Nano Energy 131 (2024) 110252

Contents lists available at ScienceDirect

Nano Energy

journal homepage: www.elsevier.com/locate/nanoen

Review

Self-powered wearable Internet of Things sensors for human-machine interfaces: A systematic literature review and science mapping analysis

Qihan Jiang [a], Maxwell Fordjour Antwi-Afari [a,*], Sina Fadaie [a], Hao-Yang Mi [b], Shahnawaz Anwer [c], Jie Liu [d]

[a] Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham B4 7ET, United Kingdom
[b] National Engineering Research Center for Advanced Polymer Processing Technology, Zhengzhou University, Zhengzhou, Henan 450000, China
[c] Department of Building and Real Estate, The Hong Kong Polytechnic University, China
[d] School of Civil Engineering and Transportation, Northeast Forestry University, Harbin, China

ARTICLE INFO

Keywords:
Human-machine interfaces
Internet of Things (IoT)
Self-powered sensors
Systematic literature review
Wearable sensors

ABSTRACT

With the advent of Internet of Things (IoT), self-powered wearable sensors have seen broad applications across various human-machine interface (HMI) domains, including manufacturing, healthcare, biomedicine, and automobile. However, these sensors have not yet been systematically and scientifically reviewed within the construction industry. This study aims to conduct both a systematic literature review and a science mapping analysis of self-powered wearable IoT sensors for HMI to uncover mainstream research topics, research gaps, and future research directions. Using PRISMA methodology, scientometric analysis, and qualitative discussion, 113 journal articles were retrieved from the Scopus database, analyzed with VOSviewer, and further examined regarding mainstream topics, research gaps, and future research directions. The results revealed significant findings from the co-occurrence analysis of keywords, countries, and documents. Additionally, this study identified four primary research topics: (1) TENG, PENG, and other power sources; (2) wearable, flexible, stretchable, and tactile electronics for sensing; (3) industry 4.0; (4) HMI devices and systems. Based on the qualitative discussion of these topics, corresponding research gaps and future research directions were also identified. Eventually, this review would assist scholars and practitioners in the construction sector to better understand the existing body of knowledge and lay the foundation for future research.

1. Introduction

At present, there is a trend to develop self-powered technology to overcome the challenges associated with powering electronic devices [1,2]. Additionally, due to the gradually increasing demands of electronics users for miniaturization, multifunctionality, safety, durability, and high flexibility, advancing self-powered sensing systems is essential [3]. In most current research and electronic products, wearable IoT sensors are often powered by conventional batteries [4,5]. However, despite the revolutionary impact of the lithium battery on the battery industry, even large-capacity, heavyweight lithium batteries cannot avoid the issues of repeated charging and high energy consumption [6,7]. Therefore, self-powered technology, especially for wearable sensors, should be vigorously promoted.

The sudden development and advancement of wearable Internet of Things (IoT) sensors have moved forward colossal domains, such as biomedicine, health monitoring, sports, energy, and environmental detection [8–11]. Initially, IoT could be described as a network of physical objects with embedded technology for sensing, interacting with the environment, and offering autonomous communication [12]. Additionally, it seems that the IoTs are closely related to sensors and sensing technology [13]. The reason for this connection is that a cloud-based IoT-like system is required to handle large-scale wearable sensor deployment, management, data storage, and analytics [14–23]. Clearly, within the scope of IoT, wearable sensors are bound to have broader applications and prospects.

In the world and era of IoT, as the medium of human-machine interaction, the human-machine interface (HMI) is the platform for diversified cognition and communication between humans and machines [24,25]. The importance of HMI has been boosted step by step

* Corresponding author.
E-mail addresses: 230153730@aston.ac.uk (Q. Jiang), m.antwiafari@aston.ac.uk (M.F. Antwi-Afari), 200208408@aston.ac.uk (S. Fadaie), mihaoyang@zzu.edu.cn (H.-Y. Mi), shah-nawaz.anwer@polyu.edu.hk (S. Anwer), liujie198643@nefu.edu.cn (J. Liu).

https://doi.org/10.1016/j.nanoen.2024.110252
Received 19 July 2024; Received in revised form 29 August 2024; Accepted 8 September 2024
Available online 12 September 2024

with the increasing demand for HMI [26]. In effect, there are four generations in the evolution of HMI from HMI 1.0 to HMI 4.0 [27]. Additionally, with each industrial evolution, distinguished HMIs include different presentation methods, interactions, and information types [28–30]. Recently, the new generation of HMI systems presented different work and appearance, often referred to as the generation of virtual reality (VR) and augmented reality (AR) techniques [31].

A spurt of progress in self-charging wearable IoT sensors offers more opportunities and possibilities for HMI, drawing more extensive studies and reviews. In healthcare, especially in the elderly care area, Stavropoulos examined and categorized some IoT technologies, from wearables to smart home IoT sensors [12]. Wang et al. conducted a review of the recent developments of flexible and wearable sensors, especially those applied to the bio-medicine field [32]. Zhang et al. proposed and summarized the triboelectric sensing technology-based self-powered HMI system for wireless remote telemetry and the control of intelligent cars for the automobile industry [33]. However, in the construction domain, no systematic review concentrates on the self-powered wearable IoT sensors for HMIs, which is deemed the research gap scientifically addressed in this paper.

This research reviews the current status of self-powered wearable IoT sensors for HMI, to identify mainstream research topics on self-powered wearable IoT sensors for HMIs in the construction domain, and further proposes future research directions. This paper aims to achieve these objectives: (1) Analyzing the annual research publication trends and peer-reviewed journals on self-powered wearable IoT sensors for HMIs; (2) conducting a scientometric analysis on the co-occurrence analysis of keywords, countries/regions, and document analysis; (3) identifying mainstream research topics on self-powered wearable IoT sensors for HMIs and summarizing them in the construction field; and (4) recommending future research directions on self-powered wearable IoT sensors for HMIs.

The remainder of this study is organized as follows. Section 2 discusses the overview and characteristics of self-powered wearable IoT sensors, the concept of HMI, and previous review studies on self-powered wearable IoT sensors. Section 3 presents the research methodology, which combines a systematic literature review and science mapping analysis. The results of annual publication trends, journal sources, co-occurrence analysis of keywords, countries/regions, and document analysis are reported in Section 4. Section 5 discusses mainstream research topics, research gaps, and future research directions for self-powered wearable IoT sensors for HMI. Lastly, the conclusions, study implications, and limitations of the study are summarized in Section 6.

2. Literature review

2.1. Overview and characteristics of self-powered wearable IoT sensors

There are different types of self-powered wearable IoT sensors ranging from simple to complex, employing various mechanisms [34]. In terms of working principles, wearable IoT sensing platforms that incorporate self-powered techniques can be roughly divided into four categories: physical sensors, chemical sensors, biosensors, and a combination of different types of sensors [35]. In addition, regardless of the type of self-powered sensors used, energy transformation devices play fundamental roles in self-powered sensing systems, converting energy from organisms or the environment into electrical energy. Generally, the mature power generation technologies within common conversion devices can be segmented into five types. These are piezoelectric nanogenerators (PENG), triboelectric nanogenerators (TENG), electromagnetic generators (EMG), thermoelectric generators/pyroelectric nanogenerators (TEG/PyNG), and solar cells [36–40]. Among them, PENG and TENG have a relatively broad range of energy sources, high output voltage, and high energy conversion rates. They can harvest small-scale mechanical energy and respond to low-frequency mechanical motion [41,42]. Thus, it is clear that the essence of self-powered technology aligns closely with the development concept of wearable IoT sensors.

Self-powered IoT sensors have successfully emerged in many fields, including biomedical, healthcare, chemical and environmental monitoring, smart traffic, smart cities, robotics, and among others [43]. Without a doubt, wearable IoT sensors applied in diverse fields are expected to showcase distinct features, characteristics, and functionalities. With the maturity of semiconductor technology and the industrialization of self-powered wearable electronics, miniaturized and precise self-powered IoT sensors, along with higher capability and more sustainable output, are highly sought after [5,11]. Additionally, considering their portability and ease of fabrication, lightweight wearable IoT sensors are intended to be pursued, especially for human body sensor networks, such as those monitoring respiration or eye movements [44,45]. Furthermore, stretchability, flexibility, and biocompatibility are critical requirements for continuous advancement of PENGs in biomedical devices [46,47]. To achieve efficient energy harvesting for wearable devices in healthcare monitoring and wireless communications, flexible, lightweight, miniaturized, and reliable designs of TENGs are required [48]. Simultaneously, the harvesting circuit should have high conversion efficiency and sensitivity, like triboelectric e-skins, to capture low power levels [48,49]. Energy storage, another main component of self-powered sensing systems, directly affects the cost, size, and operating lifetime [50]. However, TENGs currently face challenges and can hardly be used in some industrial or commercial applications due to low power density, unpredictable magnitudes and frequencies of input sources, durability/stability issues, and inefficient power management [46,51].

2.2. Concept of HMI

As early as 1995, the design of HMIs for dynamic technical systems was regarded as quite complicated and could no longer be handled intuitively [52]. The prime objective of HMI is to create a harmonious relationship between humans and machines, where they work together towards a common goal. To achieve this, designers must consider the diverse needs of users, including those with disabilities and elderly populations [53]. Thereby, Wołczowski and Kurzyński [54] presented a general concept of HMI that can be applied to the control of a dexterous hand, an agile wheelchair, as well as other types of prostheses and exoskeletons.

Johannsen [55] elaborated on several technologies and concepts for multi-human-machine interfaces connected with visual and mental coherence, multimedia communication, computer-supported cooperative work, etc. Additionally, the actions generated by individuals to master HMIs should not only be simple to generate but also must lead to signals that are distinct from one another to facilitate classification [56]. Dearden and Harrison [57] revealed that some techniques still need to be developed to elicit judgments from risk analysts and safety engineers on the relative impacts of different actions in a form useful to HMI designers. Additionally, in autonomous unmanned aircraft systems, the HMI must be designed to constantly keep the human operator updated about the automation's behavior and processes [58]. Consequently, Kerschbaum et al. [59] suggested that the success of highly automated cars is closely tied to the effectiveness of their HMIs. Notably, the implementation of HMIs addresses one of the main reasons why users still prefer conventional vehicles with internal combustion engines over electric vehicles (EVs), potentially accelerating the popularity of EV technology [60]. Khramov [61] presented an updated concept of the man-machine system within the framework of digitalizing the management of socio-economic systems. Meanwhile, HMIs are a vital component of Society 5.0, enabling technology to be harnessed for social good [53]. Table 1 presents some articles on the concept of HMI in various sectors.

Table 1
Articles on the concepts of HMI in various sectors.

Source	Year	Research type	Main work
[53]	2023	Literature review and bibliometric analysis	Identifying the capabilities and distinguishing characteristics of both humans and machines, for improving HMI.
[61]	2020	Research study	Considering adaptive hybrid intelligent control schemes for a man-machine system.
[55]	1997	Systematic literature review	Some concepts, technologies, and design processes of muti-HMI.
[59]	2015	Systematic literature review	Challenges, exemplary concepts, and studies of the HMI for highly automated cars.
[57]	1996	Research study	Considering the concept of the impact of an action or human-error and showing how this concept is useful to HMI designers.
[58]	2021	Research study	Introducing a display design concept that intends to enable an operator to deal with the unique safety challenges related to autonomous small unmanned aircraft systems.
[56]	2007	Research study	A new communication and control concept using tongue movements is introduced to generate, detect, and classify signals that can be used in novel hands-free HMI applications.
[54]	2010	Research study	Presenting a concept of HMI intended for the task of bioprosthesis decision control.
[60]	2015	Literature review	Dealing with a HMI of electric vehicles, describing currently used system elements, and providing evaluation of their advantages and disadvantages.
[52]	1995	Literature review	Concepts and examples of knowledge-based support for the design process of HMIs.

2.3. Previous review studies of self-powered wearable IoT sensors

Self-charging wearable IoT sensors, which register a wide range of features and functionalities across different sectors such as robotics, HMI, electronic skin, and smart cities, have been extensively researched in recent review studies [62]. Lama et al. [63] highlighted the advantages of textile-based TENGs for biomonitoring and discussed various wearable textile-based TENG sensors. Baali et al. [64] systematically reviewed the current state of research on wearable healthcare sensors from both technical and data processing perspectives. In a related field, Wahba et al. [65] evaluated the applications of energy-harvesting wireless sensor network nodes in wearable healthcare devices. Wang et al. [66] focused on self-powered piezoelectric sensors with high sensitivity capable of monitoring human motion and physiological signals. Moreover, Jiang et al. [67] explored the research progress of self-powered sensors based on TENGs in IoTs and intelligent medical fields. Dong et al. [68] and Yang et al. [69] highlighted the future development prospects of self-powered flexible IoT sensors towards enhanced wearability, multifunctionality, better self-sustainability, and stability. Table 2 summarizes the previous review studies of self-powered wearable IoT sensors.

3. Research methods

This review study utilized a "mixed-method approach" that can be divided into 6 steps to summarize the research on self-powered wearable IoT sensors for HMI. This approach encompasses both a systematic literature review (qualitative approach) and a science mapping review (quantitative approach) in sequence, for synthesizing and analyzing the available literature on a subject [70]. According to Pluye and Hong [71],

Table 2
Summary of review studies of self-powered wearable IoT sensors.

Source	Year	Research type	Research domain
[62]	2020	Systematic literature review	Healthcare, environmental monitoring, security / forensic, and on-site testing
[63]	2021	Systematic literature review	Biomonitoring
[68]	2021	Systematic literature review	Smart home
[64]	2017	Systematic literature review	Healthcare industry
[65]	2020	Systematic literature review	Medical care and healthcare industry
[66]	2022	Systematic literature review	Human motion and physiological signals
[67]	2021	Systematic literature review	Intelligent medical
[69]	2021	Systematic literature review	Intelligent prostheses, robotics, biomedical implants, and digital twins.

the "mixed-methods" approach has been broadly adopted in numerous previous reviews and is convergent in that it synchronously integrates different data and methods of analysis. More specifically, in this section, the systematic literature review adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to provide an in-depth qualitative illustration, assist in revealing knowledge gaps, and propose areas for future studies. Conversely, utilizing VOSviewer, the science mapping review employs a quantitative method that includes scientometric analysis and qualitative discussion [72]. By combining the scientometric analysis with the systematic review, this review overcomes the challenge of biased and subjective judgements and interpretations. The six steps of the review are illustrated in Fig. 1.

3.1. Systematic literature review

PRISMA guidelines were followed for conducting the systematic literature review of this study [73]. PRISMA methodology can improve the reporting of systematic literature reviews and meta-analyses, and result in more transparent, complete, and accurate systematic reviews [73–75]. Over other relevant methodologies, systematic literature reviews based on PRISMA guidelines can enhance and advance the research methods in order to identify, select, appraise, and synthesize studies [76]. PRISMA outlines the steps for the identification of documents in systematic literature reviews, which are sequentially: identification, screening, eligibility, inclusion of articles, data extraction, and quality assessment.

3.1.1. Identification

The literature search was conducted using the Scopus search engine without any limitations. Compared to other available academic digital resources (e.g., Web of Science), Scopus covers more journals and more recent publications and is widely considered a more comprehensive and reliable database [77]. The search involved using keywords with the retrieval range of "Article title, Abstract, Keywords" in the Scopus database. The keywords "self-powered" + "wearable or sensors or internet-of-things or IoT" + "human machine interface OR HMI" were used to retrieve literature samples in the Scopus database without any constraints, resulting in 278 documents initially identified.

3.1.2. Screening

Next, these documents were further screened and limited according to specific criteria: subject area (engineering), document type (article), source type (journal), publication stage (final), language (English), and year range (2014 – 2024). The search string used in the Scopus database was TITLE-ABS-KEY (self-powered AND wearable OR sensors OR internet-of-things OR IoT AND human machine interface OR HMI) AND (LIMIT-TO (PUBYEAR $\geq$ 2014)) AND (LIMIT-TO (PUBYEAR $\leq$ 2024))

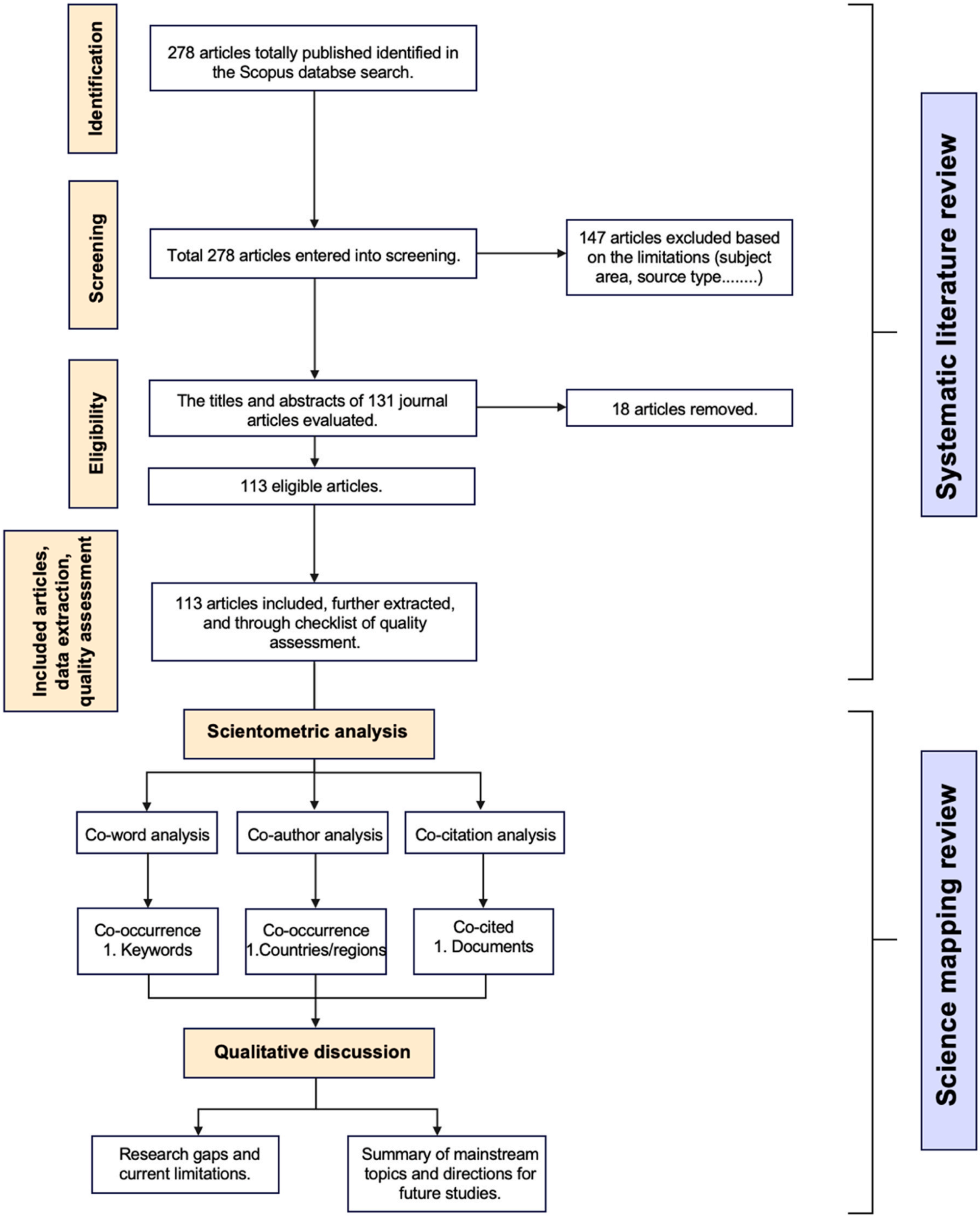


Fig. 1. Six steps in the "mixed-method approach" involving systematic literature review and science mapping analysis.

AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")). It should be noted that this literature screening was conducted on January 29, 2024. Due to the rigorous peer review process for academic journal articles and the preference of many authors to publish in scholarly journals, the search outcomes were restricted to journal articles written in English [78]. Following this screening, 131 journal articles were retained for further review.

3.1.3. *Eligibility*

At this stage, the main objective was to review and single out journal articles specifically on self-powered wearable IoT sensors for HMI within engineering-related domains. Thus, it was essential to filter out all papers outside the scope of the study. Journal articles were excluded by carefully examining and evaluating the titles, abstracts, and full-texts of the remaining 131 articles. As a result of this screening and filtering, we found that some articles, like Xu et al. [79], Ye et al. [80], Li et al. [81], Su et al. [82], only mentioned self-powered electronic devices or their peculiar structures and materials related to self-charging principles, rather than the sensors and their mechanisms or self-powered sensing systems. For example, Nie et al. [83] reported a novel approach to achieve piezotronics analog-to-digital converters based on strain-gated transistors, which only pertain to self-powered devices. Additionally, Fang et al. [84] focused merely on human-machine integration or interface without referring to self-powered TENGs or PENGs sensors. Furthermore, some articles only studied wearable sensors without establishing a relationship with HMI or related applications, such as Zhao et al. [85], and Cao et al. [86]. Eventually, with the removal of 18 journal articles, 113 articles were deemed eligible and assessed in the next step.

3.1.4. Included articles, data extraction, and quality assessment

In this case, 113 articles were included and retained for subsequent scientometric analysis. Bibliographic data on these 113 journal articles were downloaded from the Scopus database and stored in a.csv (comma-separated values) file. The extracted data comprised author names, author affiliations, article titles, keywords, abstracts, publication years, and journal titles. Then, a quality assessment was conducted using the checklist provided in Table 3, as in similar reviews [87–89]. Through the checklist inspection, 100 percent of the journal articles passed the assessment and were considered for further analysis and discussion. Additionally, a copy of the.csv file containing the same information was saved in Excel for use in scientometric analysis [90].

3.2. Science mapping review

Science mapping aims to establish quantitative bibliometric maps that describe how specific disciplines, scientific domains, or research areas are conceptually, intellectually, and socially structured [91]. In this review, science mapping review is presented as a form of scientometric analysis and qualitative discussion.

3.2.1. Scientometric analysis

Scientometric analysis can objectively visualize the research status quo while a critical review is used to identify the research themes and research gaps of ontology research [92]. It addresses problems inherent in conventional review processes, such as a lack of in-depth analysis or rigor, and allows for the objective visualization of research databases [93]. In our study, the first section aimed to identify publication trends over a specific period and analyze associated peer-reviewed journals. Subsequently, scientometric analysis was conducted using VOSviewer software. The main advantages of VOSviewer over other scientometric software include its capacity for graphical presentation, suitability for large-scale data, and multifunctionality in adapting to distinct databases and sources in different formats [94]. Consistent with the previous section's methodology, 113 journal articles and associated data were extracted, quality-evaluated, and fed into VOSviewer. Moreover, the data indexed in VOSviewer were visualized, and the results were presented in the form of keyword co-occurrence analysis, country/region co-occurrence analysis, and co-cited document analysis [95].

3.2.2. Qualitative discussion

It is universally acknowledged that qualitative discussions involve comparing concepts, themes, theories, developments, and research findings [96]. This section discusses the significant contributions of self-powered wearable IoT sensors for HMI, based on the generations from the preceding scientometric analysis. It builds on previous journal articles, identifies research gaps, and addresses current limitations. Furthermore, a scientometric analysis of keywords, countries/regions, and documents was conducted to explore mainstream research topics on how self-powered wearable IoT sensors impact HMI applications. Finally, some directions for future studies were recommended, considering research macro trends for scholars in the engineering and construction fields.

Table 3
Checklist of quality assessment.

No.	Checklist
1.	Are the aim and objectives clearly stated?
2.	Is the reporting logical, cohesive, and coherent?
3.	Is the proposed technique well described?
4.	Is the used research methodology appropriate for the objectives?
5.	Are the methods for data collection adequately depicted?
6.	Do the explanations and conclusion hinge on the data?
7.	Is there a tangible and substantial contribution to knowledge?
8.	Are the aims and objectives fulfilled?
9.	Is the research process well documented?
10.	Is the study reproducible?

4. Results

4.1. Annual publication trend

Overall, 113 articles were reviewed in this study, covering the period from 2014 to 2024. As illustrated in Fig. 2, there is a general upward trend in the number of articles on self-powered wearable IoT sensors for HMI from 2014 to 2024, with a peak of 30 articles reached in 2022. The inflection point in 2022 likely indicates a significant period of innovation in HMI, influenced by emerging technologies and concepts such as Industry 4.0 and Web 4.0. It is also notable that no articles were published in 2015 and 2016, and only 5 articles were published in 2024, likely due to the data extraction date of January 29, 2024. Based on the distribution and trends of the articles, it is anticipated that more researchers and authors will focus on self-charging wearable sensors and electronics, IoT technology, and human-machine interaction in the future.

4.2. Journal sources

Table 4 indicates that 113 articles were retrieved from 28 engineering-related journals, where articles associated with self-powered wearable IoT sensors for HMI were primarily published. Notably, only 14 journals (accounting for 50 % of the total) had 2 or more published articles showcased in this table. Among these, it is evident that "*Nano Energy*" leads significantly with 58 articles, far surpassing any other journal in this field. "*Nano Energy*" is a multidisciplinary, high-quality forum for original peer-reviewed contributions on the science and engineering of nanomaterials and nanodevices involved in energy harvesting, storage, conversion, utilization, and policy [97]. Following "*Nano Energy*", the journals "*Advanced Science*" and "*ACS Nano*" are ranked second and third, with 10 and 6 articles, respectively. Additionally, 14 articles (12.39 % of the total) were published as single articles in their respective journals. The centrality of article publications in the "*Nano Energy*" journal suggests there is still substantial room for growth in terms of journal sources, study papers, and interdisciplinary research.

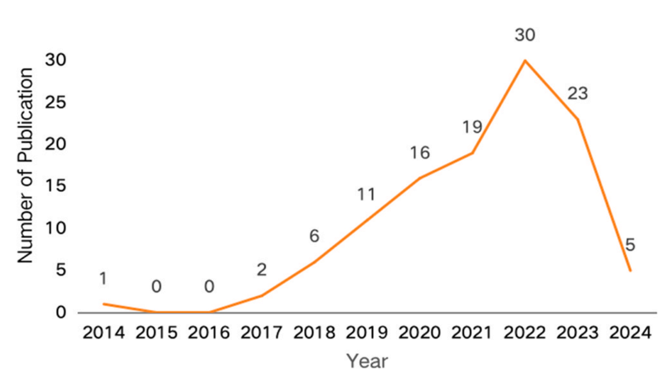


Fig. 2. Annual distribution of related articles from 2014 to 2024 (Until January 2024).

Table 4
Selected journal sources and their percentage distribution.

Journal sources	Count	Percentage (%)
Nano Energy	58	51.33
Advanced Science	10	8.85
ACS Nano	6	5.31
Advanced Materials Technologies	3	2.65
Chemical Engineering Journal	3	2.65
IEEE Sensors Journal	3	2.65
Advanced Materials	2	1.77
Biosensors and Bioelectronics	2	1.77
Materials Letters	2	1.77
Materials Horizons	2	1.77
Nanotechnology	2	1.77
Nano-Micro Letters	2	1.77
Smart Materials and Structures	2	1.77
Sensors and Actuators A: Physical	2	1.77
Others	14	12.39
Total	113	100

4.3. Keyword co-occurrence analysis

Keyword co-occurrence analysis explores the connections between keywords in literature to illustrate the knowledge components and structure of a scientific domain [98,99]. This analysis can efficiently capture the links among different concepts at a micro-level, providing insights into their respective effects and implications. For this science mapping review, a keywords co-occurrence analysis based on bibliographic data was conducted to organize and map the body of knowledge on self-powered wearable IoT sensors related to HMI. By using "Author keywords", selecting "Full counting" in VOSviewer, and setting the minimum occurrence of keywords at 3, 25 out of a total of 367 keywords met the threshold as an initial outcome. Further, semantically synonymous and tautological terms such as "TENGs", "self-powered sensor", "human machine interface", "human-machine interface", "human--machine interfaces", "flexible", and "wearable" were consolidated. Additionally, the keyword "human motion detection" was removed due to its lack of connection in the network. Ultimately, the keyword co-occurrence analysis network revealed 17 items with 4 clusters, 36 links, and a total link strength of 49, as displayed in Fig. 3.

The keywords with the highest occurrences (up to 5) in this study include "self-powered", "TENGs", "human-machine interaction", "self-powered sensors", "energy harvesting", "human-machine interface", and "triboelectric". Their higher occurrence also reflects the frequency with which these keywords have been utilized in previous research within certain study sectors. Both the distances and connection lines in Fig. 3 indicate the interrelatedness between a set of items [100]. For instance, "TENGs" is closely connected with "flexible electronics", "self-powered sensors", "energy harvesting", and "self-powered sensing" in Fig. 3. Specifically, the font size of items reveals the occurrence and frequency of these keywords in the 113 journal articles.

Table 5 depicts 17 filtered keywords and their statistics ranked according to their total link strength from high to low. Initially, "self-powered" and "TENGs" are the two highest occurrence keywords on the list, indicating that they are the focal points in the research on self-powered wearable IoT sensors for HMI. As illustrated in Table 5, it is evident that the occurrence of keywords is not directly proportional to the average citations or average normalized citations. For example, "self-powered sensors", with an occurrence of 9, have lower average citations and average normalized citations than "energy harvesting", which has an occurrence of 8. However, it is noteworthy that the average citations of keywords generally decrease as the average publication year rises. "self-powered sensing" with an average of 21.33 citations, has the latest average publication year among keywords studied in Table 5. In addition, the links represent the number of connections between a specific node and other nodes, while the total link strength showcases the total strength linked to a given item [101]. For example, the total link strength of "TENGs" is 14, indicating a strong interrelatedness between "human-machine interaction" and "TENGs".

From the observation of Table 5 and the different colors of items shown in Fig. 3, the authors' keywords can be sorted into four primary clusters representing the mainstream research areas of self-powered wearable IoT sensors for HMI:

1. TENG, as a high-power energy-harvesting device, inaugurates a crucial avenue to address the choke point of power supply for versatile sensing platforms or sensors in flexible electronic devices that need to autonomously operate without charge in remote areas [102–107].
2. Considering the effective mechanical-to-electrical signal conversion technologies, PENGs and TENGs can be adopted as both active sensing devices and power sources for HMI applications [43, 108–110]. Additionally, some recent TENG-enabled HMI applications, including tactile and gesture sensing, wireless remote controls, and interactive patches, have attracted significant interest from scholars and researchers [43,85,111,112]. Particularly, for the

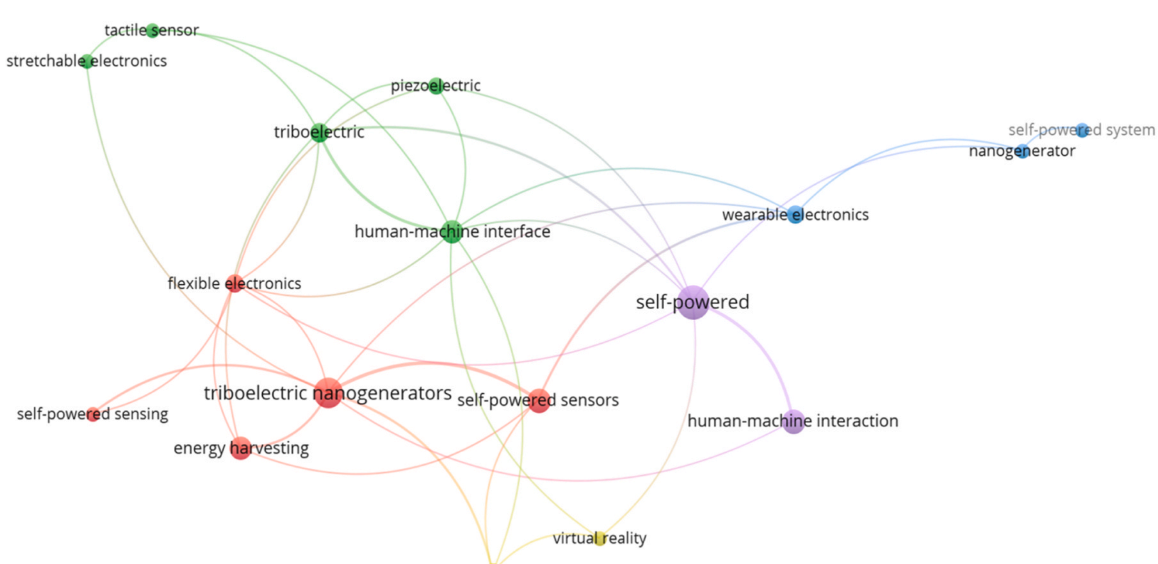


Fig. 3. The network of keywords co-occurrence associated with self-powered wearable IoT sensors for HMI.

Table 5
Quantitative summary of selected keywords co-occurrence analysis.

Keywords	Occurrences	Average publication year	Links	Average citations	Average normalized citations	Total link strength
Triboelectric nanogenerators (TENGs)	15	2021	8	56.27	1.30	14
Self-powered	20	2021	7	76.90	1.19	11
Human-machine interface	8	2021	8	64.62	1.12	10
Triboelectric	6	2020	6	69.83	0.91	9
Self-powered sensors	9	2022	4	20.33	0.59	8
Flexible electronics	5	2020	7	119.60	1.55	7
Human-machine interaction	9	2021	2	101.44	1.53	5
Energy harvesting	8	2021	4	70.88	1.21	5
Machine learning	5	2022	4	71.60	1.44	5
Wearable electronics	5	2021	4	53.40	0.92	5
Piezoelectric	4	2022	4	33.75	0.62	4
Nanogenerator	3	2021	3	72.00	1.15	3
Self-powered sensing	3	2023	2	21.33	2.30	3
Tactile sensor	3	2020	3	57.00	0.73	3
Virtual reality	3	2020	3	75.00	0.92	3
Stretchable electronics	3	2021	2	30.00	0.74	2
Self-powered system	3	2022	1	51.33	1.31	1

design of wearable and tactile electronics, sensors have been developed to be more stretchable, flexible, sensitive, efficient, and multifunctional, even exhibiting human-like intelligence as desired [113–115].

3. In response to societal progress, researchers have begun designing different mechanisms of nanogenerators into distinct types of self-powered systems, facilitating the development of self-powered wearable electronics [5,116–119]. Moreover, numerous

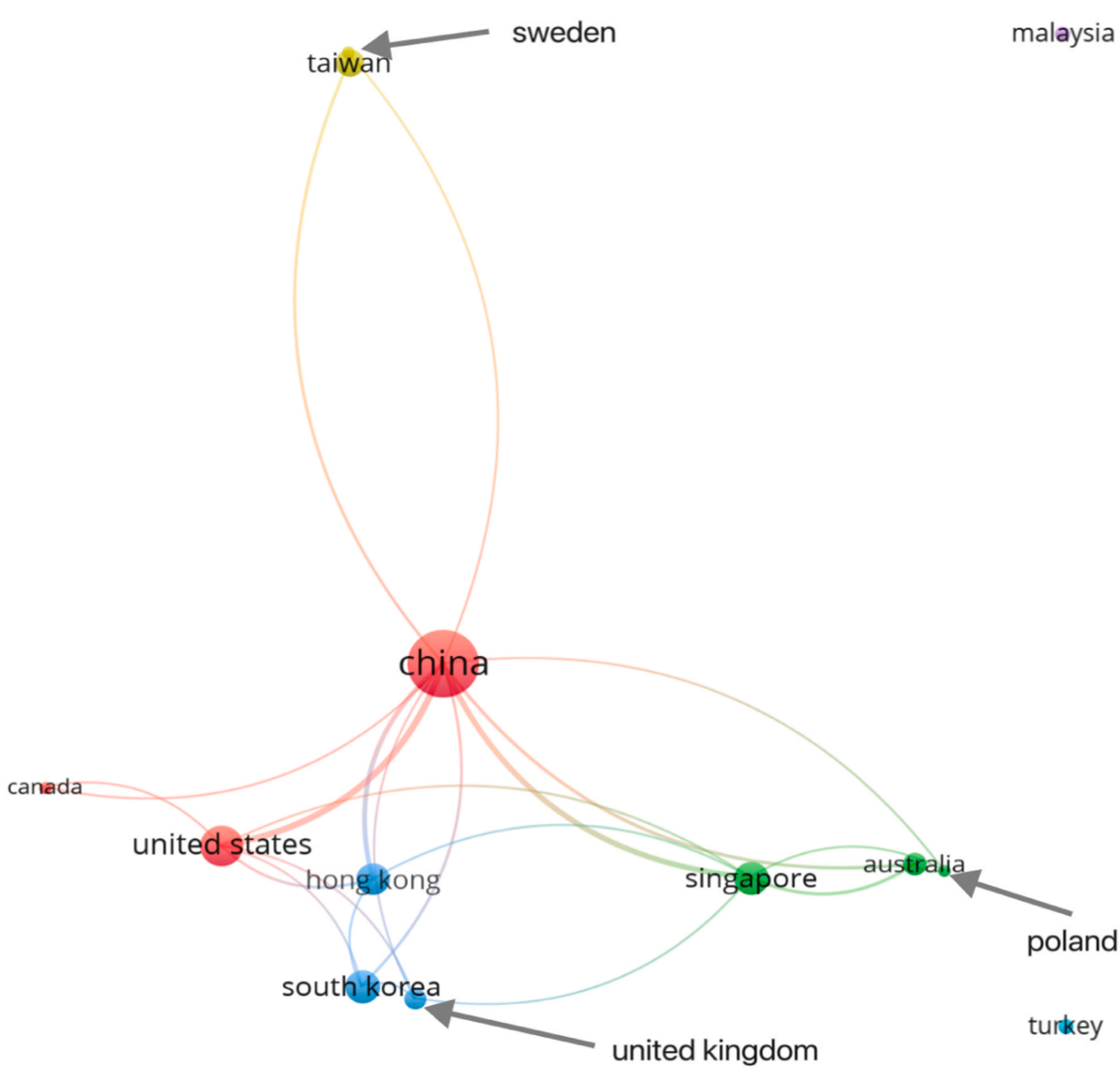


Fig. 4. Countries/regions co-occurrence analysis of self-powered wearable IoT sensors for HMI.

self-powered systems are primarily achieved by nanogenerators as the energy harvesting component of energy conversion devices, including self-powered wearable diagnosis systems, body temperature monitoring systems, and motion information detecting systems [120–124].

