Enhancing Indoor Thermal Comfort Education: A Virtual Reality Platform Introducing Fanger's Model

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ABSTRACT

This study introduces an immersive Virtual Learning Environment (VLE) utilizing Virtual Reality (VR) to educate building service engineering students on indoor thermal comfort. Integrated with Fanger's Predicted Mean Vote Model, the VLE offers a multi-user platform with interactive interfaces spanning theoretical concepts to real-world application. Through Unity, users manipulate virtual environment parameters, gaining practical thermal comfort assessment experience. By merging theory and practice within VR, it deepens understanding of indoor environmental quality's impact on human comfort. Leveraging Human-Computer Interaction (HCI) principles, the VLE ensures intuitive interaction using interactive system and tools, notably User Interface Toolkits (UIT). Virtual Reality enhances engagement and learning outcomes, providing a realistic, immersive environment. Incorporating Fanger's model offers a structured approach to analyze indoor thermal conditions, fostering critical thinking. This research showcases VR's potential in teaching building service engineering and indoor environmental quality.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools; User interface toolkits.

KEYWORDS

Human computer interaction (HCI), Interactive system and tools, User interface toolkits (UIT), Virtual Reality, Fanger's model

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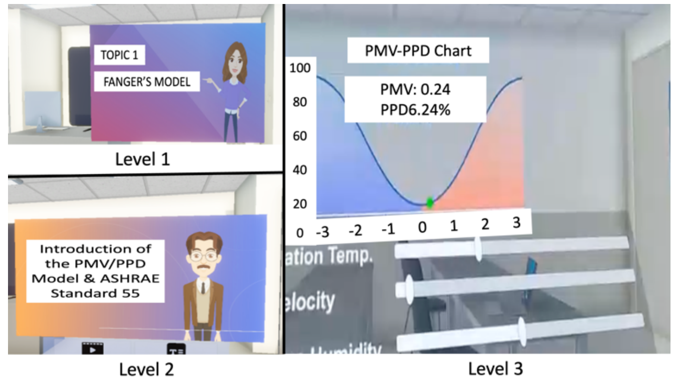

Figure 1: An overview of the virtual classroom for learning Fanger's model

1 INTRODUCTION

Indoor thermal comfort education seeks to convey a comprehensive understanding of the diverse factors influencing occupants' satisfaction with their indoor environment. This includes instruction on the fundamental principles governing ventilation, temperature, and humidity. Standardised guidelines are difficult to establish due to the dynamic and subjective nature of comfort perception and the multifaceted nature of these factors. Virtual Reality (VR) presents a potential avenue for enhancing education through the provision of interactive and immersive platforms, thereby connecting theoretical concepts with practical implementations [1]. The utilisation of virtual reality (VR) in academic environments is intended to accelerate the learning process and improve understanding of the complexities of indoor thermal comfort, with possible connections to its effective implementation in medical education. As an introductory course on indoor thermal conditions and human thermal comfort, this research paper introduces building service engineering students to a virtual learning environment featuring a multi-interactive interface (Figure 1). The three dimensions of interactive interfaces within the virtual learning environment are denoted by Levels 1 through 3. Students in the advanced semester are introduced to the Fanger's model via the platform, which may also equip them with the necessary skills for research projects. In the domain of thermal comfort, Fanger's model, more precisely referred to as the Predicted Mean Vote (PMV) model, is an extensively implemented framework. The model, which was suggested by Professor P.O. Fanger, attempts to forecast the mean thermal sensation rating of a sizable cohort of individuals who have been exposed to a specific indoor setting. The PMV model estimates the thermal comfort of individuals by considering a number of variables, including air temperature, radiant temperature, air velocity, humidity, and apparel insulation. In general, the PMV scale spans from -3 to +3, where negative values signify a perception of coldness, zero represents thermal neutrality, and positive values signify warmth [2].

