Integration of Virtual Reality and Smart Home System: Current Trends, Challenges, and Innovations

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***Abstract*: This study explores the convergence of virtual reality (VR) technology and smart home systems, highlighting the transformative potential of integrating these fields. Virtual reality, a high-tech simulation system, combines advancements in computer graphics, human-computer interaction, and sensor technologies to create immersive and interactive three-dimensional environments. The smart home industry, though relatively nascent, has seen significant global advancements, with countries like the United States, Japan, and Germany leading in the development and adoption of intelligent systems. Despite these advancements, the integration of VR with smart home technology remains underexplored, particularly in the context of enhancing user interaction and experience. This research addresses the current limitations in smart home simulation and proposes a novel approach by combining VR, augmented reality (AR), and physical reality. The study aims to improve the user experience through a context-aware smart home system, leveraging technologies such as Unity3D for cross-platform compatibility. A significant focus is placed on the needs of the elderly, proposing innovative solutions for fall detection and emergency response using advanced sensor and VR technologies. The findings suggest that the integration of VR into smart home systems not only enhances the user experience but also opens new avenues for personalized and immersive home environments. This research contributes to the field by proposing a hybrid simulation model that bridges the gap between virtual and physical realities, offering a comprehensive solution for the future of smart homes.**

***Keywords*—Virtual Reality (VR), Smart Home Systems, Human-Computer Interaction and 3D Technology.**

I. INTRODUCTION

The rapid advancements in digital technology have ushered in a new era of interactive systems, where the lines between physical and virtual worlds are increasingly blurred. Virtual Reality (VR), as a comprehensive integration of computer graphics, human-computer interaction, sensor technology, and artificial intelligence, has emerged as a revolutionary tool that enables users to experience and interact with computer-generated environments in a highly immersive manner. This technology has evolved from early computer graphics simulations to complex, real-time interactive experiences that replicate the sensory perceptions of sight, sound, and even touch [1][2].

Parallel to the rise of VR, the concept of smart home has gained significant traction globally. Smart home system leverages the Internet of Thing (IoT) to integrate household devices into a cohesive network, allowing for enhanced control, automation, and efficiency. Since the introduction of the first intelligent building in the United States in 1984, smart home has evolved from inches' luxury projects to essential components of modern living, particularly in technologically advanced nations such as the United States, Japan, and Germany [3][4]. These systems, however, often face challenges related to user interaction, scalability, and adaptability to individual needs.

This research seeks to explore the intersection of VR technology and smart home systems, proposing a novel framework that combines the immersive capabilities of VR with the functional sophistication of smart homes. The primary aim is to create an integrated environment where users can naturally interact with their living spaces through VR, enhancing both the utility and experience of smart home technologies [5]. Furthermore, this study places a special focus on the elderly, addressing critical issues such as fall detection and emergency response through advanced VR-bases solutions [6].

The integration of VR into smart home systems represents a significant leap in human-computer interaction, offering not just a tool for control, but a means of transforming the living experience into an intuitive, immersive, and responsive environment. This introduction sets the stage for a deeper investigation into the current state of VR and smart home technologies, the challenges faced in them integration, and the innovative approaches proposed in this study to overcome these barriers [7].

II. THE PROPOSED VIRTUAL REALITY SYSTEM

Through the analysis of user research, we evaluated the proposed method, and we found that the user experience based on mixed reality can be complementary to augmented reality (AR) and VA to obtain a good user experience, although the learning of mixed reality is very complicated. This method has been successfully implemented in wimm-based smart homes, and we still need to improve the interoperability between virtual-physical objects by applying this method to the actual smart home environment. Improve the graphic quality of virtual objects and replace the real smart home environment. In addition, the user must be provided with visual or tactile feedback. We also need to investigate the feasibility of the proposed method by applying to different situations and evaluating different user. In addition, we also need to improve the multi-modal interaction capabilities of virtual object operations in mixed reality smart homes.

Design background

The smart home technologies become more integrated into daily life, they are continually evolving to meet modern demands. However, there is often a gap between the potential technical benefits of these innovations and their actual acceptability and availability to different age groups. To bridge this gap, a survey was conducted among individuals aged 20-30, 30-50, and over 50 to assess their priorities and ultimate acceptability of smart home technologies.