4. Driven by advancements in machine learning (ML), artificial intelligence (AI), the information industry, and HMI technology, VR technology can be combined with electronic devices to form an entire interactive system in 3D space, broadly applied in areas such as gesture identification, drone control, and sickness detection [125–131].

It is anticipated that self-powered electronics will act as a bridge for information interaction between humans and machines, accelerating more possibilities of breakthroughs in human–machine interaction [5, 125,132–135].

4.4. Countries/regions co-occurrence analysis

This section emphatically analyzes the contributions of countries/regions in the research sector of self-powered wearable IoT sensors. After careful screening in VOSviewer, the minimum number of documents for a country/region was set at 1, and the minimum number of citations for a country/region was set at 13. Eventually, out of 21 countries/regions, a total of 13 met the threshold.

Fig. 4 distinctly presents the geospatial distribution of the selected articles from 13 countries/regions in this studied domain. As Fig. 4 illustrates, the countries/regions are divided into several connected nodes, with China acquiring the largest node. In this collaborative network, the United States of America, along with some Asian countries, including China, its Hong Kong SAR and Taiwan district, South Korea, and Singapore, are the top 6 contributors to this domain. Additionally, in terms of connecting lines, China forms the maximum number of connections with other countries/regions as shown in Fig. 4.

Table 6 displays a quantitative analysis of 13 active countries/regions in the research domain, ranked chronologically by the average normalized citations. In terms of total citations listed in Table 6, China, with 5158 citations, unexpectedly becomes one of the most prolific countries globally. At the same time, the United States of America and Singapore, with published articles in this area also reaching four figures, contribute immensely to the output. From another perspective, Sweden leads significantly in the numerical value of average normalized citations, indicating its dominance in the field of self-powered wearable IoT sensors for HMI. Moreover, except for Poland, the average publication years of other countries/regions shown in Table 6 are after 2020. Based on both Fig. 4 and Table 6, even though Malaysia and Turkey lack collaboration and connection with other countries/regions in the network, they are still making efforts to create more value in the relevant sector.

4.5. Document analysis

Document analysis is a kind of analysis that enables scholars to scientifically assess the quality and quantity of references cited by other articles within a particular research domain. Meanwhile, in VOSviewer software, a higher number of citations corresponds to a higher academic value. By setting the minimum citation threshold to 72, a total of 24 out of 113 documents met the criteria.

Table 7 provides a summary of highly cited articles (with normalized citation values over 1.80) related to the self-powered wearable IoT

Table 7
Summary of highly cited published articles related to the studied domain.

Article	Title	Total citations	Normalized citations
[139]	Ultra-Sensitive, deformable, and transparent triboelectric tactile sensor based on micro-pyramid patterned ionic hydrogel for interactive human-machine interfaces	114	3.66
[140]	Stretchable freezing-tolerant triboelectric nanogenerator and strain sensor based on transparent, long-term stable, and highly conductive gelatin-based organohydrogel	108	3.47
[141]	Cowpea-structured PVDF/ZnO nanofibers based flexible self-powered piezoelectric bending motion sensor towards remote control of gestures	326	3.40
[137]	Biofuel-powered soft electronic skin with multiplexed and wireless sensing for human-machine interfaces	375	3.16
[142]	Machine learning glove using self-powered conductive superhydrophobic triboelectric textile for gesture recognition in VR/AR applications	283	2.39
[144]	Artificial intelligence of things (AIoT) enabled virtual shop applications using self-powered sensor-enhanced soft robotic manipulator	132	2.34
[136]	A stretchable yarn embedded triboelectric nanogenerator as electronic skin for biomechanical energy harvesting and multifunctional pressure sensing	393	2.05
[143]	Breath-based human-machine interaction system using triboelectric nanogenerator	189	1.97
[138]	Screen-printed washable electronic textiles as self-powered touch/gesture tribo-sensors for intelligent human-machine interaction	374	1.95
[145]	Multifunctional coaxial energy fiber toward energy harvesting, storage, and utilization	105	1.86

Table 6
Quantitative summary of selected countries/regions co-occurrence analysis.

Country/Region	Documents	Average publication year	Total citations	Average citations	Average normalized citations
Sweden	1	2023	16	16.00	4.13
United Kingdom	4	2022	147	36.75	1.62
Taiwan	8	2022	169	21.12	1.31
China	83	2021	5158	62.14	1.13
United States of America	23	2020	2349	102.13	1.11
Singapore	14	2020	1210	86.43	1.04
Hong Kong SAR	12	2021	398	23.42	0.73
Australia	5	2020	342	68.40	0.70
South Korea	13	2021	398	30.62	0.67
Poland	1	2019	61	61.00	0.65
Turkey	1	2021	31	31.00	0.60
Canada	1	2020	58	58.00	0.57
Malaysia	1	2021	13	13.00	0.25

Table 8
Some studies for TENG, PENG, and other sources.

Power source	Focus	Purpose	References
TENG	Transparent TENG (T-TENG)	Reporting a single-electrode mode based T-TENG with remarkable electrical performance and good stretchability	[160]
		Reporting a T-TENG with the flexible-stretchable polyvinyl alcohol/phytic acid (PVA/PA) hydrogel	[161]
	Fabric-based TENG (F-TENG)	Presenting a highly flexible and self-powered fully F-TENG with sandwiched structure	[146]
		Reporting a new track to develop Textile-based TENGs with a facile, low-cost, and scalable embroidery technique	[148]
		Combining the commercially available conductive fabric with the polydimethylsiloxane (PDMS) layer to conduct a F-TENG	[149]
		Presenting and developing a new form of fabric-rebound TENG (FR-TENG)	[162]
		Developing a customizable screen-printed textile TENG (SPT-TENG)	[163]
		Designing a humidity-resistant and stretchable single-electrode F-TENG consisting of the porous flexible layer (PFL) and waterproof flexible conductive fabric (WFCF)	[147]
		Developing a thermal-insulating fabric-based TENG (FI-TENG) composed of multiple functional layers	[164]
		Utilizing thermoplastic polyurethane (TPU) film laminated silver nanowires (AgNWs) modified fabrics as TENG electrodes	[165]
	Biocompatible bacterial cellulose TENG (BC-TENG)	Developing an eco-friendly and recyclable all-cellulose energy-harvesting and interactive device based on sandwich-structured BC-TENG	[150]
	Cellulose carbon nanotubes aerogel TENG (CCA-TENG)	Preparing a CCA-TENG with high output, moisture-proof, simplified structure, and biodegradability	[166]
	Breath-driven TENG	Reporting a breath-driven TENG acting as a HMI sensor	[167]
	Noncontact TENG (NTENG)	Developing a novel NTENG with self-powering sensing, anti-impact and self-healing properties	[153]
	Liquid-metal-based TENG	Providing a feasible approach to generate a stretchable multifunctional self-powered system, which consists of a liquid-metal-based fully soft TENG	[168]
	Coffee ground waste TENG (CG-TENG)	Developing an economic and environment-friendly TENG derived from the discarded coffee ground waste	[151]
	Multilayered TENG	Developing a stretchable, humidity-resistant, and high-performance multilayered TENG	[169]
	Skin-inspired TENG (SI-TENG)	Developing a stretchable and washable SI-TENG	[136]
PENG	Tungsten disulfide (WS2) nanosheets PENG (W-PENG)	Evaluating the energy harvesting capability via fabricating the as-grown WS2 nanosheets into a PENG	[170]
	MDABCO-NH4I3-based PENG (MN-PENG)	Integrating metal-free perovskite (MDABCO-NH4I3) into PENG	[155]
	Skin-conformal PENG	Fabricating a skin-conformal BaTiO3/Ecoflex-based PENG	[156]
	Composite thin film-based PENG	Synthesizing a bismuth titanate, Bi4Ti3O12 (BiTO), and polyvinylidene fluoride (PVDF) composite thin film-based PENG	[154]
PyNG	PVDF PyNG	Presenting a pyroelectric temperature sensor in a smart soft robotic manipulator	[144]
Hybrid generator	Triboelectric-electromagnetic hybrid generator	Proposing a triboelectric-electromagnetic hybrid generator built on freestanding magnet (FMHG)	[159]
	Magnetic-interaction assisted hybridized triboelectric-electromagnetic nanogenerator (MAHN)	Verifying the MAHN as an effective energy harvester	[171]
	Triboelectric-piezoelectric hybrid nanogenerator (TPHNG)	Reporting a transparent, flexible TPHNG using PDMS, PVDF, and AgNWs	[158]

sensors for HMI, listed in descending order of their normalized citation values. The vast majority of journal articles focus on research involving TENGs or PENGs for self-powered sensors, and sensors used in wearable electronics and HMI applications. According to Table 7, the top three most cited articles in this study area are Dong et al. [136] (393 citations), Yu et al. [137] (375 citations), and Cao et al. [138] (374 citations), through their normalized citation values are relatively low in comparison. This suggests that articles focusing on sensing technology for HMI applications are more popular and have become mainstream topics in this research area. For example, Dong et al. [136] had the highest number of total citations because of its early publication date, informative introduction, and outstanding experimental findings. The journal articles in Table 7 primarily report and discuss self-powered TENG-based sensors [138–140], electronic skins [136,137], HMIs and their applications [139,141,142], and human-machine interaction [138,143].

5. Discussion

5.1. Mainstream research topics of self-powered wearable IoT sensors for HMI

Through scientometric analysis of the selected literature samples, this study identifies the mainstream research topics of self-powered wearable IoT sensors for HMI applications. It should be noted that the keyword co-occurrence analysis and document analysis are used to mainly identify four key clusters. Based on the closed connection of the key clusters, four mainstream research topics are summarized and discussed in this section.

5.1.1. TENG, PENG, and other power sources

In general, TENGs attract significant attention and have been successful in development due to their advantages, such as lightweight design, low cost, high energy-conversion efficiency, flexible structure, and environmental friendliness [146]. As a prominent and common power generation method, TENGs are manufactured using a variety of materials to meet specific functional requirements. As detailed in Table 8, the integration of fabric and TENG, known as fabric-based TENG (F-TENG), combines the comfort of fabrics with the ability to harvest biomechanical energy, demonstrating strong application prospects in the intelligence era [147,148]. Notably, in the implementation of F-TENG, Yang et al. [149] utilized conductive fabric in conjunction with polydimethylsiloxane (PDMS), a type of polymer-supporting material with strong electron-withdrawing capability. Furthermore, there is a growing focus on eco-friendly and economically viable energy-harvesting modes and TENGs [150,151]. Additionally, Table 8 presents various types of TENGs made from different materials, designed to achieve distinct characteristics and functions for diverse applications, such as breath-driven TENG, and noncontact TENG (NTENG) [152,153].

For all PENGs, materials with a harmless piezoelectric effect are essential. An example is polyvinylidene fluoride (PVDF), which is fabricated into PVDF-Bi4Ti3O12 (BiTO) composite films, resulting in PENGs with high flexibility, non-toxicity, and excellent properties [154]. Moreover, Wu et al. [155] reported the development of the first metal-free, stable, non-toxic, and flexible MDABCO-NH4I3-based PENG (MN-PENG) by integrating metal-free perovskite into the PENG. Furthermore, Yu et al. [156] presented a skin-conformal BaTiO3/Ecoflex-based PENG (BPNG), which demonstrates significant skin conformability, high stretchability, and excellent electrical performance.

In addition to TENG and PENG, the two most common power sources, other power sources such as EMG, TEG/PyNG, and hybrid generators also play essential roles in self-powered systems and fields. In particular, hybrid generators often integrate two or more types of generators to increase power output and expand the scope of application [157]. For instance, Yu et al. [158] described a transparent and flexible triboelectric-piezoelectric hybrid nanogenerator (TPHNG) using PDMS, PVDF, and silver nanowire (AgNW) electrodes. Also, to scavenge low-frequency vibration energy and actively detect multi-directional in-plane vibration, a triboelectric-electromagnetic hybrid generator based on a freestanding magnet is proposed by Chen et al. [159].

5.1.2. Wearable, flexible, stretchable, and tactile electronics for sensing

There is no denying that current researchers are discovering more advanced wearable electronics and materials with stronger properties for self-powered sensing functions. Recently, hydrogel-based ionic electronics have become commonly used materials, showcasing significant potential in tactile sensing as well as unique electrical and/or environment-responsive properties. These properties meet the requirements for strain sensors, screen sensors, flexible all-solid-state supercapacitors, smart wound care, and healthcare monitoring [140,172–174]. Specifically, Tao et al. [139] report a tactile hydrogel sensor (THS) based on micro-pyramid-patterned double-network (DN) ionic organohydrogels that detect subtle pressure changes by evaluating variations in the triboelectric output signal without an external power source. Similarly, dense aerogels like polymer-regenerated cellulose aerogel, which have high output performance under high humidity, can also be converted from hydrogel materials and used as electrodes for sensors [166]. Additionally, nanomaterials play a crucial role in achieving high output power density and remarkable sensitivity for electrodes. For example, the MoS2-CQD-DNA nanocomposite as electrodes displays a high triboelectric open-circuit voltage of 1.6 kV (average) and an output power density of 275 mW cm−2, which is sufficient to turn on hundreds of light-emitting diodes and provide highly sensitive motion sensing [175].

Apart from this, other nanomaterials and nanocomposites make substantial contributions to the design and production of wearable, flexible, and stretchable electronics. Silicon nanowire arrays (SiNWs) incorporating nanowire material are qualified as sensing elements for self-powered humidity sensors [176]. Similarly, An et al. [177] embedded vertically aligned standing gold nanowires (v-AuNWs) into ultrathin elastomer, which were micro-patterned, peeled off, and transferred to any receiving surface, leading to the fabrication of skin-like triboelectric pressure-sensing tattoos on human skin for HMI applications. Furthermore, Zhu et al. [178] present a triboelectric sensor with polymer-nanowires, showing exceptional pressure sensitivity of 44 mV/Pa (0.09 % Pa-1) and maximum touch sensitivity of 1.1 V/Pa (2.3 % Pa-1) in the extremely low-pressure region (<0.15 KPa). Additionally, friction nanofiber materials can be produced by electrostatic spinning, significantly enhancing the sensitivity of the sensor and optimizing the overall electronic device conversion efficiency [179]. Moreover, a type of PVDF/cellulose composite fiber, comprising cellulose nanocrystals (CNCs) via wet spinning and drawing, can be woven into fabrics and subsequently assembled into flexible and stretchable sensors [180]. Table 9 presents some studies of wearable, flexible, stretchable, and tactile electronics for sensing.

5.1.3. Industry 4.0

The impact of ML algorithms, such as PCA and MLR, on Industry 4.0 is far-reaching and multifaceted, changing various production processes, accelerating efficiency, enhancing product quality, and fostering innovation [126,187]. Among the many algorithms, CNN, a special type of deep learning (DL) architecture, is specifically designed to handle data with a grid-like structure and automatically extract data features [188]. As demonstrated by Ge et al. [189], through 1000 iterations of training and testing, high-accuracy gesture recognition is achieved by the CNN model, further increasing the feasibility of intelligent and personalized applications of FMTS.

Bluetooth technology plays a significant role in achieving the goals of Industry 4.0, particularly in promoting equipment interconnection, enabling intelligent monitoring and maintenance, and improving overall operational efficiency. Moreover, the applications of Bluetooth and BLE with low power characteristics are becoming more widespread and important in the Industry 4.0 revolution [137]. While BLE focuses on energy efficiency, it still maintains compatibility with conventional Bluetooth technology, guaranteeing broad application support and device interoperability [190]. The Bluetooth wireless module is a crucial component that enables Bluetooth technology to be integrated into devices. For instance, the TENG device can transmit signals to a mobile phone through a Bluetooth wireless module for real-time display [149].

The development of Industry 4.0 will be accompanied by increasing tasks and demands for humans in the factory, who cannot operate without machines and a series of technologies [191]. Technologies involved in human-machine interaction, such as VR, ML, AI, and natural language processing (NLP), work together to enhance the user's interaction experience with a system, device, or machine [192,193]. For instance, in an HMI device, a glove with a superhydrophobic textile incorporating ML and VR enables real-time gesture recognition tasks, allowing for highly accurate VR/AR controls with minimized effects from sweat during operation [142]. Additionally, a digital-twin-based virtual shop successfully implemented by Sun et al. [144] provides users with real-time feedback about product details by leveraging IoT and AI analytics, showcasing the technical diversity and comprehensiveness of human-machine interaction. Table 10 shows some studies for Industry 4.0.

5.1.4. HMI devices and systems

One vital reason we develop and propel HMI technologies is to better serve human activities and promote the living standards of people both materially and spiritually, which also demonstrates care for individuals. Pang et al. [196] demonstrated a breathing-driven HMI system for severely disabled people to operate electrical household appliances and illustrated an intelligent respiration monitoring system for emergence alarms. Building on this, a smart wireless breath-driven HMI system has been introduced and researched for its ability to transform real-time human breathing into signals that control electrical appliances without relying on physical movements or language [143]. This invention would bring considerable convenience to people, particularly the elderly, disabled individuals, and vulnerable populations. Meanwhile, the latest self-powered wearable body-detecting/brain-stimulating system for monitoring and restraining epilepsy, displaying the potential of brain-machine interface (BMI) systems for personalized treatment of brain diseases, has been fabricated [197]. Additionally, based on the BaTiO3/Ecoflex material, a type of skin-conformal PENG can be directly attached to an elbow as an active sensor for joint monitoring, which is promising for prospective medical research and more HMI applications [156].

The mimicry of human skin's sensory ability through electronics is an innovative field of study with wide applications in robotics, AI, and HMI, fostering the development of e-skin [198,199]. Yu et al. [137] reported a flexible and fully perspiration-powered integrated electronic

Table 9
Some studies for wearable, flexible, stretchable, and tactile electronics for sensing.

