms is a key aspect of the metaverse and Space Verse. In the metaverse, this integration is achieved through the use of VR and AR technologies, which allow users to interact with virtual objects and environments in a more natural way. In the Space Verse, this integration is achieved through the use of robotics and other technologies that allow humans to interact with the environment in space.

There are several challenges and opportunities in scalability, interoperability, and privacy for both the metaverse and Space Verse. Scalability is a challenge because these concepts require large amounts of computing power and storage. Interoperability is a challenge because different platforms and technologies need to be able to work together seamlessly. Privacy is a challenge because these concepts involve the collection and use of large amounts of personal data. However, there are also opportunities in these areas. For example, advances in cloud computing and distributed systems are making it easier to scale these concepts. Advances in blockchain technology are making it easier to achieve interoperability, while advances in cryptography and other security technologies are making it easier to protect privacy.

5.1 Outlook for the Future of the Metaverse

The future of the metaverse is being shaped by several key technologies:

(i). Extended Reality (XR) Technologies: These include VR, AR, and Brain-Computer Interfaces. XR technologies are expected to revolutionise human digital experiences and serve as entry points to the metaverse. Major tech. companies like Apple, Google, Meta Platforms (Facebook), Microsoft, Niantic, and Valve are actively developing the hardware and software that will define the future of the metaverse.

(ii). Lighter Weight Hardware: As the metaverse evolves, hardware advancements will play a crucial role. Lighter and more comfortable headsets are essential for prolonged use. Innovations in materials, form factors, and weight distribution will enhance user comfort and encourage widespread adoption.

(iii). Improved Visibility and Clarity: Clearer displays, higher resolutions, and wider field-of-view will enhance the visual experience. Reducing screen door effects (the visible grid between pixels) and minimising motion sickness are ongoing challenges. Advancements in optics and display technology will contribute to better visibility.

(iv). Interoperability and Seamless Integration: The metaverse will thrive on interoperability—allowing users to seamlessly transition between virtual and physical spaces. Software platforms need to communicate effortlessly, enabling shared experiences across devices and ecosystems.

(v). Brain-Computer Interfaces (BCIs): These futuristic interfaces allow direct communication between the brain and computers. BCIs could revolutionise how we interact with the metaverse, making it more intuitive and responsive.

While it will take several years for the metaverse to evolve further, concerted efforts from tech. giants and innovative startups are needed to push forward our digital frontier which will reshape how we perceive and interact with the world.

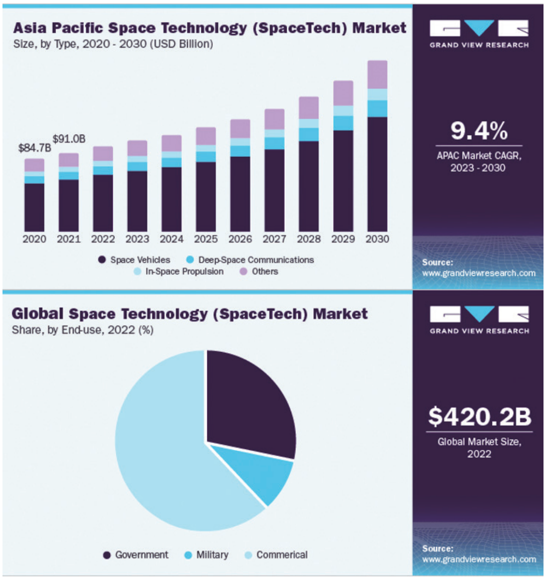
5.2 Outlook for the Future of the Space Verse

The future of the space verse and AI in space exploration is very promising. AI is already being used in many areas of space exploration, including mission planning and operations, data collection, autonomous navigation and maneuvering, and spacecraft maintenance. One of the most significant ways in which AI is revolutionising space exploration is through the use of autonomous spacecraft. These craft are equipped with AI algorithms that allow them to make decisions on their own, without human intervention. This is particularly useful for long-duration missions, where communication delays make it difficult to control spacecraft in real-time. The metaverse and space verse have the potential to revolutionise our entertainment and life styles. In the metaverse, people can interact with each other in virtual environments that are more immersive and engaging than traditional communication methods which we have presented in previous sections. It has the potential to create new jobs and industries, as well as change the way we work and interact with each other.