The survey results revealed distinct preferences across age groups. Young adults (20-30) are particularly drawn to the technological aspects of smart homes, such as somatosensory games and smart assistants, with a strong focus on entertainment and comfort. In contrast, middle-aged individuals (30-50) prioritize the practical benefits of smart homes, valuing features that alleviate the pressures of work and family life, and emphasizing health monitoring services. Older adults (50+) generally have a limited understanding of smart home technologies, yet the growing trend of aging populations suggests a significant market demand for senior-friendly smart homes, especially for those living alone. Their primary concern is the ease of use, as overly complex systems may be challenging to learn and operate. Telemedicine is the smart home feature that interests them the most.

Given the diverse needs of different age groups, this paper focuses on designing smart home technologies tailored to the elderly. The survey shows that older adults are open to using technologies that support their daily activities, with preferences including nanotechnology (53.8%), smart showers (28.6%), home sensors (66.6%), telemedicine (81.5%), smart appliances (40.0%), personal sensors (55.5%), and voice-controlled devices (64.3%). The discussion emphasizes the importance of prioritizing user-centered design in the development and implementation of future smart home technologies, particularly those intended to enhance the lives of older adults.

Innovation

Smart homes for the elderly, this paper focuses on two key aspects: ease of use and health monitoring. Firstly, ease of operation is crucial for the elderly, as the primary advantage of smart homes lies in simplifying the management of multiple facilities. To address this, the paper proposes a solution that integrates a mixed reality-based user experience, combining VR and AR. This approach offers immersive visualization and multimodal interaction, enhancing the usability if context-aware smart home services for seniors. Secondly, monitoring the user and their home environment is essential to ensure physical health and quality of life. The paper emphasizes the importance of assessing the user's health, including cardiopulmonary function, and designing home sensors that cater to the unique needs of the elderly, such as reduced mobility, impaired vision, hearing loss, and cognitive decline. By gathering user needs and evaluating their health status, a customized smart home solution can be developed to enhance residents well-being and autonomy. The method proposed in this paper is grounded in three important principles for context-aware smart homes: (1) integrating context awareness with interactive visualization; (2) enhancing user experience through hybrid reality-based interaction; and (3) conducting systematic reviews based on end-user feedback. These principles aim to create a smart home environment that is both user-friendly and supportive of the elderly's health and happiness.

Key Technology

This paper presents methods to compare and enhance smart home user experiences, emphasizing the integration of virtual and physical environments. We focus on five key features essential for a smart home user experience: (1) virtual reality interface, (2) interaction with virtual physical objects, (3) multiple perspectives, (4) context awareness, and (5) visibility. While previous research has explored various aspects of smart home user experiences, few studies have addressed the integration of virtual reality and virtual-physical object interaction within these environments. Additionally, many approaches fail to support immersive and interactive experiences between virtual and physical objects. The paper delves into a reality-based hybrid user experience layer, which connects to the virtual physical component via a context management layer. This integration enables context acquisition, inference, 3D enhancement, and synchronization with physical objects. The system combines the first-person perspective of virtual reality with the third-person perspective of augmented reality through a multimodal interface, as illustrated in Figure 1

Figure 1 Rich user experiences through Hybrid Reality: (a) Egocentric (first-person) VR environment (b) Exocentric (third-person) AR environment (c) HMD-based immersive VR (d) Smart device-based AR

The user experience in a smart home is achieved through a reality-based hybrid user experience layer, as illustrated in Figures 2 and 3. This layer comprises three key modules: (1) the perception module, (2) the coordination module, and (3) the VR/AR object management module.

The perception module is responsible for registering physical-virtual objects, acquiring context information from these objects, and interfacing with the context manager to exchange and control event data. The coordination module synchronizes the behavior of AR and VR activities, manages communication between virtual and physical objects during user interactions, and handles events triggered by users for controlling and interacting with 3D objects. It also relays changes in object states and user interactions to the perception module