Electronics	Mechanism	References
Polyacrylamide/starch double-network hydrogel (PSH)	Self-powered, flexible, triboelectric sensor(s) is integrated on top of PSH for multi-tactile sensing.	[174]
Ionic elastomer (IE)	A skin-like thin triboelectric sensor array using IE as the electrode is further designed to demonstrate efficient human motion energy harvesting.	[181]
Double network (DN) ionic organohydrogel	An anti-freezing, self-healing, adhesive, and tough conductive double network ionic organohydrogel is constructed by simultaneously introducing NaCl and glycerol (Gly) into poly (vinyl alcohol)/poly(acrylic amide-acrylic acid) (PVA/PAMAA).	[172]
Micro-pyramid-patterned double-network (DN) ionic organohydrogel	A tactile hydrogel sensor (THS) is based on micro-pyramid-patterned DN ionic organohydrogels to detect subtle pressure changes.	[139]
Silicon nanowire arrays (SiNWs)	A self-powered humidity sensor could be built on the moisture-directly triggered electricity generation (MEG) effect, where SiNWs function as the sensing element.	[176]
Perspiration-powered integrated electronic skin (PPES)	A flexible and fully PPES can be for multiplexed metabolic sensing in situ.	[137]
Heterogeneous mechanoluminescent materials and polymer matrix	An all-optical tactile sensing platform consisting of heterogeneous mechanoluminescent materials and polymer matrix is proposed for the conversion of multiple tactile stimuli into heterochromatic lights.	[182]
Vertically aligned standing gold nanowires (v-AuNWs)	The v-AuNWs could also be embedded into ultrathin elastomers, micro-patterned, peeled off, and transferred to any receiving surfaces, leading to fabrication of skin-like triboelectric pressure-sensing tattoos on human skins for HMI applications.	[177]
Cellulose carbon nanotubes aerogel (CCA)	The CCA can be utilized not only as a tribolayer but also as an electrode for sensors.	[166]
Oriented silk fibroin mat and a micro-structured electrode	A green and high-output self-powered force/pressure sensor is composed of an oriented silk fibroin mat and a micro-structured electrode for disposable force sensor applications in a simple and scalable way.	[183]
Self-powered wearable keyboard (SPWK)	A self-powered wearable keyboard (SPWK) is fabricated by integrating large-area F-TENG sensor arrays, which can trace and record electrophysiological signals.	[146]
Electrostatic spinning	Electrostatic spinning could be utilized to generate degradable friction nanofiber films, which significantly boosted the sensitivity of the sensor and improved the overall device conversion efficiency.	[178]
Self-powered wireless sensing e-sticker (SWISE)	To address the challenges of real-time sensing, power supply, and wireless signal transmission in current wireless sensors, SWISE based on the triboelectric-discharge effect has been proposed.	[35]
Cellulose nanocrystals (CNCs)	By incorporation of CNCs, continuous β-phase enriched PVDF/cellulose composite fibers are prepared via wet spinning and drawing. The composite fibers are woven into fabrics and subsequently assembled into a flexible sensor.	[179]
Electromagnetic vibration energy harvester (EVEH)	A high-density stacked microcoil integrated microminiaturized EVEH is proposed for self-powered acceleration sensing.	[184]
MoS2-CQD-DNA nanocomposite as electrodes	With nanomaterial-based electrodes, the MoS2-CQD-DNA nanocomposite exhibits a high triboelectric open-circuit voltage of 1.6 kV (average) and an output power density of 275 mW cm−2, which is sufficient for turning on hundred light-emitting diodes and for a highly sensitive motion sensing.	[175]
Scalable fiber electronics	A scalable fiber electronics that can simultaneously visualize and digitize the mechanical stimulus without external power supply can adopted for self-powered optoelectronic synergistic fiber sensors (SOEFSs).	[185]
Triboelectrification-induced electroluminescence (TIEL)	A hybrid self-powered porous-structured tactile sensor (SPTS) is proposed by monolithically integrating a porous TIEL component.	[186]
Gelatin/NaCl organohydrogel (GNOH)	A strain sensor has been developed based on a transparent, long-term stable, and highly conductive GNOH.	[140]
Polymer-nanowires	Enabled by the unique sensing mechanism and surface modification by polymer-nanowires, the triboelectric sensor shows an exceptional pressure sensitivity of 44 mV/Pa (0.09 % Pa−1) and a maximum touch sensitivity of 1.1 V/Pa (2.3 % Pa−1) in the extremely low-pressure region (<0.15 KPa).	[178]

skin (PPES) for multiplexed metabolic sensing in situ, which is also able to monitor muscle contraction as an HMI for human-prosthesis walking. Inspired by natural skin, an ultra-conformable, adhesive multi-functional ionic skin (MiS) can recover the skin-mimicking tactile sensing functions of both touch location and intensity, thereby serving as an HMI for accurate external robotic control [174]. Additionally, the interacting patch is a typical HMI device with diverse functions such as writing trace recognition, 2D/3D virtual control, and entertainment [111,200]. For instance, Tang et al. [201] showcased a minimalist and self-charging interacting patch, achieving the simultaneous detection of multi-parameter sensory information from finger operations, such as contact position, sliding trace, and applied pressure. Table 11 illustrates some studies of HMI devices and systems.

5.2. Research gaps of self-powered wearable IoT sensors for HMI

With the sustainable innovation and significant progress of advanced technologies in recent years, the area of self-powered wearable IoT sensors for HMI is experiencing rapid and dynamic development in

Table 10
Some studies for Industry 4.0.

Technologies	Examples	Focus	References
Machine learning and deep learning algorithms	Long short-term memory (LSTM)	LSTM is employed in the training and testing of smart bandage systems.	[192]
	Principal component analysis (PCA) algorithm, gaussian mixed model (GMM) algorithm, K-means clustering (K-means) algorithm, multiple linear regression (MLR)	To classify fast and slow finger motions with obvious visualization performance, MLR and the PCA+K-means are presented and demonstrated substantially in terms of clustering, visualization, and motion speed interference.	[126]
	Convolutional neural networks (CNN)	Based on the PyTorch framework, a CNN model (consisting of three convolutional and ReLU layers, three max-pooling layers, and three fully connected layers) was constructed to deal with classification problems and automatically extract data features.	[188]
	1D-CNN, t-distributed stochastic neighbor embedding (t-SNE) algorithm	A three-layer 1D-CNN is constructed for data feature extraction and automatic recognition to verify the sensing ability of the proposed intelligent manipulator system. The t-SNE algorithm can diminish the dimensionality of extracted features achieved by 1D-CNN and visualize the clustered results of the data set of vertical and horizontal grip.	[144]
	CNN	High accuracy recognition of gestures is achieved by CNN model training, which further increases the feasibility of intelligent and personalized applications of flexible microfluidic triboelectric sensors (FMTS).	[189]
	Dense convolutional network (Densenet), Residual Network (ResNet)	The sound signal with extracted feature values from Mel spectrogram is input into DenseNet to train. Furthermore, in order to verify the advantages of the model, this research trains the voice data with DenseNet and ResNet for 20 rounds of training.	[194]
Bluetooth	Bluetooth low energy (BLE)	The personalized information is wirelessly transmitted to a user interface via BLE.	[137]
	Bluetooth wireless module	A F-TENG device transmits signals to the mobile phone through a Bluetooth wireless module for a real-time display.	[149]
Virtual reality	Virtual reality 3D-control sensor (VR−3D-CS)	A novel self-powered virtual reality 3D-control sensor (VR−3D-CS) based on a triboelectric mechanism is used for controlling the attitude (both the position and rotation) of object in 3D virtual space.	[193]
Other integrated technologies	ML+VR/AR	Through leveraging ML technology, various gesture recognition tasks are done in real-time by using gestures to achieve highly accurate VR/AR controls including gun shooting, baseball pitching, and flower arrangement, with minimized effect from sweat during operation.	[141]
	ML+Morse code	By taking advantage of ML algorithms and Morse code, safe, accurate (96.3 %), and stable communication	[195]

(continued on next page)

Table 10 (*continued*)

Technologies	Examples	Focus	References
		aid HMI applications are achieved.	
	AI+IoT	By leveraging the IoT and AI analytics, a digital-twin-based virtual shop is successfully implemented to provide users with real-time feedback about the details of the product.	[144]
	Bluetooth+microcomputer	Integration of Bluetooth and microcomputer technologies allows the self-powered tactile sensor embedded within the glove to facilitate voice broadcasts and remote information transmission.	[179]

construction, manufacturing, the automobile industry, healthcare, smart homes, sports, and among others. However, due to the demand for more efficient, unobtrusive, reliable, and continuous human-machine interaction and higher performance of HMI applications, uncharted problems and challenges in energy harvesting, wearable electronics, industry 4.0 technologies, and HMI devices across different fields have also become apparent, which will be concretely detailed below.

5.2.1. Research gaps in TENG, PENG, and other power sources

TENG and PENG, along with other new-style power sources, provide sustainable, clean, and efficient solutions for energy harvesting and generation from ambient sources. They are specifically promising applications in self-powered systems, wearable electronics, and the IoT domain. Enhancing the performance of TENG, PENG, and other power sources largely depends on advancements in their materials, which sometimes encounter fabrication limitations [148,169]. For instance, the use of customizable screen-printed textiles [132], liquid metal [168], and PDMS [149], offers new strategies and broad scenarios for energy harvesting and self-powered sensing. In the past five years, although many scholars have focused on understanding the basic working modes and optimizing the nature of materials, it is obvious that their contributions are still insufficient. It is generally accepted that integrating AI with TENG and PENG devices is considered a potential solution to overcome current limitations in analysis, design, fabrication, and application [144]. AI technology could aid in optimizing the mechanical-to-electrical performance of these nanogenerators; however, comprehensive literature and research on AI-promoted TENG and PENG are still lacking.

Additionally, the development of hybrid schemes and approaches combining TENG, PENG, and other energy harvesting mechanisms could result in increased energy generation efficiency, which urgently needs further exploration. Such schemes could harness energy from diverse ambient sources, including human motion, aiming to offer a versatile solution for electronics and sensors. Ultimately, optimizing these hybrid devices is crucial for maximizing their energy harvesting capabilities and storage efficiency [103,158].

Table 11
Some studies for HMI devices and systems.

HMI devices/systems	Applied areas	References
Multi-functional ionic skin (MiS)	Smart, expedited wound care and robotic control	[174]
Perspiration-powered integrated electronic skin (PPES)	Key metabolic analytes and skin temperature monitoring, human-prosthesis, and muscle contraction monitoring	[137]
Energy fiber	Real-time finger motion monitoring, intelligent robotic skin, and security tactile switches	[145]
Smart bandage	Human motion monitoring, gesture recognition, and biomedicine	[192]
Artificial perception, and transmission nerve (APTN) based prosthetic arm	Artificial intelligence and robotics applications	[202]
Glove with human motion sensing capabilities	Gesture recognition, and energy harvesting	[165]
Skin-conformal $BaTiO_3$/Ecoflex-based PENG	Joint monitoring, and medical research	[156]
Self-powered wearable body-detecting/brain-stimulating system	Tiny movements detecting, and brain-machine interface (BMI) system for personalized treatment of brain disease	[197]
Smart breathing-driven HMI system	Controlling electrical household appliances for severely disabled people, emergence alarms, elderly and disabled people care	[143,196]
Finger sweeping via in-plane magnetized flexible micropillars	Demonstrating smartphone page flip, Morse code communication, and game-playing	[203]
Touch panel	Healthcare monitoring, and biomechanical energy harvesting	[140]
Interacting patch	Writing pad, writing trace recognition, identification code system, a 2D virtual vehicle control, a 3D virtual drone control, energy harvesting, automation control, robotics, security, and entertainment	[111,200,201]
3D touch pad	Motion monitoring, electronic skin, and robotics	[204]
Tactile interactive system (TIS)	Intelligent mechanosensation, precise digital control, smart home systems, and advanced industrial manufacturing	[205]

5.2.2. Challenges of wearable, flexible, stretchable, and tactile electronics for sensing

Initially, the core components of these electronics are tactile sensing devices that detect external stimuli and derive timely information from the surroundings. Innovations and studies in conductive polymer-based composites, integrating nanomaterials into polymer substrates, will raise expectations for wearable, flexible, tactile electronics [166,178,182]. These advancements encompass a wide range of sensor categories, including triboelectric, piezoelectric, and piezoresistive sensors, each with unique advantages but challenges in terms of sensitivity, durability, and response time. Furthermore, mechanical mismatches between conventional rigid electronic materials and soft skin can cause substantial sensor errors during epidermal measurement, which is still not thoroughly addressed. Pursuing the fusion of multimode sensing while maintaining basic features of electronics and sensors, such as sensitivity, biocompatibility, repeatability, linearity, and durability, and conforming to the arbitrary surfaces of applications, is a significant challenge as well [206]. To sum up, the difficulties in enhancing wearable, flexible, stretchable, and tactile electronics for sensing are multifaceted, requiring interdisciplinary efforts in materials science, engineering, and biomedicine.

5.2.3. Industry 4.0: identifying research needs

Industry 4.0, known as the Fourth Industrial Revolution, introduces a wave of innovative technologies, techniques, and practices aimed at revolutionizing manufacturing and related sectors through cyber-physical systems. However, the transition towards Industry 4.0 certainly faces challenges spanning technical, managerial, socio-economic, and political domains that require further study [207]. In the technical aspect, implementing Industry 4.0 technologies involves solving various technological challenges associated with cyber-physical systems, IoT, big data analytics, cloud computing, and more. System designers must identify these challenges and be aware of their interrelationships to effectively navigate the implementation process [208]. On the non-technical side, Industry 4.0 introduces significant challenges such as the need for new educational methods to prepare future employees, the complexity of fixing errors in sophisticated software and training datasets, and the responsibility of designers and developers. These challenges, while rooted in the technical field, generate extensive social impacts, indicating a need for more interdisciplinary research and approaches [209].

Small and Medium-sized Enterprises (SMEs) face unique challenges in adopting Industry 4.0 technologies. These challenges include market uncertainty, the need for competitive advantage, and the significance of top management support. The complexity of advanced manufacturing and the market transparency of Industry 4.0 solutions remain crucial barriers, especially in regions like Japan [210]. Additionally, SMEs in developing countries find it difficult to achieve ethical and sustainable operations. Furthermore, operational and financial constraints are compounded by a lack of motivation from partners and customers to use these technologies [211].

5.2.4. Existing problems of HMI devices and systems

In the context of a human-oriented and served-focused concept, the advancement of HMI devices and systems still needs to overcome some existing problems. For effective communication and cooperation between humans and machines, HMI devices need to be flexible, stretchable, imperceptible, and self-healable to integrate seamlessly with the human body. In addition, designing automated HMI systems must consider human abilities and limitations to prevent system disruptions, accidents, and injuries. Accordingly, a framework concentrating on human-centered design might enhance the capabilities of operators and address problems during human-machine interaction, which has still been inadequately considered and studied [196].

Construction machinery operates in complex environments and requires interfaces capable of handling various tasks such as construction, transportation, and loading. Considering the cognitive processes involved in handling information from both machines and the environment, the complexity of these systems necessitates interfaces that facilitate easy and intuitive communication between operators and machines [165]. Recently, robots and machines have been increasingly utilized to assist with hazardous, repetitive, and strenuous tasks, requiring interfaces that support safe and efficient human-robot collaboration, particularly in unstructured environments such as construction sites. Additionally, Brosque et al. [212] stress that adapting haptic interfaces for construction tasks, which have seen success in other fields, presents an additional challenge. Moreover, in applications in construction work, unmanned Ground Vehicle (UGV), examples of vehicles with no direct human control, highlight the technological gaps in autonomous operation and HMI aspects that restrict their utilization. Importantly, addressing these gaps requires a deeper understanding of the operational demands and the improvement of interfaces that can effectively manage UGV operations in construction scenarios [213]. Regarding UGVs, it is evident that in the construction field, there are still issues in defining the usage and operational requirements of HMI before its design [200,201].

5.3. Future research directions of self-powered wearable IoT sensors for HMI

By virtue of keyword co-occurrence analysis and qualitative discussion of mainstream research topics, along with corresponding research gaps, Fig. 5 showcases the research framework of existing research areas, research themes, and future research directions of self-powered wearable IoT sensors for HMI. It is worth noting that these mainstream research themes presented in Fig. 5 are not in isolation but are closely connected with each other. For example, energy harvesting/generation devices like TENG, with the assistance of wearable, flexible, tactile electronics as electronic materials for sensing, could form an important component of self-powered sensors. Using advanced technologies, TENG/PENG-based sensors are utilized to design and produce diverse categories of HMI applications. Several directions for future research in the construction sector can be summarized and anticipated, incorporating:

1. Further promotion of wearability, durability, and portability of TENGs and PENGs for self-powered HMIs that are capable of operating in real-world construction environments.
2. Development of more stretchable and softer skin-like wearable electronics to better fit the dynamic environment of construction sites.
3. Integration with AI and Haptic Feedback (HF) for more advanced and immersive HMIs aimed at achieving safer and more effective construction processes.
4. Enhancing the multi-functionality and other synthetic properties of self-powered wearable IoT sensors in the construction domain.
5. Focusing on energy efficiency issues and innovative designs of HMIs with sustainable materials, diminishing energy consumption while maximizing stability in harsh construction environments.
6. Continuous studies and discovery on hybrid schemes and approaches combining TENG, PENG, and other energy harvesting mechanisms, to increase energy generation efficiency.
7. Facilitating the human-centered design of HMI devices and systems particularly used by operators and staff in working environments, such as construction sites.

5.4. Potential implications of self-powered wearable IoT sensors for HMI in the construction industry

There are potential implications of self-powered wearable IoT sensors for HMI in construction and other industries. Due to the characteristics (e.g., flexibility, wireless communications, lightweight, and energy storage) of self-powered wearable IoT sensors (e.g., TENGs, PENGs, PyNGs), they can provide numerous implications (i.e., application scenarios and user experience to workers) in the construction industry. This review study identified five potential implications including (1) real-time monitoring of physiological metrics; (2) construction activity recognition; (3) Hazard, fatigue, and fall risk detection; (4) integration with other digital technologies; and (5) workers' training and education. First, self-powered wearable IoT sensors for HMI can monitor physiological metrics such as heart rate, heart rate variability, skin temperature, electromyographic, and respiration rate in real-time [4,124,214]. Monitoring construction workers' physiological metrics could help safety managers to detect ergonomic risk factors such as awkward postures, stress, allowing for proactive interventions on workers' health on construction sites. Second, self-powered wearable IoT sensors for HMI scenarios could be used to detect and recognize workers' movements and activities such as repetitive manual handling tasks (e.g., lifting, pulling, pushing), rebar tying, which would optimize activity levels/workflows and reduce downtime [197]. Safety managers can use sensor stream data from HMI devices to facilitate task allocation and manage workplace productivity throughout the construction lifecycle. Third, self-powered wearable IoT sensors for HMI scenarios could detect

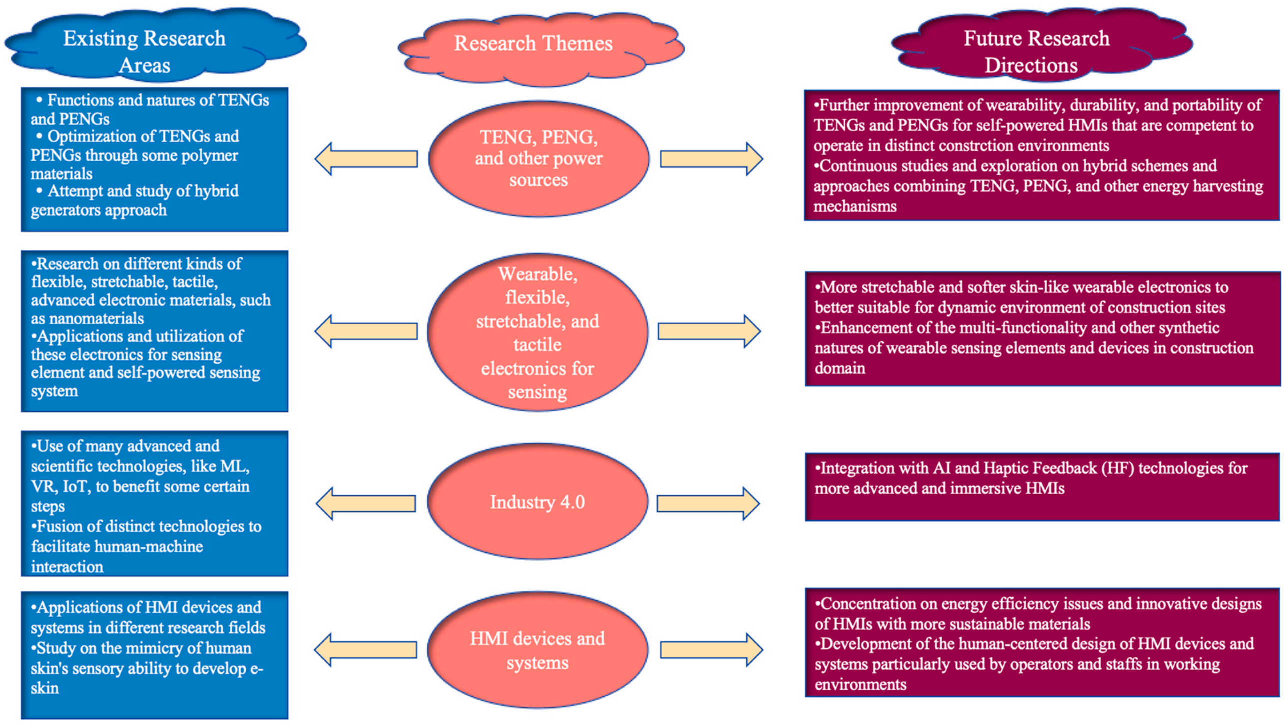


Fig. 5. Research framework of existing research areas, research themes, and future research directions in self-powered wearable IoT sensors for HMI.

construction environmental hazards such as exposure to harmful gases, excessive noise, or vibration levels and non-fatal fall risks such as slips, trips, alerting workers and supervisors to take some preventive measures [188,215]. In addition, workers' fatigue (i.e., physical or mental fatigue) is a critical issue in real-world construction industry, widely due to high-demand jobs, repetitive activities, extended periods of working time, psychological stressors, and among others [216]. By using self-powered wearable IoT sensors, physical and mental signals such as energy expenditure, cardiovascular response, and blink rates corresponding to HMI systems would help to optimize construction work-rest schedules and worker reassignment, reducing the risk of developing fatigue, and thus promoting workers' productivity. Fourth, due to the seamless wireless communication, energy storage, and lightweight characteristics of self-powered wearable IoT sensors, they can be integrated with other advanced digital technologies such as building information modeling (BIM), drones, robotics, VR/AR, artificial intelligence (e.g., machine/deep learning algorithms), etc. The integration can facilitate data-driven decision-making and smart construction sites [131,202,217]. Fifth, attaching self-powered wearable IoT sensors to intelligent personal protective equipment (PPE) such as gloves, helmets, safety boots, goggles, and large construction equipment such as cranes, excavators could help provide safety alerts to workers working in confined spaces or dangerous areas on construction sites [142,218]. Collected data streams from workers' PPE and construction equipment can be used to improve training programs, especially in areas where accidents frequently occur on construction sites.