A number of obstacles may arise when attempting to instruct Fanger's model in the classroom. In the first place, the model is potentially difficult for students lacking a solid foundation in thermal physics or environmental science due to its complex mathematical

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equations and considerations of multiple variables. Moreover, the model operates under the assumption of a steady-state condition, which might not consistently represent dynamic and fleeting situations that occur in the real world. As distinct individuals may perceive and react differently to thermal conditions, the subjectivity of individual thermal comfort preferences further complicates the instruction of the model. As a result, it is imperative that educators find a way to impart the practical implications of Fanger's model in real-world thermal comfort assessments while also ensuring that students comprehend its technical nuances. In order to bridge these gaps and augment students' understanding of the model, practical exercises, simulations, and case studies may prove advantageous.

2 RELATED WORK

2.1 Virtual reality application in education

In virtual reality (VR) education, practical exercises, simulations, and case studies offer diverse and immersive learning experiences across disciplines. Architecture students engage in a virtual design studio, experimenting with designs and layouts [3]. Medical students practice surgeries and diagnostics in realistic virtual scenarios [4]. Chemistry students conduct experiments in a simulated laboratory, and history students explore historical events through virtual reconstructions [5]. Language learners immerse themselves in language-rich environments, while physics students interact with virtual objects to understand fundamental principles [6]. Emergency response personnel undergo virtual training for firefighting and disaster response, business students simulate strategic decisions in virtual business environments, and environmental science students take virtual field trips to ecosystems [7]. Psychology students apply theories in interactive case studies [8]. These examples demonstrate the broad applicability of VR in creating engaging and educational experiences for students in various fields.

2.2 Education of thermal comfort

Understanding thermal comfort has traditionally been incorporated into HVAC (heating, ventilation, and air conditioning) curricula. A comprehensive curriculum encompassing fundamental principles of thermodynamics, fluid mechanics, heat transfer, and control systems is customary in HVAC education. Particular courses may explore subjects including the design of HVAC systems, refrigeration, air distribution, energy conservation, and adherence to environmental regulations. Over the last decade, various innovative pedagogies have been implemented to support cutting-edge education and improve students' understanding of complex HVAC systems. These pedagogies include project-based pedagogy [9, 10], experiential learning [11], the adoption of virtual reality technology [12], and online self-learning [13].

Megri [13] underscored the significance of the capstone design programme and put forth a methodical project methodology to direct students through the complete HVAC design procedure. This methodology encompasses sizing systems, estimating heating and cooling loads, commissioning, ensuring appropriate airflow distribution, and addressing administrative considerations. It has been demonstrated that the structured approach assisted students in gaining a methodological comprehension of the HVAC design process. A teaching and learning facility, as described by Butler and Yuill [9], has been developed with the intention of augmenting the efficacy of HVAC system education for architectural engineering students. By establishing the facility in support of an architectural engineering programme, the hypothesis that learning can be expedited through practical engagement with operational HVAC systems as opposed to conventional lecture-based approaches will be examined. Hutzel [12] presents a virtual HVAC laboratory that has been specifically designed to provide students with hands-on experience in diverse aspects of sustainable technologies and energy systems. An Augmented Reality (AR) environment was utilised by Xie and Yang [14] to expand and enrich a library of virtual laboratory modules derived from our initial learning application. In this environment, virtual objects are superimposed onto a physical learning environment in the course of online lecture instruction. In their study, Chao et al. [11] present a novel online-learning approach to simulating the characteristics of an office building, with an emphasis on the building model's adaptive updating in response to the dynamic conditions of the physical environment. In contrast to conventional control methods that depend on simulators or offline learning, this methodology allows for the dynamic adaptation of the building model to actual environmental conditions. By optimising temperature reference points, the proposed action agent employs this dynamic model to intelligently regulate the heating, ventilation, and air conditioning (HVAC) system. Studies have underscored the significance of thermal comfort in educational environments, as a result of the attention it has received regarding the design and operation of buildings. The correlation between indoor thermal conditions and both building energy efficiency and human thermal comfort has been empirically established.