NASA is using AR technology and robotics to revolutionise the assembly of the Roman Space Telescope at the Goddard Space Flight Centre. This innovative approach has enhanced precision and efficiency, leading to significant time and cost savings. Using AR tools has helped astronauts and technicians improve accuracy and save time on maintenance and checks. In one instance, manipulating a digital model revealed design flaws, allowing them to make necessary adjustments before construction. Advanced measuring equipment and AR headsets provide a virtual check of the telescope structures before building or moving them. This enables precise positioning of flight hardware with accuracy down to thousandths of an inch. Engineers have also used a robotic arm for precision measuring and 3D laser scanning to map the spacecraft's complex wiring harness, identifying potential interference with the propulsion assembly. This allows them to adjust the design before building, avoiding costly delays. These key metaverse technologies enable remote collaboration, reverse engineering, and advanced training, opening up many possibilities for future applications. Future metaverse innovations will help rapidly produce spacecraft and instruments, saving significant time and resources for deep space explorations.

However, there are several ethical and legal considerations related to the Space Verse. For example, there are concerns about privacy and data protection in virtual environments, as well as about the use of virtual environments for illegal activities such as cybercrime and terrorism. Additionally, there is some disquiet about the impact of virtual environments on human rights and freedoms.

In the short term, we can expect to see continued growth in emerging technologies such as VR, AR, and AI. We can also look forward to increased investment in these technologies from both public and private sectors. In the Space Verse, the global space technology (SpaceTech) market size was valued at USD 420.2 billion in 2022 and is expected to grow at a compound annual growth rate of 7.5% from 2023 to 2030. This growth is driven by technological advancements, increasing private sector participation, and growing government initiatives. The sector encompasses a wide range of activities, including satellite manufacturing and operations, launch services, space exploration, and the development of innovative space-related technologies.



Report Attribute	Details
The market size value in 2023	USD 442.0 billion
The revenue forecast in 2030	USD 731.8 billion
Growth rate	CAGR of 7.5% from 2023 to 2030
The base year for estimation	2022
Historical data	2018 - 2021
Forecast period	2023 - 2030

Report Attribute	Details
Country scope	U.S., Canada, UK, Germany, France, Italy, Spain, China, Japan, India, South Korea, Australia, Brazil, Mexico
Key companies profiled	Northrop Grumman Corp.; Lockheed Martin Corp.; SpaceX; Maxar Technologies; Boeing; Thales Group; Safran S.A.; Rocket Lab USA; ICEYE; Airbus SE; China Aerospace Science & Tech. Corp.; Honeywell Int'l Inc.; Ball Corp; General Dynamics Corp.; Sierra Nevada Corp.; Virgin Galanctic; Blue Origin LLC; Hindustan Aeronautics; Beijing Commsat Tech Development, OHB System AG; Astra Space Inc.; Hedron

Figure 9. Report by Type (Space Vehicles, Deep-space Communication, In-space Propulsion), by Agency Type, by Application, by Region, and Segment Forecasts, 2023 – 2030

Moreover, navigation and mapping applications are the most common use of space technology, followed by satellite communication. Navigation systems like GPS have revolutionised transportation and outdoor recreation. Satellite communication provides global connectivity and supports broadcasting. North America dominates the market, with government initiatives and private investments driving growth. Europe and Asia Pacific are also significant markets, with the European Space Agency and countries like China, India, and Japan leading the way.

In the long term, as well as its impact in entertainment and culture, the Space Verse has the potential to revolutionise the way we live and work. The metaverse could become a new form of social and economic organisation, with virtual communities and economies that are independent of physical location. In the Space Verse, we could see the development of new technologies that allow us to travel to other planets and even other star systems. These technologies could also enable us to establish permanent settlements in space. On the other hand, the implications for society, culture, and human existence are significant. In the metaverse, we could see the development of new forms of social interaction and collaboration that are not limited by physical location. However, there are also concerns about the impact of the metaverse on mental health and addiction.

Overall, the outlook for the metaverse and Space Verse is very exciting and challenging. These technologies have the potential to change the world in many ways, but it is important to carefully consider the implications of these technologies and ensure that they are developed in a way that is safe, equitable, and inclusive. The Space Verse could become fully integrated with the physical world. Virtual environments could become indistinguishable from the real world, and people could interact with each other in ways that are not limited by physical location. The metaverse and Space Verse could also become a new form of social economic and business organisation for new entrepreneurships with virtual communities and economies that are independent of physical location. We can expect to see increased interstellar exploration and colonisation within the Space Verse. We could anticipate the development of new metaverse technologies that allow us to transform other planets and establish permanent settlements into the deep space making use of innovative spacecrafts, robots and machines for resource utilisation on the Moon, Mars and other planets in the next decade.

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