6. Conclusion

Even though many studies have focused on self-powered wearable IoT sensors and HMI devices, there is no state-of-the-art review on self-powered wearable IoT sensors for HMI in the construction domain with potential implications, future research directions, and contributions to both theory and practice. Therefore, this review aims to conduct both a systematic literature review and a science mapping analysis of self-powered wearable IoT sensors for HMI, identifying mainstream research topics, research gaps, and future research directions. By adopting the PRISMA approach in the systematic literature review, 113 journal articles were extracted from the Scopus database. Then, utilizing VOSviewer as a visualization tool, these articles were analyzed using scientometric analysis and qualitatively discussed. In the journal sources analysis, it is evident that *Nano Energy*, *Advanced Science*, and *ACS Nano* are more productive than other journals in publishing articles in the studied domain. Keyword co-occurrence analysis indicates some mainstream keywords with up to 5 occurrences, including "self-powered", "TENGs", "human-machine interaction", "self-powered sensors", "energy harvesting", "human-machine interface", and "triboelectric". In addition, China was one of the most prolific countries in this research field. The results presented four mainstream research themes closely linked to this research work: (1) TENG, PENG, and other power sources, (2) Wearable, flexible, stretchable, and tactile electronics for sensing, (3) Industry 4.0, and (4) HMI devices and systems. Consistent with these four mainstream research topics, related research gaps and future research directions were displayed and discussed in detail. The sections below discuss the theoretical and practical contributions, and limitations of the research.

6.1. Contributions to theory

This study aims to conduct a systematic literature review and science mapping analysis of self-powered wearable IoT sensors for HMI to identify mainstream research topics, research gaps, and future research directions. Although existing research has analyzed current self-powered wearable sensors, it is essential to specifically review self-powered wearable IoT sensors for HMI applications and their implications for the construction industry. This paper also proposed a theoretical framework for future research directions through qualitative discussion supported by scientometric results and closed connections with existing research areas and research themes. This review examines the development and application of self-powered wearable IoT sensors in the HMI field since 2014, highlighting the significance of keywords, countries/regions, and document analysis. Based on our analysis and a review of the extant literature, numerous TENG/PENG-based wearable sensors are already being used in HMI devices to meet various functions and demands. The optimization and development of TENGs and PENGs propel the capabilities of these sensors in multiple directions. Theoretically, with the support of advanced technologies, these sensors could enable more applications of HMI devices and systems in diverse areas such as construction, manufacturing, smart homes, automobiles, and healthcare.

6.2. Contributions to practice

This is the first state-of-the-art review of self-powered wearable IoT sensors for HMI, utilizing both systematic literature review and science mapping analysis approaches. The findings of this review provide an in-depth understanding of the most advanced wearable IoT sensors for HMI applications and outline future requirements for researchers, scholars, and practitioners across various fields and industries. For instance, the analysis of key journals, keywords, countries, and highly cited articles serves as a reference guide for other scholars during their literature searches within this research field. Additionally, the identified main research topics offer valuable insights for practitioners and scholars to discover more practical applications of HMI using self-powered wearable IoT sensors. Furthermore, the proposed future research directions could enable researchers and scholars to address current research gaps, expand research developments, and contribute to the existing body of knowledge. Finally, as HMI devices utilizing wearable IoT sensors can be applied in numerous domains, it is crucial for researchers in various fields, particularly in the construction domain, to explore and engage with the suggested study directions.

6.3. Limitations of the study

It is common for studies to have limitations in their methodology and study design, which can influence the results and conclusions drawn. As observed in this review, several shortcomings should be noted and addressed. Initially, this review may not include the latest articles published after February 2024 and other relevant articles from conference proceedings. Therefore, future studies should incorporate more conference articles and recently published articles. Second, during the literature screening step utilizing the Scopus database, this review was restricted to literature written in English and focused on subject areas such as healthcare, manufacturing, and sports, thereby excluding research in other languages and valid studies in other sectors. Hence, future research should include peer-reviewed journal articles from databases like Web of Science, ScienceDirect, and others.

CRediT authorship contribution statement

Qihan JIANG: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Maxwell Fordjour Antwi-Afari:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Sina FADAIE:** Writing – review & editing, Visualization. **Jie LIU:** Writing – review & editing, Visualization. **Hao-Yang MI:** Writing – review & editing, Visualization, Resources. **Shahnawaz ANWER:** Writing – review & editing, Visualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability

Data will be made available on request.

Acknowledgements

The authors are grateful to the Department of Civil Engineering, Aston University, UK, for supporting this research. The authors are also grateful to the Editor and reviewers for their comments to improve the quality of this paper. This paper forms part of the first author's research project where similar research backgrounds but different scopes and/or analyses may have been published.

References

[1] Y. Zou, P. Tan, B. Shi, H. Ouyang, D. Jiang, Z. Liu, H. Li, M. Yu, C. Wang, X. Qu, L. Zhao, Y. Fan, Z.L. Wang, Z. Li, A bionic stretchable nanogenerator for underwater sensing and energy harvesting, Nat. Commun. 10 (2019) 2695, https://doi.org/10.1038/s41467-019-10433-4.

[2] H. Ouyang, Z. Li, The first technology can compete with piezoelectricity to harvest ultrasound energy for powering medical implants, Sci. Bull. (Beijing) 64 (2019) 1565–1566, https://doi.org/10.1016/j.scib.2019.09.010.

[3] Aaryashree, S. Sahoo, P. Walke, S.K. Nayak, C.S. Rout, D.J. Late, Recent developments in self-powered smart chemical sensors for wearable electronics, Nano Res. 14 (2021) 3669–3689, https://doi.org/10.1007/s12274-021-3330-8.

[4] J. Dai, L. Li, B. Shi, Z. Li, Recent progress of self-powered respiration monitoring systems, Biosens. Bioelectron. 194 (2021) 113609, https://doi.org/10.1016/j.bios.2021.113609.

[5] P. Tan, Y. Zou, Y. Fan, Z. Li, Self-powered wearable electronics, (n.d.).

[6] X. Yu, Y. Fu, X. Cai, H. Kafafy, H. Wu, M. Peng, S. Hou, Z. Lv, S. Ye, D. Zou, Flexible fiber-type zinc–carbon battery based on carbon fiber electrodes, Nano Energy 2 (2013) 1242–1248, https://doi.org/10.1016/j.nanoen.2013.06.002.

[7] L. Wang, X. Fu, J. He, X. Shi, T. Chen, P. Chen, B. Wang, H. Peng, Application challenges in fiber and textile electronics, Adv. Mater. 32 (2020) 1901971, https://doi.org/10.1002/adma.201901971.

[8] D. Jiang, B. Shi, H. Ouyang, Y. Fan, Z.L. Wang, Z. Li, Emerging Implantable energy harvesters and self-powered implantable medical electronics, ACS Nano 14 (2020) 6436–6448, https://doi.org/10.1021/acsnano.9b08268.

[9] W. Liu, Z. Long, G. Yang, L. Xing, A self-powered wearable motion sensor for monitoring volleyball skill and building big sports data, Biosensors 12 (2022) 60, https://doi.org/10.3390/bios12020060.

[10] L. Manjakkal, S. Mitra, Y.R. Petillot, J. Shutler, E.M. Scott, M. Willander, R. Dahiya, Connected sensors, innovative sensor deployment, and intelligent data analysis for online water quality monitoring, IEEE Internet Things J. 8 (2021) 13805–13824, https://doi.org/10.1109/JIOT.2021.3081772.

[11] S. Mohsen, A. Zekry, K. Youssef, M. Abouelatta, A Self-powered wearable wireless sensor system powered by a hybrid energy harvester for healthcare applications, Wirel. Pers. Commun. 116 (2021) 3143–3164, https://doi.org/10.1007/s11277-020-07840-y.

[12] T.G. Stavropoulos, A. Papastergiou, L. Mpaltadoros, S. Nikolopoulos, I. Kompatsiaris, IoT wearable sensors and devices in elderly care: a literature review, Sensors 20 (2020) 2826, https://doi.org/10.3390/s20102826.

[13] H. Landaluce, L. Arjona, A. Perallos, F. Falcone, I. Angulo, F. Muralter, A Review of IoT sensing applications and challenges using RFID and wireless sensor networks, Sensors 20 (2020) 2495, https://doi.org/10.3390/s20092495.

[14] Y.-F.Y. Chan, P. Wang, L. Rogers, N. Tignor, M. Zweig, S.G. Hershman, N. Genes, E.R. Scott, E. Krock, M. Badgeley, R. Edgar, S. Violante, R. Wright, C.A. Powell, J. T. Dudley, E.E. Schadt, The Asthma mobile health study, a large-scale clinical observational study using researchKit, Nat. Biotechnol. 35 (2017) 354–362, https://doi.org/10.1038/nbt.3826.

[15] D.V. Dimitrov, Medical internet of things and big data in healthcare, Health Inf. Res 22 (2016) 156–163, https://doi.org/10.4258/hir.2016.22.3.156.

[16] S.M. Hossain, T. Hnat, N. Saleheen, N.J. Nasrin, J. Noor, B.-J. Ho, T. Condie, M. Srivastava, S. Kumar, mCerebrum: A Mobile Sensing Software Platform for Development and Validation of Digital Biomarkers and Interventions. Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems, Association for Computing Machinery, New York, NY, USA, 2017, pp. 1–14, https://doi.org/10.1145/3131672.3131694.

[17] S.M.R. Islam, D. Kwak, M.D.H. Kabir, M. Hossain, K.-S. Kwak, The internet of things for health care: a comprehensive survey, IEEE Access 3 (2015) 678–708, https://doi.org/10.1109/ACCESS.2015.2437951.

[18] B. Li, Q. Dong, R.S. Downen, N. Tran, J.H. Jackson, D. Pillai, M. Zaghloul, Z. Li, A wearable IoT aldehyde sensor for pediatric asthma research and management, Sens. Actuators B: Chem. 287 (2019) 584–594, https://doi.org/10.1016/j.snb.2019.02.077.

[19] O.D. Lara, M.A. Labrador, A survey on human activity recognition using wearable sensors, IEEE Commun. Surv. Tutor. 15 (2013) 1192–1209, https://doi.org/10.1109/SURV.2012.110112.00192.

[20] J. Ko, C. Lu, M.B. Srivastava, J.A. Stankovic, A. Terzis, M. Welsh, Wireless Sensor Networks for Healthcare, Proc. IEEE 98 (2010) 1947–1960, https://doi.org/10.1109/JPROC.2010.2065210.

[21] S. Patel, H. Park, P. Bonato, L. Chan, M. Rodgers, A review of wearable sensors and systems with application in rehabilitation, J. Neuroeng. Rehabil. 9 (2012) 21, https://doi.org/10.1186/1743-0003-9-21.

[22] N. Saleheen, A.A. Ali, S.M. Hossain, H. Sarker, S. Chatterjee, B. Marlin, E. Ertin, M. al'Absi, S. Kumar, puffMarker: a multi-sensor approach for pinpointing the timing of first lapse in smoking cessation. Proceedings of the 2015 ACM

International Joint Conference on Pervasive and Ubiquitous Computing, Association for Computing Machinery, New York, NY, USA, 2015, pp. 999–1010, https://doi.org/10.1145/2750858.2806897.

[23] E. Wilhelm, S. Siby, Y. Zhou, X.J.S. Ashok, M. Jayasuriya, S. Foong, J. Kee, K. L. Wood, N.O. Tippenhauer, Wearable environmental sensors and infrastructure for mobile large-scale urban deployment, IEEE Sens. J. 16 (2016) 8111–8123, https://doi.org/10.1109/JSEN.2016.2603158.

[24] C. Gong, Human-machine interface: design principles of visual information in human-machine interface design, : 2009 Int. Conf. Intell. Hum. -Mach. Syst. Cybern. (2009) 262–265, https://doi.org/10.1109/IHMSC.2009.189.

[25] H.S. Saini, R.D. Daruwala, Human machine interface in internet of things system, : 2016 Int. Conf. Comput. Commun. Control Autom. (ICCUBEA) (2016) 1–4, https://doi.org/10.1109/ICCUBEA.2016.7860151.

[26] N. Kumar, S.C. Lee, Human-machine interface in smart factory: A systematic literature review, Technol. Forecast. Soc. Change 174 (2022) 121284, https://doi.org/10.1016/j.techfore.2021.121284.

[27] S. Aghaei, Evolution of the World Wide Web: From Web 1.0 to Web 4.0, IJWesT 3 (2012) 1–10, https://doi.org/10.5121/ijwest.2012.3101.

[28] S. Adwernat, M. Wolf, D. Gerhard, Optimizing the design review process for cyber-physical systems using virtual reality, Procedia CIRP 91 (2020) 710–715, https://doi.org/10.1016/j.procir.2020.03.115.

[29] V. Alcácer, V. Cruz-Machado, Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems, Eng. Sci. Technol., Int. J. 22 (2019) 899–919, https://doi.org/10.1016/j.jestch.2019.01.006.

[30] D. Gorecky, M. Schmitt, M. Loskyll, D. Zühlke, Human-machine-interaction in the industry 4.0 era, : 2014 12th IEEE Int. Conf. Ind. Inform. (INDIN) (2014) 289–294, https://doi.org/10.1109/INDIN.2014.6945523.

[31] M. Abrash, Creating the future: augmented reality, the next human-machine interface, : 2021 IEEE Int. Electron Devices Meet. (IEDM) (2021) 1–11, https://doi.org/10.1109/IEDM19574.2021.9720526.

[32] Y. Wang, B. Yang, Z. Hua, J. Zhang, P. Guo, D. Hao, Y. Gao, J. Huang, Recent advancements in flexible and wearable sensors for biomedical and healthcare applications, J. Phys. D: Appl. Phys. 55 (2021) 134001, https://doi.org/10.1088/1361-6463/ac3c73.

[33] T. Zhang, L. Xie, J. Li, Z. Huang, H. Lei, Y. Liu, Z. Wen, Y. Xie, X. Sun, All-in-one self-powered human–machine interaction system for wireless remote telemetry and control of intelligent cars, Nanomaterials 11 (2021) 2711, https://doi.org/10.3390/nano11102711.

[34] D. Sehrawat, N.S. Gill, Smart sensors: analysis of different types of iot sensors, : 2019 3rd Int. Conf. Trends Electron. Inform. (ICOEI) (2019) 523–528, https://doi.org/10.1109/ICOEI.2019.8862778.

[35] H. Wang, X. Xia, J. Fu, J. Li, C. Chen, Y. Dai, Z. Fan, G. Hu, Y. Zi, A general self-powered wireless sensing solution based on triboelectric-discharge effect, Nano Energy 105 (2023) 107982, https://doi.org/10.1016/j.nanoen.2022.107982.

[36] Z. Liu, S. Zhang, Y.M. Jin, H. Ouyang, Y. Zou, X.X. Wang, L.X. Xie, Z. Li, Flexible piezoelectric nanogenerator in wearable self-powered active sensor for respiration and healthcare monitoring, Semicond. Sci. Technol. 32 (2017) 064004, https://doi.org/10.1088/1361-6641/aa68d1.

[37] H. Ouyang, J. Tian, G. Sun, Y. Zou, Z. Liu, H. Li, L. Zhao, B. Shi, Y. Fan, Y. Fan, Z. L. Wang, Z. Li, Self-Powered Pulse Sensor for Antidiastole of Cardiovascular Disease, Adv. Mater. 29 (2017) 1703456, https://doi.org/10.1002/adma.201703456.

[38] P. Tan, Q. Zheng, Y. Zou, B. Shi, D. Jiang, X. Qu, H. Ouyang, C. Zhao, Y. Cao, Y. Fan, Z.L. Wang, Z. Li, A Battery-Like Self-Charge Universal Module for Motional Energy Harvest, Adv. Energy Mater. 9 (2019) 1901875, https://doi.org/10.1002/aenm.201901875.

[39] D. Zhang, Y. Song, L. Ping, S. Xu, D. Yang, Y. Wang, Y. Yang, Photo-thermoelectric effect induced electricity in stretchable graphene-polymer nanocomposites for ultrasensitive strain sensing, Nano Res 12 (2019) 2982–2987, https://doi.org/10.1007/s12274-019-2541-2.

[40] Z. Zhang, X. Li, G. Guan, S. Pan, Z. Zhu, D. Ren, H. Peng, A Lightweight Polymer Solar Cell Textile that Functions when Illuminated from Either Side, Angew. Chem. Int. Ed. 53 (2014) 11571–11574, https://doi.org/10.1002/anie.201407688.

[41] X.-Z. Jiang, Y.-J. Sun, Z. Fan, T.-Y. Zhang, Integrated Flexible, Waterproof, Transparent, and Self-Powered Tactile Sensing Panel, ACS Nano 10 (2016) 7696–7704, https://doi.org/10.1021/acsnano.6b03042.