3 FANGER'S PREDICTED MEAN VOTE (PMV) MODEL

The Predicted Mean Vote (PMV) model, which serves as a comprehensive framework for quantifying and forecasting human thermal comfort in indoor environments, was devised by Professor P.O. Fanger. Temperature, humidity, air velocity, apparel insulation, and other physiological and environmental factors were systematically incorporated into the model's development. Fanger employed heat balance principles in order to fathom the exchange of heat between the human body and its surroundings, taking into account convection, radiation, metabolic heat, and clothing impact. The experiments in which he subjected subjects to diverse thermal conditions were pivotal in establishing a connection between environmental factors and human comfort. Fanger formulated the mathematical equations that serve as the foundation of the PMV model, which utilise empirical data to quantify thermal sensitivity based on input parameters. The model forecasts average sensation by introducing the Predicted Mean Vote (PMV), which ranges from -3 (indicating frigid) to +3 (indicating warm), with 0 serving as the neutral rating. Fanger bolstered the model with supplementary data, thereby ensuring its validity and calibration under a variety of conditions. His PMV model, which provides a methodical evaluation of indoor environments in terms of human well-being, continues to be seminal.

PPD (Predicted Percentage of Dissatisfied) calculates the proportion of occupants in each environment who would be dissatisfied

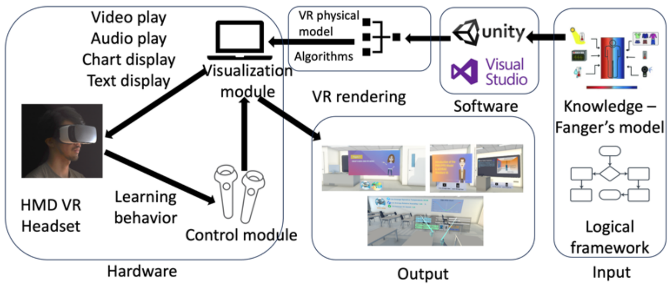

Figure 2: Virtual learning environment (VLE) working mechanism diagram; Note: the Fanger's model illustration is adjusted based on Ghahramani et al. [15]

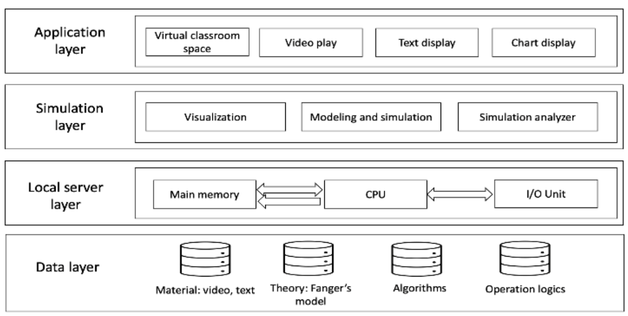

Figure 3: Virtual learning environment system architecture

with the thermal conditions. In addition to the PMV, it offers an evaluation of the degree of discomfort that may be encountered by the occupants. By considering the variability of individual thermal comfort preferences, PPD estimates, using PMV values, the proportion of individuals who may find the conditions unsatisfactory.

4 DEVELOPMENT OF THE VIRUTAL LEARNING ENVIRONMENT (VLE)

A virtual learning environment working mechanism diagram (Figure 2) was developed to guide the design of the virtual learning environment. Figure 3 illustrates the system architecture of the VLE.

The virtual learning environment (VLE) operates through a meticulous process, starting with the incorporation of subject-specific knowledge and a logical framework as foundational inputs. Leveraging *Unity* and *Visual Studio* software, the VLE engages in VR rendering, transforming the educational content into immersive digital environments. Within this virtual space, VR physical models and algorithms are developed, ensuring the accurate representation of principles of Fanger's model. Users enter the VLE though Head-Mounted Display (HMD) VR headsets, allowing them to access audio-visual content and interact with charts and text. The use of VR controllers further empowers users to navigate and manipulate elements within the virtual environment, fostering a dynamic and engaging learning experience. As users engage with the VLE, their learning behaviors are meticulously observed in the interactive virtual environment. The culmination of the interactive process yields three layers of interaction scenarios as outputs.