[42] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, Z.L. Wang, Self-powered nanowire devices, Nat. Nanotechnol. 5 (2010) 366–373, https://doi.org/10.1038/nnano.2010.46.

[43] Z. Wu, T. Cheng, Z.L. Wang, Self-Powered Sensors and Systems Based on Nanogenerators, Sensors 20 (2020) 2925, https://doi.org/10.3390/s20102925.

[44] P. Maharjan, T. Bhatta, H. Cho, X. Hui, C. Park, S. Yoon, M. Salauddin, M. T. Rahman, S.S. Rana, J.Y. Park, A Fully Functional Universal Self-Chargeable Power Module for Portable/Wearable Electronics and Self-Powered IoT Applications, Adv. Energy Mater. 10 (2020) 2002782, https://doi.org/10.1002/aenm.202002782.

[45] L. Liu, X. Guo, W. Liu, C. Lee, Recent Progress in the Energy Harvesting Technology—From Self-Powered Sensors to Self-Sustained IoT, and New Applications, Nanomaterials 11 (2021) 2975, https://doi.org/10.3390/nano11112975.

[46] M. Zhu, Z. Yi, B. Yang, C. Lee, Making use of nanoenergy from human – Nanogenerator and self-powered sensor enabled sustainable wireless IoT sensory systems, Nano Today 36 (2021) 101016, https://doi.org/10.1016/j.nantod.2020.101016.

[47] J. Li, C. Carlos, H. Zhou, J. Sui, Y. Wang, Z. Silva-Pedraza, F. Yang, Y. Dong, Z. Zhang, T.A. Hacker, B. Liu, Y. Mao, X. Wang, Stretchable piezoelectric biocrystal thin films, Nat. Commun. 14 (2023) 6562, https://doi.org/10.1038/s41467-023-42184-8.

[48] M. Ha, J. Park, Y. Lee, H. Ko, Triboelectric Generators and Sensors for Self-Powered Wearable Electronics, ACS Nano 9 (2015) 3421–3427, https://doi.org/10.1021/acsnano.5b01478.

[49] F. Akhtar, M.H. Rehmani, Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review, Renew. Sustain. Energy Rev. 45 (2015) 769–784, https://doi.org/10.1016/j.rser.2015.02.021.

[50] H. Elahi, K. Munir, M. Eugeni, S. Atek, P. Gaudenzi, Energy Harvesting towards Self-Powered IoT Devices, (2020).

[51] A. Alagumalai, W. Shou, O. Mahian, M. Aghbashlo, M. Tabatabaei, S. Wongwises, Y. Liu, J. Zhan, A. Torralba, J. Chen, Z. Wang, W. Matusik, Self-powered sensing systems with learning capability, Joule 6 (2022) 1475–1500, https://doi.org/10.1016/j.joule.2022.06.001.

[52] G. Johannsen, Knowledge-based design of human-machine interfaces, Control Eng. Pract. 3 (1995) 267–273, https://doi.org/10.1016/0967-0661(94)00085-U.

[53] D. Mourtzis, J. Angelopoulos, N. Panopoulos, The Future of the Human–Machine Interface (HMI) in Society 5.0, Future Internet 15 (2023) 162, https://doi.org/10.3390/fi15050162.

[54] A. Wołczowski, M. Kurzyński, Human–machine interface in bioprosthesis control using EMG signal classification, Expert Syst. 27 (2010) 53–70, https://doi.org/10.1111/j.1468-0394.2009.00526.x.

[55] G. Johannsen, Conceptual design of multi-human machine interfaces, Control Eng. Pract. 5 (1997) 349–361, https://doi.org/10.1016/S0967-0661(97)00012-9.

[56] R. Vaidyanathan, B. Chung, L. Gupta, H. Kook, S. Kota, J.D. West, Tongue-Movement Communication and Control Concept for Hands-Free Human–Machine Interfaces, IEEE Trans. Syst., Man, Cybern. - Part A: Syst. Hum. 37 (2007) 533–546, https://doi.org/10.1109/TSMCA.2007.897919.

[57] A.M. Dearden, M.D. Harrison, Impact and the design of the human-machine interface, IEEE Aerosp. Electron. Syst. Mag. 12 (1997) 19–25, https://doi.org/10.1109/62.577434.

[58] M. Friedrich, M. Vollrath, Human–Machine Interface Design for Monitoring Safety Risks Associated with Operating Small Unmanned Aircraft Systems in Urban Areas, Aerospace 8 (2021) 71, https://doi.org/10.3390/aerospace8030071.

[59] P. Kerschbaum, L. Lorenz, S. Hergeth, K. Bengler, Designing the human-machine interface for highly automated cars — Challenges, exemplary concepts and studies, : 2015 IEEE Int. Workshop Adv. Robot. Its Soc. Impacts (ARSO) (2015) 1–6, https://doi.org/10.1109/ARSO.2015.7428223.

[60] D. Rozhdestvenskiy, P. Bouchner, A. Mashko, K. Abishev, R. Mukanov, Dynamic Human-Machine Interface for Electrical vehicle design guidelines, Smart Cities Symp. . Prague (SCSP) 2015 (2015) 1–5, https://doi.org/10.1109/SCSP.2015.7181573.

[61] V.V. Khramov, Development of a Human-Machine Interface Based on Hybrid Intelligence, СовреМенные ИнфорМационные Технологии и ИТ-Образование 16 (2020) 893–900, https://doi.org/10.25559/SITITO.16.202004.893-900.

[62] F. Wen, T. He, H. Liu, H.-Y. Chen, T. Zhang, C. Lee, Advances in chemical sensing technology for enabling the next-generation self-sustainable integrated wearable system in the IoT era, Nano Energy 78 (2020) 105155, https://doi.org/10.1016/j.nanoen.2020.105155.

[63] J. Lama, A. Yau, G. Chen, A. Sivakumar, X. Zhao, J. Chen, Textile triboelectric nanogenerators for self-powered biomonitoring, J. Mater. Chem. A 9 (2021) 19149–19178, https://doi.org/10.1039/D1TA02518J.

[64] H. Baali, H. Djelouat, A. Amira, F. Bensaali, Empowering Technology Enabled Care Using IoT and Smart Devices: A Review, IEEE Sens. J. 18 (2018) 1790–1809, https://doi.org/10.1109/JSEN.2017.2786301.

[65] M.A. Wahba, A.S. Ashour, R. Ghannam, Prediction of Harvestable Energy for Self-Powered Wearable Healthcare Devices: Filling a Gap, IEEE Access 8 (2020) 170336–170354, https://doi.org/10.1109/ACCESS.2020.3024167.

[66] Y. Wang, Y. Yu, X. Wei, F. Narita, Self-Powered Wearable Piezoelectric Monitoring of Human Motion and Physiological Signals for the Postpandemic Era: A Review, Adv. Mater. Technol. 7 (2022) 2200318, https://doi.org/10.1002/admt.202200318.

[67] M. Jiang, Y. Lu, Z. Zhu, W. Jia, Advances in Smart Sensing and Medical Electronics by Self-Powered Sensors Based on Triboelectric Nanogenerators, Micromachines 12 (2021) 698, https://doi.org/10.3390/mi12060698.

[68] B. Dong, Q. Shi, Y. Yang, F. Wen, Z. Zhang, C. Lee, Technology evolution from self-powered sensors to AIoT enabled smart homes, Nano Energy 79 (2021) 105414, https://doi.org/10.1016/j.nanoen.2020.105414.

[69] L. Yang, Z. Ma, Y. Tian, B. Meng, Z. Peng, Progress on Self-Powered Wearable and Implantable Systems Driven by Nanogenerators, Micromachines 12 (2021) 666, https://doi.org/10.3390/mi12060666.

[70] X. Mu, M.F. Antwi-Afari, The applications of Internet of Things (IoT) in industrial management: a science mapping review, Int. J. Prod. Res. 62 (2024) 1928–1952, https://doi.org/10.1080/00207543.2023.2290229.

[71] P. Pluye, Q.N. Hong, Combining the Power of Stories and the Power of Numbers: Mixed Methods Research and Mixed Studies Reviews, Annu. Rev. Public Health 35 (2014) 29–45, https://doi.org/10.1146/annurev-publhealth-032013-182440.

[72] X. Ding, Z. Yang, Knowledge mapping of platform research: a visual analysis using VOSviewer and CiteSpace, Electron. Commer. Res. 22 (2022) 787–809, https://doi.org/10.1007/s10660-020-09410-7.

[73] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, The PRISMA Group, Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA

Statement, PLOS Med. 6 (2009) e1000097, https://doi.org/10.1371/journal.pmed.1000097.
[74] M.J. Page, D. Moher, P.M. Bossuyt, I. Boutron, J.E. Mckenzie, PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews, BMJ (Online) 372 (2021) n160, https://doi.org/10.1136/bmj.n160.
[75] M.J. Page, D. Moher, Evaluations of the uptake and impact of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Statement and extensions: a scoping review, Syst. Rev. 6 (2017) 263, https://doi.org/10.1186/s13643-017-0663-8.
[76] M.J. Page, J.E. Mckenzie, P.M. Bossuyt, I. Boutron, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, Syst. Rev. 10 (2021), https://doi.org/10.1186/s13643-021-01626-4.
[77] A.A. Chadegani, H. Salehi, M.M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, N. A. Ebrahim, A Comparison between Two Main Academic Literature Collections: Web of Science and Scopus Databases, Asian Soc. Sci. 9 (2013) p18, https://doi.org/10.5539/ass.v9n5p18.
[78] T.O. Olawumi, D.W.M. Chan, J.K.W. Wong, Evolution in the intellectual structure of BIM research: a bibliometric analysis, J. Civ. Eng. Manag. 23 (2017) 1060–1081, https://doi.org/10.3846/13923730.2017.1374301.
[79] W. Xu, S. Liu, J. Yang, Y. Meng, S. Liu, G. Chen, L. Jia, X. Li, Self-powered flexible handwriting input panel with 1D output enabled by convolutional neural network, Nano Energy 101 (2022) 107557, https://doi.org/10.1016/j.nanoen.2022.107557.
[80] G. Ye, Y. Wan, J. Wu, W. Zhuang, Z. Zhou, T. Jin, J. Zi, D. Zhang, X. Geng, P. Yang, Multifunctional device integrating dual-temperature regulator for outdoor personal thermal comfort and triboelectric nanogenerator for self-powered human-machine interaction, Nano Energy (2022).
[81] X. Li, P. Zhu, S. Zhang, X. Wang, X. Luo, Z. Leng, H. Zhou, Z. Pan, Y. Mao, A Self-Supporting, Conductor-Exposing, Stretchable, Ultrathin, and Recyclable Kirigami-Structured Liquid Metal Paper for Multifunctional E-Skin, ACS Nano 16 (2022) 5909–5919, https://doi.org/10.1021/acsnano.1c11096.
[82] Y. Su, W. Li, L. Yuan, C. Chen, H. Pan, G. Xie, G. Conta, S. Ferrier, X. Zhao, G. Chen, H. Tai, Y. Jiang, J. Chen, Piezoelectric fiber composites with polydopamine interfacial layer for self-powered wearable biomonitoring, Nano Energy 89 (2021) 106321, https://doi.org/10.1016/j.nanoen.2021.106321.
[83] J. Nie, G. Hu, L. Li, Y. Zhang, Piezotronic Analog-To-Digital Converters Based on Strain-gated Transistors, Nano Energy (2018) S2211285518301022.
[84] D. Fang, S. Ding, Z. Dai, J. Zhong, B. Zhou, Wearable patch with direction-aware sensitivity of in-plane force for self-powered and single communication channel based human-machine interaction, Chem. Eng. J. 468 (2023) 143664, https://doi.org/10.1016/j.cej.2023.143664.
[85] J. Zhao, D. Wang, F. Zhang, Y. Liu, B. Chen, Z.L. Wang, J. Pan, R. Larsson, Y. Shi, Real-Time and Online Lubricating Oil Condition Monitoring Enabled by Triboelectric Nanogenerator, ACS Nano 15 (2021) 11869–11879, https://doi.org/10.1021/acsnano.1c02980.
[86] Y. Cao, J. Figueroa, W. Li, Z. Chen, Z.L. Wang, N. Sepúlveda, Understanding the dynamic response in ferroelectret nanogenerators to enable self-powered tactile systems and human-controlled micro-robots, Nano Energy 63 (2019) 103852, https://doi.org/10.1016/j.nanoen.2019.06.048.
[87] N. Genc-Nayebi, A. Abran, A systematic literature review: Opinion mining studies from mobile app store user reviews, J. Syst. Softw. 125 (2017) 207–219, https://doi.org/10.1016/j.jss.2016.11.027.
[88] S. Mohamad Suhaili, N. Salim, M.N. Jambli, Service chatbots: A systematic review, Expert Syst. Appl. 184 (2021) 115461, https://doi.org/10.1016/j.eswa.2021.115461.
[89] A.B. Saka, L.O. Oyedele, L.A. Akanbi, S.A. Ganiyu, D.W.M. Chan, S.A. Bello, Conversational artificial intelligence in the AEC industry: A review of present status, challenges and opportunities, Adv. Eng. Inform. 55 (2023) 101869, https://doi.org/10.1016/j.aei.2022.101869.
[90] P. Hallinger, J. Kovačević, A Bibliometric Review of Research on Educational Administration: Science Mapping the Literature, 1960 to 2018, Rev. Educ. Res. (2019), https://doi.org/10.3102/0034654319830380.
[91] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, Science mapping software tools: Review, analysis, and cooperative study among tools, (n.d.). 〈https://doi.org/10.1002/asi.21525〉.
[92] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, L. He, A scientometric analysis and critical review of construction related ontology research, Autom. Constr. 101 (2019) 17–31, https://doi.org/10.1016/j.autcon.2018.12.013.
[93] P. Martinez, M. Al-Hussein, D.R. Ahmad, A scientometric analysis and critical review of computer vision applications for construction, Autom. Constr. 107 (2019) 102947.
[94] N.J. van Eck, L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics 84 (2010) 523–538, https://doi.org/10.1007/s11192-009-0146-3.
[95] W. Sun, M.F. Antwi-Afari, I. Mehmood, S. Anwer, W. Umer, Critical success factors for implementing blockchain technology in construction, Autom. Constr. 156 (2023) 105135, https://doi.org/10.1016/j.autcon.2023.105135.
[96] C. Debrah, A.P.C. Chan, A. Darko, Artificial intelligence in green building, Autom. Constr. 137 (2022) 104192, https://doi.org/10.1016/j.autcon.2022.104192.
[97] N. Gogurla, B. Roy, S. Kim, Self-powered artificial skin made of engineered silk protein hydrogel, Nano Energy 77 (2020) 105242, https://doi.org/10.1016/j.nanoen.2020.105242.
[98] H.-N. Su, P.-C. Lee, Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in Technology Foresight, Scientometrics 85 (2010) 65–79, https://doi.org/10.1007/s11192-010-0259-8.
[99] C. Yuan, G. Li, S. Kamarthi, X. Jin, M. Moghaddam, Trends in intelligent manufacturing research: a keyword co-occurrence network based review, J. Intell. Manuf. 33 (2022) 425–439, https://doi.org/10.1007/s10845-021-01885-x.
[100] R. Jin, P.X.W. Zou, P. Piroozfar, H. Wood, Y. Yang, L. Yan, Y. Han, A science mapping approach based review of construction safety research, Saf. Sci. 113 (2019) 285–297, https://doi.org/10.1016/j.ssci.2018.12.006.
[101] M.F. Antwi-Afari, H. Li, A.H.S. Chan, J. Seo, S. Anwer, H.-Y. Mi, Z. Wu, A.Y. L. Wong, A science mapping-based review of work-related musculoskeletal disorders among construction workers, J. Saf. Res. 85 (2023) 114–128, https://doi.org/10.1016/j.jsr.2023.01.011.
[102] S.W. Chen, X. Cao, N. Wang, L. Ma, H.R. Zhu, M. Willander, Y. Jie, Z.L. Wang, An Ultrathin Flexible Single-Electrode Triboelectric-Nanogenerator for Mechanical Energy Harvesting and Instantaneous Force Sensing, Adv. Energy Mater. 7 (2017) 1601255, https://doi.org/10.1002/aenm.201601255.
[103] T. Chen, Q. Shi, K. Li, Z. Yang, H. Liu, L. Sun, J.A. Dziuban, C. Lee, Investigation of Position Sensing and Energy Harvesting of a Flexible Triboelectric Touch Pad, (2018).
[104] H.-Y. Mi, X. Jing, Q. Zheng, L. Fang, H.-X. Huang, L.-S. Turng, S. Gong, High-performance flexible triboelectric nanogenerator based on porous aerogels and electrospun nanofibers for energy harvesting and sensitive self-powered sensing, Nano Energy 48 (2018) 327–336, https://doi.org/10.1016/j.nanoen.2018.03.050.
[105] P. Munirathinam, A.A. Mathew, V. Shanmugasundaram, V. Vivekananthan, Y. Purusothaman, S.-J. Kim, A. Chandrasekhar, A comprehensive review on triboelectric nanogenerators based on Real-Time applications in energy harvesting and Self-Powered sensing, Mater. Sci. Eng.: B (2023).
[106] V. Slabov, S. Kopyl, M.P. Soares dos Santos, A.L. Kholkin, Natural and Eco-Friendly Materials for Triboelectric Energy Harvesting, Nano-Micro Lett. 12 (2020) 42, https://doi.org/10.1007/s40820-020-0373-y.
[107] J. Tian, X. Chen, Z.L. Wang, Environmental energy harvesting based on triboelectric nanogenerators, Nanotechnology 31 (2020) 242001 (30pp).
[108] W. Ding, A.C. Wang, C. Wu, H. Guo, Z.L. Wang, Human–Machine Interfacing Enabled by Triboelectric Nanogenerators and Tribotronics, John Wiley & Sons, Ltd, 2019.
[109] Y. Luo, Z. Wang, J. Wang, X. Xiao, H.Y. Fu, Triboelectric Bending Sensor based Smart Glove towards Intuitive Multi-Dimensional Human-Machine Interfaces, Nano Energy 89 (2021) 106330.
[110] K. Wildner, A Coupled Piezoelectric Sensor for MMG-Based Human-Machine Interfaces, Sensors 21 (2021).
[111] Q. Shi, Z. Zhang, T. Chen, C. Lee, Minimalist and multi-functional human machine interface (HMI) using a flexible wearable triboelectric patch, Nano Energy 62 (2019) 355–366, https://doi.org/10.1016/j.nanoen.2019.05.033.
[112] J. Xu, J. Pan, T. Cui, S. Zhang, Y. Yang, T.-L. Ren, Recent Progress of Tactile and Force Sensors for Human–Machine Interaction, Sensors 23 (2023) 1868, https://doi.org/10.3390/s23041868.
[113] C. Chi, X. Sun, N. Xue, T. Li, C. Liu, Recent Progress in Technologies for Tactile Sensors, Sensors 18 (2018) 948, https://doi.org/10.3390/s18040948.
[114] H. Souri, H. Banerjee, A. Jusufi, N. Radacsi, A.A. Stokes, I. Park, M. Sitti, M. Amjadi, Wearable and Stretchable Strain Sensors: Materials, Sensing Mechanisms, and Applications, Adv. Intell. Syst. 2 (2020) 2000039, https://doi.org/10.1002/aisy.202000039.
[115] P. Soonjae, L. Jaeyong, B.K.S. Jongbaeg, Recent Progress in Flexible Tactile Sensors for Human-Interactive Systems: From Sensors to Advanced Applications, Adv. Mater. 33 (2021) 2005902.1–2005902.26.
[116] T.-T. Huang, W. Wu, Inkjet-Printed Wearable Nanosystems for Self-Powered Technologies, Adv. Mater. Interfaces 7 (2020) 2000015, https://doi.org/10.1002/admi.202000015.
[117] E.P. Gilshteyn, D. Amanbaev, M.V. Silibin, A. Sysa, V.A. Kondrashov, A. S. Anisimov, T. Kallio, A.G. Nasibulin, Flexible self-powered piezo-supercapacitor system for wearable electronics, Nanotechnology 29 (2018) 325501, https://doi.org/10.1088/1361-6528/aac658.
[118] Y. Lu, Z. Lou, K. Jiang, D. Chen, G. Shen, Recent progress of self-powered wearable monitoring systems integrated with microsupercapacitors, Mater. Today Nano 8 (2019) 100050, https://doi.org/10.1016/j.mtnano.2019.100050.
[119] J. Zhao, J. Zha, Z. Zeng, C. Tan, Recent advances in wearable self-powered energy systems based on flexible energy storage devices integrated with flexible solar cells, J. Mater. Chem. A 9 (2021) 18887–18905, https://doi.org/10.1039/D1TA02493K.
[120] X. Zhang, Y. Jing, Q. Zhai, Y. Yu, H. Xing, J. Li, E. Wang, Point-of-Care Diagnoses: Flexible Patterning Technique for Self-Powered Wearable Sensors, Anal. Chem. 90 (2018) 11780–11784, https://doi.org/10.1021/acs.analchem.8b02838.
[121] J. Yuan, R. Zhu, A fully self-powered wearable monitoring system with systematically optimized flexible thermoelectric generator, Appl. Energy 271 (2020) 115250, https://doi.org/10.1016/j.apenergy.2020.115250.
[122] K. Yu, S. Rich, S. Lee, K. Fukuda, T. Yokota, T. Someya, Organic Photovoltaics: Toward Self-Powered Wearable Electronics, Proc. IEEE 107 (2019) 2137–2154, https://doi.org/10.1109/JPROC.2019.2929797.
[123] S. Shi, Y. Jiang, Q. Xu, J. Zhang, Y. Zhang, J. Li, Y. Xie, Z.-P. Cao, A self-powered triboelectric multi-information motion monitoring sensor and its application in wireless real-time control, Nano Energy 97 (2022) 107150, https://doi.org/10.1016/j.nanoen.2022.107150.
[124] V. Leonov, R.J.M. Vullers, Wearable electronics self-powered by using human body heat: The state of the art and the perspective, J. Renew. Sustain. Energy 1 (2009) 062701, https://doi.org/10.1063/1.3255465.

[125] Z. Zhang, F. Wen, Z. Sun, X. Guo, T. He, C. Lee, Artificial Intelligence-Enabled Sensing Technologies in the 5G/Internet of Things Era: From Virtual Reality/ Augmented Reality to the Digital Twin, Adv. Intell. Syst. 4 (2022) 2100228, https://doi.org/10.1002/aisy.202100228.
[126] J. Zhu, S. Ji, J. Yu, H. Shao, H. Wen, H. Zhang, Z. Xia, Z. Zhang, C. Lee, Machine learning-augmented wearable triboelectric human-machine interface in motion identification and virtual reality, Nano Energy 103 (2022) 107766, https://doi.org/10.1016/j.nanoen.2022.107766.
[127] F. Moncada, S. Martín, V.M. González, V.M. Álvarez, B. García-López, A.I. Gómez-Menéndez, J.R. Villar, Virtual reality and machine learning in the automatic photoparoxysmal response detection, Neural Comput. Applic 35 (2023) 5643–5659, https://doi.org/10.1007/s00521-022-06940-z.
[128] N. Martin, N. Mathieu, N. Pallamin, M. Ragot, J.-M. Diverrez, Virtual reality sickness detection: an approach based on physiological signals and machine learning, : 2020 IEEE Int. Symp. . Mixed Augment. Real. (ISMAR) (2020) 387–399, https://doi.org/10.1109/ISMAR50242.2020.00065.
[129] W. Juan, Gesture recognition and information recommendation based on machine learning and virtual reality in distance education, J. Intell. Fuzzy Syst. 40 (2021) 7509–7519, https://doi.org/10.3233/JIFS-189572.
[130] M.R. Fraune, A.S. Khalaf, M. Zemedie, P. Pianpak, Z. NaminiMianji, S.A. Alharthi, I. Dolgov, B. Hamilton, S. Tran, P.O. Toups, Dugas, Developing Future Wearable Interfaces for Human-Drone Teams through a Virtual Drone Search Game, Int. J. Hum. -Comput. Stud. 147 (2021) 102573, https://doi.org/10.1016/j.ijhcs.2020.102573.
[131] F. Covaciu, A.-E. Iordan, Control of a Drone in Virtual Reality Using MEMS Sensor Technology and Machine Learning, (2022).
[132] T. Zhang, Y. Ding, C. Hu, M. Zhang, W. Zhu, C.R. Bowen, Y. Han, Y. Yang, Self-Powered Stretchable Sensor Arrays Exhibiting Magnetoelasticity for Real-Time Human–Machine Interaction, Adv. Mater. (2023) 35.
[133] X. Shi, S. Zhang, S. Gong, A self-powered and arch-structured triboelectric nanogenerator for portable electronics and human-machine communication, J. Mater. Chem. A 8 (2020), https://doi.org/10.1039/D0TA02178D.
[134] H. Hu, F. Zhang, Rational design of self-powered sensors with polymer nanocomposites for human–machine interaction, Chin. J. Aeronaut. 35 (2022) 155–177, https://doi.org/10.1016/j.cja.2022.04.005.
[135] H. Guo, J. Wan, H. Wang, H. Wu, H. Zhang, Self-Powered Intelligent Human-Machine Interaction for Handwriting Recognition, Research 2021 (2021) 1–9, https://doi.org/10.34133/2021/4689869.
[136] Dong Kai, Wu Zhiyi, Deng Jianan, C. Aurelia, Haiyang Wang, A Stretchable Yarn Embedded Triboelectric Nanogenerator as Electronic Skin for Biomechanical Energy Harvesting and Multifunctional Pressure Sensing, Adv. Mater. (2017), https://doi.org/10.1002/adma.201804944.
[137] Y. Yu, J. Nassar, C. Xu, J. Min, W. Gao, Biofuel-powered soft electronic skin with multiplexed and wireless sensing for human-machine interfaces, Sci. Robot. 5 (2020) eaaz7946, https://doi.org/10.1126/scirobotics.aaz7946.
[138] Ran Cao, Xianjie Pu, Xinyu Du, Wei Yang, Jiaona Wang, Hengyu Guo, Shuyu Zhao, Zuqing Yuan, Chi Zhang, Congju Li, Screen-Printed Washable Electronic Textiles as Self-Powered Touch/Gesture Tribo-Sensors for Intelligent Human-Machine Interaction, ACS Nano 12 (2018) 5190–5196, https://doi.org/10.1021/acsnano.8b02477.
[139] K. Tao, Z. Chen, J. Yu, H. Zeng, J. Wu, Z. Wu, Q. Jia, P. Li, Y. Fu, H. Chang, Ultra-Sensitive, Deformable, and Transparent Triboelectric Tactile Sensor Based on Micro-Pyramid Patterned Ionic Hydrogel for Interactive Human–Machine Interfaces, Adv. Sci. 9 (2022), https://doi.org/10.1002/advs.202104168.
[140] M. Wu, X. Wang, Y. Xia, Y. Zhu, S. Zhu, C. Jia, W. Guo, Q. Li, Z. Yan, Stretchable freezing-tolerant triboelectric nanogenerator and strain sensor based on transparent, long-term stable, and highly conductive gelatin-based organohydrogel, Nano Energy (2022). ⟨https://www.nstl.gov.cn/paper_detail.html?id=eef406fa4f9922c13a92ff26ba3251c8⟩ (accessed August 18, 2024).
[141] W. Deng, T. Yang, L. Jin, C. Yan, W. Yang, Cowpea-structured PVDF/ZnO Nanofibers Based Flexible Self-powered Piezoelectric Bending Motion Sensor Towards Remote Control of Gestures, Nano Energy 55 (2018), https://doi.org/10.1016/j.nanoen.2018.10.049.
[142] F. Wen, Z. Sun, T. He, Q. Shi, M. Zhu, Z. Zhang, L. Li, T. Zhang, C. Lee, Machine Learning Glove Using Self-Powered Conductive Superhydrophobic Triboelectric Textile for Gesture Recognition in VR/AR Applications, Adv. Sci. 7 (2020) 2000261, https://doi.org/10.1002/advs.202000261.
[143] B. Zhang, Y. Tang, R. Dai, H. Wang, X. Sun, C. Qin, Z. Pan, E. Liang, Y. Mao, Breath-based human–machine interaction system using triboelectric nanogenerator, Nano Energy 64 (n.d.). ⟨https://doi.org/10.1016/j.nanoen.2019.103953⟩.
[144] Z. Sun, M. Zhu, Z. Zhang, Z. Chen, Q. Shi, X. Shan, R.C.H. Yeow, C. Lee, Artificial Intelligence of Things (AIoT) Enabled Virtual Shop Applications Using Self-Powered Sensor Enhanced Soft Robotic Manipulator, Adv. Sci. 8 (2021) 2100230, https://doi.org/10.1002/advs.202100230.
[145] Jing Han, Chongyang Xu, Jintao Zhang, Nuo Xu, Yao Xiong, Xiaole Cao, Yuchen Liang, Li Zheng, Jia Sun, Junyi Zhai, Multifunctional Coaxial Energy Fiber toward Energy Harvesting, Storage, and Utilization, ACS Nano 15 (2021) 1597–1607, https://doi.org/10.1021/acsnano.0c09146.
[146] J. Yi, K. Dong, S. Shen, Y. Jiang, X. Peng, C. Ye, Z.L. Wang, Fully Fabric-Based Triboelectric Nanogenerators as Self-Powered Human–Machine Interactive Keyboards, Nano-Micro Lett. 13 (2021) 103, https://doi.org/10.1007/s40820-021-00621-7.
[147] J. Wang, J. He, L. Ma, Y. Yao, X. Zhu, L. Peng, X. Liu, K. Li, M. Qu, A humidity-resistant, stretchable and wearable textile-based triboelectric nanogenerator for mechanical energy harvesting and multifunctional self-powered haptic sensing, Chem. Eng. J. 423 (2021) 130200, https://doi.org/10.1016/j.cej.2021.130200.
[148] Y. Chen, E. Chen, Z. Wang, Y. Ling, R. Fisher, M. Li, J. Hart, W. Mu, W. Gao, X. Tao, B. Yang, R. Yin, Flexible, durable, and washable triboelectric yarn and embroidery for self-powered sensing and human-machine interaction, Nano Energy 104 (2022) 107929, https://doi.org/10.1016/j.nanoen.2022.107929.
[149] C.-R. Yang, C.-T. Ko, S.-F. Chang, M.-J. Huang, Study on fabric-based triboelectric nanogenerator using graphene oxide/porous PDMS as a compound friction layer, Nano Energy 92 (2022) 106791, https://doi.org/10.1016/j.nanoen.2021.106791.
[150] J. Zhang, S. Hu, Z. Shi, Yifei Lei, Yanqiang Han, Jing Xiong, Yao Sun, Jia Zheng, Li Sun, Qijun Yang, Guang Wang, Zhong Lin, Eco-friendly and recyclable all cellulose triboelectric nanogenerator and self-powered interactive interface, Nano Energy 89 (2021). ⟨https://www.zhangqiaokeyan.com/journal-foreign-detail/0704065618535.html⟩ (accessed August 18, 2024).
[151] M. Li, Wei-Yuan Li, Yi-Chiun Wu, Hsing-Mei Wu, Yan-Cheng Lu, Hong-Wei Cheng, Shueh-Lian Li, Lei Chang, Kuan-Chang Liu, Heng-Jui Lin, Yen-Fu Lin, Lu-Yin Lai, Ying-Chih, Deformable, resilient, and mechanically-durable triboelectric nanogenerator based on recycled coffee waste for wearable power and self-powered smart sensors, Nano Energy 79 (2021). ⟨https://www.zhangqiaokeyan.com/journal-foreign-detail/0704028836599.html⟩ (accessed August 18, 2024).
[152] P. Zhu, B. Zhang, H. Wang, Y. Wu, H. Cao, L. He, C. Li, X. Luo, X. Li, Y. Mao, 3D printed triboelectric nanogenerator as self-powered human–machine interactive sensor for breathing-based language expression (null-null), Nano Res. (2022), https://doi.org/10.1007/s12274-022-4339-x.
[153] F. Yuan, S. Liu, J. Zhou, S. Wang, X. Gong, Smart touchless triboelectric nanogenerator towards safeguard and 3D morphological awareness, Nano Energy 86 (2021) 106071, https://doi.org/10.1016/j.nanoen.2021.106071.
[154] C. Ryu, S. Hajra, M. Sahu, S.I. Jung, I.R. Jang, H.J. Kim, PVDF-bismuth titanate based self-powered flexible tactile sensor for biomechanical applications, Mater. Lett. 309 (2022), https://doi.org/10.1016/j.matlet.2021.131308.
[155] H.S. Wu, S. Wei, S.W. Chen, H.C. Pan, W.P. Pan, S.M. Huang, M. Tsai, P. Yang, Metal-Free Perovskite Piezoelectric Nanogenerators for Human–Machine Interfaces and Self-Powered Electrical Stimulation Applications, Adv. Sci. 9 (2022), https://doi.org/10.1002/advs.202105974.
[156] J. Yu, X. Hou, M. Cui, N. Zhang, X. Chou, Skin-Conformal BaTiO3/Ecoflex-Based Piezoelectric Nanogenerator for Self-Powered Human Motion Monitoring, Mater. Lett. 269 (2020) 127686, https://doi.org/10.1016/j.matlet.2020.127686.
[157] V. Leonov, C.V. Hoof, R.J.M. Vullers, Thermoelectric and Hybrid Generators in Wearable Devices and Clothes, in: Thermoelectric and Hybrid Generators in Wearable Devices and Clothes, IEEE, 2009, pp. 195–200, https://doi.org/10.1109/BSN.2009.10.
[158] X. Yu, X. Liang, R. Krishnamoorthy, W. Jiang, L. Zhang, L. Ma, P. Zhu, Y. Hu, R. Sun, C.-P. Wong, Transparent and flexible hybrid nanogenerator with welded silver nanowire networks as the electrodes for mechanical energy harvesting and physiological signal monitoring, Smart Mater. Struct. 29 (2020) 045040, https://doi.org/10.1088/1361-665X/ab7737.
[159] X. Chen, H. Guo, H. Wu, H. Chen, Y. Song, Z. Su, H. Zhang, Hybrid generator based on freestanding magnet as all-direction in-plane energy harvester and vibration sensor, Nano Energy 49 (2018) 51–58, https://doi.org/10.1016/j.nanoen.2018.04.024.
[160] Y. Liu, T.H. Wong, X. Huang, C.K. Yiu, Y. Gao, L. Zhao, J. Zhou, W. Park, Z. Zhao, K. Yao, H. Li, H. Jia, J. Li, J. Li, Y. Huang, M. Wu, B. Zhang, D. Li, C. Zhang, Z. Wang, X. Yu, Skin-integrated, stretchable, transparent triboelectric nanogenerators based on ion-conducting hydrogel for energy harvesting and tactile sensing, Nano Energy 99 (2022) 107442, https://doi.org/10.1016/j.nanoen.2022.107442.
[161] J.Y.A. B, J.A.B. C, Y.S.A. B, J.Z.A. B, L.Z.B. C, H.L.A. B, T.J.A.B. C, B.C.B.C. D, Z.L. W.B.C. E, Transparent self-powered triboelectric sensor based on PVA/PA hydrogel for promoting human-machine interaction in nursing and patient safety (n.d.), Nano Energy 97 (2024), ⟨https://www.nstl.gov.cn/paper_detail.html?id=9f577abc51a7c2bb5ca419eb9e4a00dc⟩ (n.d.).
[162] C. Jiang, C.L. Lai, B. Xu, M.Y. So, Z. Li, Fabric-rebound triboelectric nanogenerators with loops and layered structures for energy harvesting and intelligent wireless monitoring of human motions, Nano Energy 93 (2022) 106807, https://doi.org/10.1016/j.nanoen.2021.106807.
[163] C. Zhang, L. Zhang, B. Bao, W. Ouyang, W. Chen, Q. Li, D. Li, Customizing Triboelectric Nanogenerator on Everyday Clothes by Screen-Printing Technology for Biomechanical Energy Harvesting and Human-Interactive Applications, Adv. Mater. Technol. 8 (2023) 2201138, https://doi.org/10.1002/admt.202201138.
[164] H. Jiao, X. Lin, Y. Xiong, J. Han, Y. Liu, J. Yang, S. Wu, T. Jiang, Z.L. Wang, Q. Sun, Thermal insulating textile based triboelectric nanogenerator for outdoor wearable sensing and interaction, Nano Energy 120 (2024) 109134, https://doi.org/10.1016/j.nanoen.2023.109134.
[165] D. Doganay, M.O. Cicek, M.B. Durukan, B. Altuntas, E. Agbahca, S. Coskun, H. E. Unalan, Fabric based wearable triboelectric nanogenerators for human machine interface, Nano Energy 89 (2021) 106412, https://doi.org/10.1016/j.nanoen.2021.106412.
[166] Z. Wang, C. Chen, L. Fang, B. Cao, X. Tu, R. Zhang, K. Dong, Ying-Chih Lai, P. Wang, Biodegradable, conductive, moisture-proof, and dielectric enhanced cellulose-based triboelectric nanogenerator for self-powered human-machine interface sensing, Nano Energy (2022), https://doi.org/10.1016/j.nanoen.2022.108151.
[167] P. Zhu, B. Zhang, H. Wang, Y. Wu, H. Cao, L. He, C. Li, X. Luo, X. Li, Y. Mao, 3D printed triboelectric nanogenerator as self-powered human–machine interactive