Figure 4: Video introduction of the virtual learning environment

In Figure 3, four layers of system architecture are illustrated. At the application layer, users interact with the virtual classroom space, engaging into video playback, text display and chart presentations for a dynamic learning environment. The simulation layer enhances this experience by incorporating visualizations, modeling and simulation capabilities, and a simulation analyzer to assess learning outcomes. The local server layer, equipped with main memory, CPU and I/O units, facilitates a real-time processing and communication. Finally, the data layer stores education materials, theoretical frameworks, alongside of algorithms and operation logics, forming the backbone of the VLE's functionality.

5 INTERACTIVE SCENARIOS IN THE VIRTUAL LEARNING ENVIRONMENT

A range of interactive scenarios, which are detailed in the subsequent subsections, have been developed. Involvement of stakeholders was incorporated into the requirements elicitation procedure. The platform is compatible with both VR and desktop PC modes. To deliver knowledge of Fanger's model in an interactive fashion, three fundamental functionalities were incorporated: a video introduction to the virtual learning environment (Figure 4), two interactive dimensions of Fanger's model (Figure 5), and practical mathematical modelling to compute the PMV-PPD values (Figure 6).

5.1 Level 1-interactive interface – overall introduction

Utilizing VR technologies including OCULUS RIFT, a VR headgear, and the Unity3D game engine, a virtual classroom was created. The inspiration for the design of this virtual classroom came from an actual classroom located in one of the university teaching facilities in Hong Kong. The classroom is furnished with all-around necessities, including a blackboard, teaching station, workstations, and chairs. Students will be greeted with an animated video that explains the educational function of the virtual learning environment as they enter the virtual classroom (Figure 4). Students will acquire knowledge of the PMV-PPD model and an understanding of how to effectively utilise the virtual classroom by watching this video. In

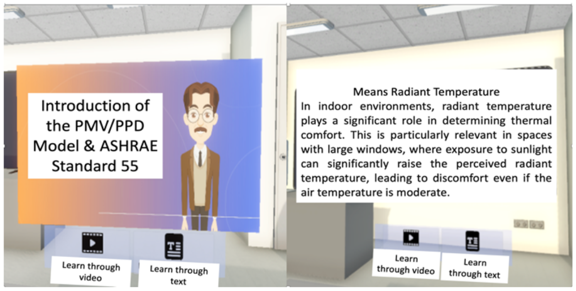

Figure 5a. Learn through video Figure 5b. Learn through text

Figure 5: Introduction of the fundamental theory of the Fanger's model

addition, beneath the animated video are two selectable icons that, when activated, toggle the virtual classroom between winter and summer conditions. As one of the critical parameters in Fanger's model for determining the PMV-PPD value, "clothing insulation" differentiates the two forms of virtual classrooms. To illustrate, selecting the button on the left will take you to the "winter" mode of the classroom; conversely, selecting the button on the right will take you to the "summer" mode of the classroom.

Fanger's model specifies the six parameters that are employed in the computation of PMV-PPD values. Air temperature, radiant temperature, air velocity, relative humidity, clothing insulation, and metabolic rate are some of these parameters. Relevant apparel insulation values were chosen for integration into the level-3 interactions in each classroom. For instance, clo-0.36, clo-0.57, clo-0.61, and clo-0.67 were integrated for student selection in the "summer" classroom. In other terms, "winter classroom" and "summer classroom" are distinguished by the insulation values of the students' clothing.

5.2 Level 2-interactive interface – learning the fundamentals

Students may select "winter classroom" or "summer classroom" as their classroom environment following the introduction animated video. Students have the option to "learn through text" or "learn through video" in each classroom (Figure 5, represented by two icons on the lower level of the virtual classroom).

The video elucidates the foundational principles of Fanger' s model as well as the process by which PMV-PPD is computed (Figure 5a). Students can access the text version of the model explanation by selecting the "learning through text" option (see Figure 5b). For example, students can learn the concept of six parameters of the Fanger's model through reading the texts embedded in the virtual environment, such as "air temperature", "air velocity", "relative humidity", "metabolic rate", "clothing insulation" and "activity level".

The virtual classroom is intended to impart knowledge necessary to prepare for an advanced level of interaction at level 3 during this phase.