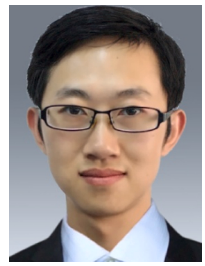
sensor for breathing-based language expression, 纳米研究：英文版 15 (2022) 7460–7467.
[168] J. Yang, J. Cao, J. Han, Y. Xiong, L. Luo, X. Dan, Y. Yang, L. Li, J. Sun, Q. Sun, Stretchable multifunctional self-powered systems with Cu-EGaIn liquid metal electrodes, Nano Energy 101 (2022) 107582, https://doi.org/10.1016/j.nanoen.2022.107582.
[169] S.M.S. Rana, M.T. Rahman, M. Abu Zahed Sang HyunDo Shin, Young Seonu, Sookyeong Kim, Dongkyun Salauddin, M. Bhatta, T. Sharstha, K. Park, Jae Yeong, Zirconium metal-organic framework and hybridized Co-NPC@MXene nanocomposite-coated fabric for stretchable, humidity-resistant triboelectric nanogenerators and self-powered tactile sensors, Nano Energy 104 (2022), https://doi.org/10.1016/j.nanoen.2022.107931.
[170] Y.X. Zhou, Y.T. Lin, S. Huang, G.T. Chen, S.W. Chen, H.S. Wu, I.-Chih Ni, W. P. Pan, M. Tsai, C.I. Wu, Tungsten Disulfide Nanosheets for Piezoelectric Nanogenerator and Human-Machine Interface Applications, Nano Energy (2022), https://doi.org/10.1016/j.nanoen.2022.107172.
[171] L. Liu, Q. Shi, Z. Sun, C. Lee, Magnetic-interaction assisted hybridized triboelectric-electromagnetic nanogenerator for advanced human-machine interfaces, Nano Energy (2021) 106154, https://doi.org/10.1016/j.nanoen.2021.106154.
[172] J. Huang, S. Peng, J. Gu, G. Chen, J. Gao, J. Zhang, L. Hou, X. Yang, X. Jiang, L. Guan, Self-powered integrated system of a strain sensor and flexible all-solid-state supercapacitor by using a high performance ionic organohydrogel, Mater. Horiz. 7 (2020), https://doi.org/10.1039/D0MH00100G.
[173] T. Feng, D. Ling, C. Li, W. Zheng, S. Zhang, C. Li, A. Emel'yanov, A. S. Pozdnyakov, L. Lu, Y. Mao, Stretchable on-skin touchless screen sensor enabled by ionic hydrogel, Nano Res 17 (2024) 4462–4470, https://doi.org/10.1007/s12274-023-6365-8.
[174] X. Lin, Y. Mao, P. Li, Y. Bai, T. Chen, K. Wu, D. Chen, H. Yang, L. Yang, Ultra-Conformable Ionic Skin with Multi-Modal Sensing, Broad-Spectrum Antimicrobial and Regenerative Capabilities for Smart and Expedited Wound Care, Adv. Sci. 8 (2021) 2004627, https://doi.org/10.1002/advs.202004627.
[175] M.R. Kesama, S. Kim, DNA-Nanocrystal Assemblies for Environmentally Responsive and Highly Efficient Energy Harvesting and Storage, Adv. Sci. 10 (2023) 2206848, https://doi.org/10.1002/advs.202206848.
[176] Y. Song, C. Shu, Z. Song, X. Zeng, X. Yuan, Y. Wang, J. Xu, Q. Feng, T. Song, B. Shao, Y. Wang, B. Sun, Self-powered health monitoring with ultrafast response and recovery enabled by nanostructured silicon moisture-electric generator, Chem. Eng. J. 468 (2023) 143797, https://doi.org/10.1016/j.cej.2023.143797.
[177] T. An, D.V. Anaya, S. Gong, L.W. Yap, W. Cheng, Self-powered gold nanowire tattoo triboelectric sensors for soft wearable human-machine interface, Nano Energy (2020) 105295, https://doi.org/10.1016/j.nanoen.2020.105295.
[178] G. Zhu, W.Q. Yang, T. Zhang, Q. Jing, J. Chen, Y.S. Zhou, P. Bai, Z.L. Wang, Self-Powered, Ultrasensitive, Flexible Tactile Sensors Based on Contact Electrification, Nano Lett. 14 (2014) 3208–3213, https://doi.org/10.1021/nl5005652.
[179] W. Liu, W. Yu, K. Li, S. Zhou, Q. Wang, H. Yu, Enhancing blind-dumb assistance through a self-powered tactile sensor-based Braille typing system, Nano Energy 116 (2023).
[180] L. Pan, Y. Wang, Q. Jin, Z. Hu, Z. Zhou, M. Zhu, Self-poled PVDF/recycled cellulose composite fibers utilizing cellulose nanocrystals to induce PVDF β-phase formation through wet-spinning as a flexible fabric piezoelectric sensor, Chem. Eng. J. 479 (2024) 147742, https://doi.org/10.1016/j.cej.2023.147742.
[181] L. Wang, Y. Wang, S. Yang, X. Tao, Y. Zi, W.A. Daoud, Solvent-free adhesive ionic elastomer for multifunctional stretchable electronics, Nano Energy 91 (2022) 106611, https://doi.org/10.1016/j.nanoen.2021.106611.
[182] R. Wei, J. He, S. Ge, H. Liu, X. Ma, J. Tao, X. Cui, X. Mo, Z. Li, C. Wang, C. Pan, Self-Powered All-Optical Tactile Sensing Platform for User-Interactive Interface, Adv. Mater. Technol. 8 (2023) 2200757, https://doi.org/10.1002/admt.202200757.
[183] J.H. Liu, W.D. Li, J. Jia, Chun-Yan Wang, Shan Yu, Peng Zhang, Zheng-Min Ke, Kai Bao, Rui-Ying Liu, Zheng-Ying Wang, Yu Zhang, Kai Yang, Wei, Structure-regenerated silk fibroin with boosted piezoelectricity for disposable and biodegradable oral healthcare device, Nano Energy 103 (2022). ⟨https://www.zhangqiaokeyan.com/journal-foreign-detail/0704065508084.html⟩ (accessed August 21, 2024).
[184] H. Xiaojuan, Z. Ruoyang, B.I. Xiaoxue, Z. Huipeng, Z. Jie, Z. Jie, G. Wenping, H. E. Jian, C. Xiujian, High-density stacked microcoils integrated microminiaturized electromagnetic vibration energy harvester for self-powered acceleration sensing, Sci. China(Technol. Sci.) (2023). ⟨http://www.cnki.com.cn/Article/CJFDTotal-JEXG202312002.htm⟩ (accessed August 21, 2024).
[185] W. Yang, W. Gong, W. Gu, Z. Liu, C. Hou, Y. Li, Q. Zhang, H. Wang, Self-Powered Interactive Fiber Electronics with Visual–Digital Synergies, Adv. Mater. 33 (2021) 2104681, https://doi.org/10.1002/adma.202104681.
[186] L. Su, Q. Xiong, H. Wang, Y. Zi, Porous-Structure-Promoted Tribo-Induced High-Performance Self-Powered Tactile Sensor toward Remote Human-Machine Interaction, Adv. Sci. 9 (2022) 2203510, https://doi.org/10.1002/advs.202203510.
[187] A. Angelopoulos, E.T. Michailidis, N. Nomikos, P. Trakadas, T. Zahariadis, Tackling Faults in the Industry 4.0 Era—A Survey of Machine-Learning Solutions and Key Aspects, Sensors 20 (2019) 109, https://doi.org/10.3390/s20010109.
[188] N. Dai, X. Guan, C. Lu, K. Zhang, S. Xu, I.M. Lei, G. Li, Q. Zhong, P. Fang, J. Zhong, A Flexible Self-Powered Noncontact Sensor with an Ultrawide Sensing Range for Human-Machine Interactions in Harsh Environments, ACS Nano (2023) 17, https://doi.org/10.1021/acsnano.3c05507.
[189] X. Ge, Z. Gao, L. Zhang, H. Ji, J. Yi, P. Jiang, Z. Li, L. Shen, X. Sun, Z. Wen, Flexible microfluidic triboelectric sensor for gesture recognition and information encoding, Nano Energy (2023) 113.
[190] T. Jacopo, T. Fabrizio, S. Marco, S. Roberto, F. Domenico, Performance Evaluation of Bluetooth Low Energy: A Systematic Review, Sensors 17 (2017) 2898, https://doi.org/10.3390/s17122898.
[191] E. Lodgaard, S. Dransfeld, Organizational aspects for successful integration of human-machine interaction in the industry 4.0 era, Procedia CIRP 88 (2020) 218–222, https://doi.org/10.1016/j.procir.2020.05.039.
[192] C. Zheng, W. Li, Y. Shi, S. Wei, K. Liu, J. Cheng, L. Ji, Y. Lu, Stretchable self-adhesive and self-powered smart bandage for motion perception and motion intention recognition, Nano Energy (2023) 109.
[193] T. Chen, M. Zhao, Q. Shi, Z. Yang, H. Liu, L. Sun, J. Ouyang, C. Lee, Novel augmented reality interface using a self-powered triboelectric based virtual reality 3D-control sensor, Nano Energy 51 (2018) 162–172, https://doi.org/10.1016/j.nanoen.2018.06.022.
[194] Yang Jiang, Yufei Zhang, Chuan Ning, Qingqing Ji, Xiao Peng, Kai Dong, Z. Lin Wang, Ultrathin Eardrum-Inspired Self-Powered Acoustic Sensor for Vocal Synchronization Recognition with the Assistance of Machine Learning, Small (Weinh. Der Bergstr., Ger.) 18 (2022) e2106960, https://doi.org/10.1002/smll.202106960.
[195] H. Zhou, D. Li, X. He, X. Hui, H. Guo, C. Hu, X. Mu, Z.L. Wang, Bionic Ultra-Sensitive Self-Powered Electromechanical Sensor for Muscle-Triggered Communication Application, Adv. Sci. 8 (2021) 2101020, https://doi.org/10.1002/advs.202101020.
[196] Y. Pang, S. Chen, Y. Cao, Z. Huang, X. Xu, Y. Fang, C. (Chase) Cao, Self-Powered Multifunctional Human–Machine Interfaces for Respiratory Monitoring and Smart System Control, Adv. Mater. Interfaces 9 (2022) 2201202, https://doi.org/10.1002/admi.202201202.
[197] R. Lin, Y. Fan, Y. Xie, D. Ge, S. Liang, H. Guan, M. Chen, Y. Zhang, L. Xing, X. Xue, Y. Zhan, A self-powered wearable seizure-monitoring/brain-stimulating system for potential epilepsy treatment, Nano Energy 107 (2023) 108121, https://doi.org/10.1016/j.nanoen.2022.108121.
[198] J.C. Yang, J. Mun, S.Y. Kwon, S. Park, S. Park, Electronic Skin: Recent Progress and Future Prospects for Skin-Attachable Devices for Health Monitoring, Robotics, and Prosthetics, Adv. Mater. 31 (2019), https://doi.org/10.1002/adma.201904765.
[199] P. Zhu, S. Mu, W. Huang, Z. Sun, Y. Lin, K. Chen, Z. Pan, M.G. Haghighi, R. Sedghi, J. Wang, Y. Mao, Soft multifunctional neurological electronic skin through intrinsically stretchable synaptic transistor, Nano Res. 17 (2024) 6550–6559, https://doi.org/10.1007/s12274-024-6566-8.
[200] Q. Shi, Chunkai He, Tianyiyi Wu, Fan Zhu, Minglu Dziuban, Jan A. Walczak, Rafal Yuce, Mehmet Rasit Lee, Cheng kuo, Triboelectric single-electrode-output control interface using patterned grid electrode, Nano Energy 60 (2019). ⟨https://www.zhangqiaokeyan.com/journal-foreign-detail/0704023797929.html⟩ (accessed August 18, 2024).
[201] G. Tang, Q. Shi, Z. Zhang, T. He, Z. Sun, C. Lee, Hybridized wearable patch as a multi-parameter and multi-functional human-machine interface, Nano Energy 81 (2021) 105582, https://doi.org/10.1016/j.nanoen.2020.105582.
[202] All in One, Self-Powered Bionic Artificial Nerve Based on a Triboelectric Nanogenerator, Adv. Sci. (2021), https://doi.org/10.1002/advs.202004727.
[203] S. Ding, M. Wang, H. Yang, F. Hu, Z. Dai, M. Lei, Q. Zhou, D. Zhao, Y. Gao, J. Zhong, J. Luo, B. Zhou, Sweeping-responsive interface using the intrinsic polarity of magnetized micropillars for self-powered and high-capacity human-machine interaction, Nano Energy 102 (2022) 107671, https://doi.org/10.1016/j.nanoen.2022.107671.
[204] X. Pu, Q. Tang, W. Chen, Z. Huang, C. Hu, Flexible triboelectric 3D touch pad with unit subdivision structure for effective XY positioning and pressure sensing, Nano Energy 76 (2020) 105047, https://doi.org/10.1016/j.nanoen.2020.105047.
[205] J. Huang, Xixi Yu, Jinran Han, Jing Jia, Chuankun Ding, Mei Sun, Jia Cao, Xiaole Sun, Qijun Wang, Zhong Lin, A universal and arbitrary tactile interactive system based on self-powered optical communication, Nano Energy 69 (2020). ⟨https://www.zhangqiaokeyan.com/journal-foreign-detail/0704028836566.html⟩ (accessed August 21, 2024).
[206] S. Hajra, S. Panda, H. Khanberh, V. Vivekananthan, E. Chamanehpour, Y. Mishra, H.J. Kim, Revolutionizing Self-Powered Robotic Systems with Triboelectric Nanogenerators, Nano Energy (2023).
[207] T. Masood, P. Sonntag, Industry 4.0: Adoption challenges and benefits for SMEs, Comput. Ind. 121 (2020) 103261, https://doi.org/10.1016/j.compind.2020.103261.
[208] B. Bajic, A. Rikalovic, N. Suzic, V. Piuri, Industry 4.0 Implementation Challenges and Opportunities: A Managerial Perspective, IEEE Syst. J. 15 (2021) 546–559, https://doi.org/10.1109/JSYST.2020.3023041.
[209] W. Cellary, Non-technical Challenges of Industry 4.0, in: L.M. Camarinha-Matos, H. Afsarmanesh, D. Antonelli (Eds.), Collaborative Networks and Digital Transformation, Springer International Publishing, Cham, 2019, pp. 3–10.
[210] M. Prause, Challenges of Industry 4.0 Technology Adoption for SMEs: The Case of Japan, (2019).
[211] R. Kumar, R.Kr Singh, Y.Kr Dwivedi, Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges, J. Clean. Prod. 275 (2020) 124063, https://doi.org/10.1016/j.jclepro.2020.124063.
[212] C. Brosque, E. Galbally, O. Khatib, M. Fischer, Human-Robot Collaboration in Construction: Opportunities and Challenges, : 2020 Int. Congr. Hum. -Comput. Interact., Optim. Robot. Appl. (HORA) (2020) 1–8, https://doi.org/10.1109/HORA49412.2020.9152888.

[213] J. Czarnowski, A. Dąbrowski, M. Maciaś, J. Główka, J. Wrona, Technology gaps in Human-Machine Interfaces for autonomous construction robots, Autom. Constr. 94 (2018) 179–190, https://doi.org/10.1016/j.autcon.2018.06.014.
[214] S. Shen, X. Xiao, J. Chen, Wearable Triboelectric Nanogenerators for Heart Rate Monitoring, Chem. Commun. 57 (2021), https://doi.org/10.1039/d1cc02091a.
[215] V. Misra, A. Bozkurt, B. Calhoun, T. Jackson, J. Jur, J. Lach, B. Lee, J. Muth, O. Oralkan, M. Ozturk, Flexible Technologies for Self-Powered Wearable Health and Environmental Sensing, Proc. IEEE 103 (2015) 665–681, https://doi.org/10.1109/JPROC.2015.2412493.
[216] K. Sadeghniiat-Haghighi, Z. Yazdi, Fatigue management in the workplace, Ind. Psychiatry J. 24 (2015) 12–17, https://doi.org/10.4103/0972-6748.160915.
[217] G. Desogus, E. Quaquero, G. Rubiu, G. Gatto, C. Perra, BIM and IoT Sensors Integration: A Framework for Consumption and Indoor Conditions Data Monitoring of Existing Buildings, (2021).
[218] L. Jin, J. Chen, B. Zhang, W. Deng, L. Zhang, H. Zhang, X. Huang, M. Zhu, W. Yang, Z.L. Wang, A Self-Powered Safety Helmet Based on Hybridized Nanogenerator for Emergency, Acs Nano (2016) 7874, https://doi.org/10.1021/acsnano.6b03760.

Mr Qihan JIANG recently completed his BSc in Construction Project Management in the transnational education programme between Northeast Forestry University and Aston University. During his undergraduate stage, his grade ranked first in the whole major. Also, he has been awarded over 30 prizes, including China National Scholarship, National Bronze Award in China International Internet plus Undergraduate Innovative Competition, Outstanding Graduate in Heilongjiang Province, "Inspirational Star" title in Northeast Forestry University. After completing his BSc degree, he successfully received a direct PhD in Structural Engineering at Tianjin University which focuses on large-span steel structures and structural earthquake-resistant.

Dr Maxwell Fordjour ANTWI-AFARI is a Lecturer in Construction & QS at the Department of Civil Engineering, Aston University, Birmingham, B4 7ET, UK. He obtained his Ph.D. in Construction Information Technology from the Department of Building and Real Estate, The Hong Kong Polytechnic University. He has published over 110 articles in peer-reviewed journals and conference proceedings. His research interests focus on construction management and engineering, construction health and safety, construction ergonomics, digital technologies and innovations (e.g., building information modeling, wearable sensors, internet-of-things, digital twin, robotics), construction informatics (e.g., machine learning, deep learning), technology transfer in construction and biomechanical analysis.

Dr Sina FADAIE recently completed his PhD in Civil Engineering at Aston University, UK. His research journey began in 2014 as a research assistant focusing on geotechnical stability issues. During his master's program, he received the Outstanding Graduate Student award, with his thesis ranked among the top in Geotechnical Engineering. His PhD, funded by UKRI Studentship Award, focused on fibre optic sensors to monitor geo-structures. Sina was a finalist in both the Royal Academy of Engineering's STEM for BRITAIN 2024 competition and the Future Game Changers Award at the British Renewable Energy Awards, showcasing his commitment to innovation and sustainability.



Dr. Hao-Yang MI is a Professor at the National Engineering Research Center for Advanced Polymer Processing Technology at Zhengzhou University in China. He received his B.S. and Ph. D. degrees from the South China University of Technology. He furthered his research as a Postdoctoral Fellow at the University of Wisconsin Madison in 2016 and as a Research Fellow at the Hong Kong Polytechnic University in 2018. His research primarily focuses on the synthesis and fabrication of multifunctional polymer composites, particularly porous polymers, and exploring their wide-ranging applications, including energy harvesting, electromagnetic interference shielding, energy absorption, oil-water separation, and tissue engineering.

Dr Shahnawaz ANWER is currently a Research Assistant Professor at The Hong Kong Polytechnic University, Hong Kong. Dr. Anwer obtained his PhD from The Hong Kong Polytechnic University, Hong Kong. His research interests focus on ergonomics, postural control, wearable sensing technology, physical fatigue, exoskeletons, and work-related musculoskeletal disorders. He was recognized as World's Top 2 % Researcher in the year 2023 by Stanford University based on citations and research performance. He is the recipient of the Young Investigator Award 2022 and Occupational Safety & Health (OSH) Award 2021. He is academic editor of PLOS One and BMC Musculoskeletal Disorder journals.

Dr Jie LIU is an academic at Northeast Forestry University, High-level Talent of Heilongjiang Province, and Visiting Scholar at Tsinghua University and University of Cambridge (UK). Over the past 5 years, she has led more than 10 national and provincial research projects, including projects funded by the National Natural Science Foundation of China and the National Social Science Foundation of China, etc. She has published nearly 20 research papers in international journals indexed by SCI/SSCI/EI as the first author or corresponding author. In 2020, she was selected as one of 'Top 100 Postdoctoral' funded by China Postdoctoral Science Foundation.