Students are instructed to turn to the left in order to engage with the mathematical models utilised in the computation of PMV and PPD, subsequent to acquiring knowledge of the fundamental

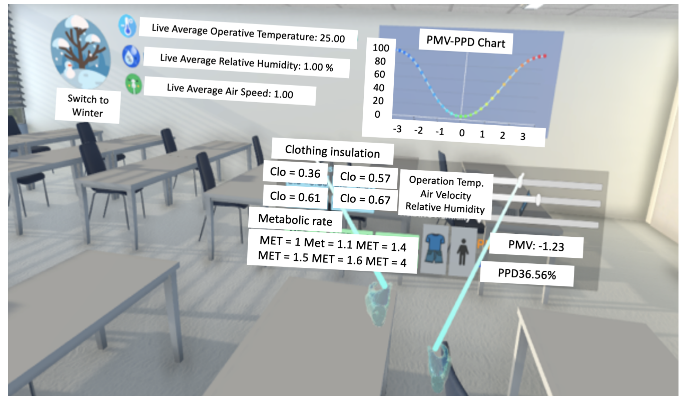

Figure 6: Hands-on mathematical modelling for calculating the PMV-PPD

concepts and mechanism of Fanger's theory via video or text. The mathematical equations are incorporated into Unity in Figure 5. This functionality enables students to manipulate a range of parameters within the virtual classroom, including radiant temperature, air velocity, air temperature, clothing insulation, and metabolic rate. By doing so, they are able to observe instantaneous modifications in the PMV and PPD values. The subsequent procedures were executed in order to achieve level 3 interaction.

5.3 Level 3-interactive interface

5.3.1 Create a user interface (UI).. The objective of this assignment is to integrate user interface (UI) components into Unity in order to enable user interaction and parameter modification for mathematical equations. This entails the integration of text fields, buttons, sliders, and analogous components to facilitate user input and adjustment of equation parameters. The objective is to develop an interface that facilitates intuitive manipulation and modification of diverse equation parameters, thereby furnishing a user-friendly setting for adjustment and interaction within the *Unity* framework.

5.3.2 Write script for equation calculation. The process entails developing a script within Unity to calculate the formula's outcome. This involves utilizing user-input parameters provided through the UI and integrating them into the formula calculation to generate the resulting value. The script creation occurs using programming languages like C# or UnityScript (JavaScript for Unity), enabling the execution of formula calculations within the Unity environment.

5.3.3 Respond to user input. The procedure involves coding functionalities to capture user interactions with UI elements like sliders or text boxes within the Unity environment. This entails establishing mechanisms to detect and respond to user input events. Additionally, the code needs to ensure that when users modify parameters through the UI, the script is designed to update the formula's necessary parameters dynamically. Consequently, the script recalculates the formula using the modified parameters, generating updated results in real-time within the Unity framework.

5.3.4 Real-time display of results. This involves the creation of an object or UI element within the Unity environment to visually present the results obtained from the mathematical equation calculations. Once established, the script responsible for performing the equation calculations needs to be programmed to update this object or UI element dynamically. As users modify parameters through the interface, the script should continuously refresh or modify the displayed object/UI element to reflect real-time changes resulting from the adjusted parameters within the Unity framework.

6 CONCLUSIONS

The paper presents an all-encompassing digital learning environment designed to instruct students of building service engineering about human thermal comfort and indoor thermal conditions. By employing interactive components within a multi-user environment, the VLE endeavours to acquaint learners with Fanger's model, specifically the Predicted Mean Vote (PMV) model. By utilising Virtual Reality (VR) technology, this novel methodology bridges the divide between theoretical understanding and practical implementation. By utilising a progression of interactive interfaces, the VLE provides students with an immersive experience as they progress from fundamental mathematical concepts to practical mathematical modelling. The integration of real-time parameter adjustments and equation calculations within Unity creates an interactive learning environment that facilitates students' investigation and comprehension of the intricate nature of thermal comfort assessment. The amalgamation of Fanger's model, virtual reality technology, and interactive learning constitutes a substantial progression in the field of indoor thermal comfort education. The findings of this research underscore the capacity of immersive virtual environments to augment students' understanding and implementation of intricate principles pertaining to the quality of indoor environments and human comfort.

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