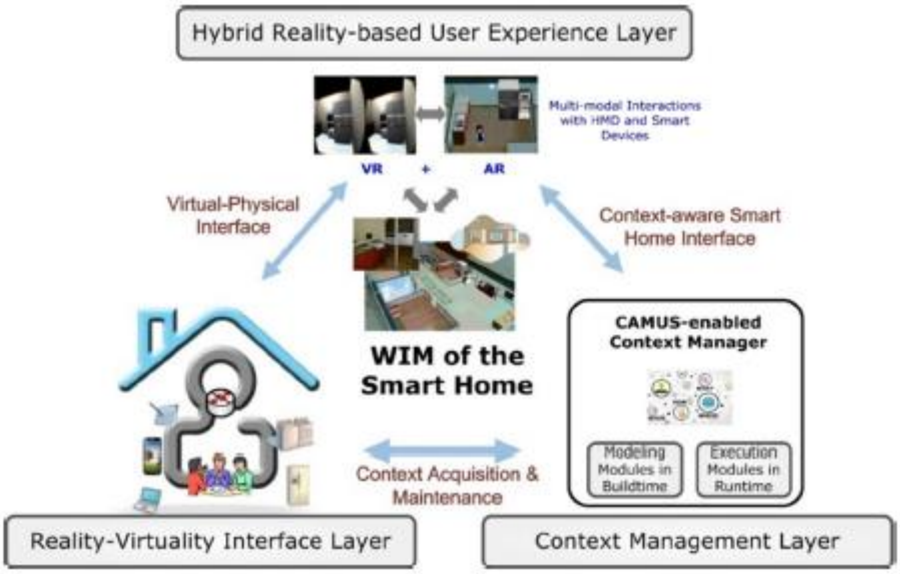

Figure 2 Framework of the Proposed Approach for Enhancing User Experience in a Smart Home Environment

The VR/AR object management module is tasked with loading and unloading the appropriate VR/AR objects to provide a reality-based hybrid user experience. This module also controls the state and behavior of 3D virtual objects by processing event data from the context manager. Notably, it supports VR-based first-person experiences and AR-based third-person experiences, as depicted in Figure 3

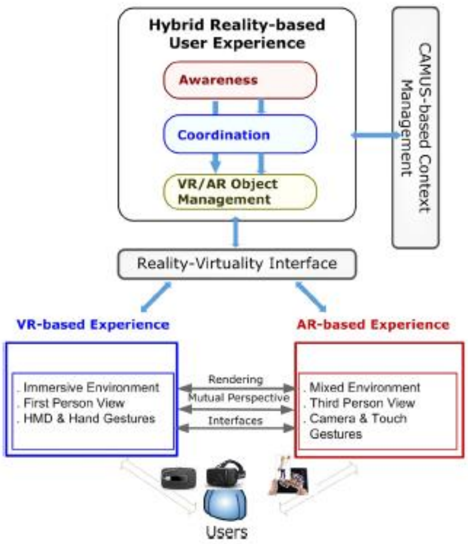

Figure 3 Hybrid Reality-based User Experience layer

In a VR-based interactive visualization environment, users wear head-mounted displays (HMDs) to explore and interact with immersive smart home spaces. However, the use of HMDs can hinder traditional navigation and interaction methods, such as mouse and keyboard inputs. To address this issue, a Leap Motion sensor is mounted on the front of the HMS, enabling gesture-based interaction. This setup supports various gestures, including grabbing, moving, rotating, and pinching, as illustrated in Figure 4, seamlessly integrating gesture control with the HMD functionality.

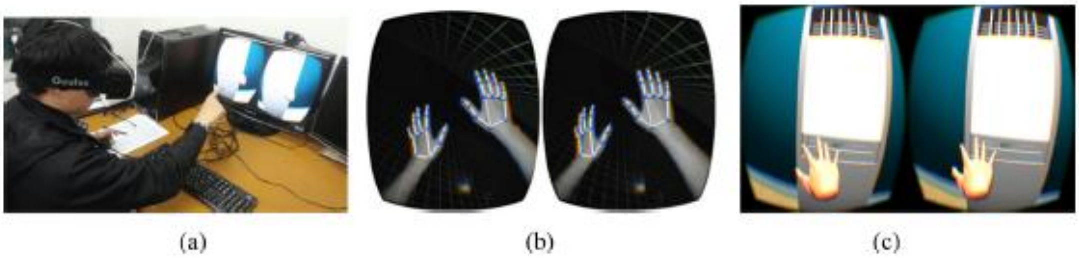

Figure 4 Multi-modal and intuitive interaction with hand gestures in a VR environment involves three key elements: (a) the user interacts with a virtual object using hand gestures, (b) hand gestures are recognized and interpreted by the Leap Motion sensor, and (c) the corresponding actions are executed within the VR space.

In the AR-based interactive visualization environment, WIM is equipped with multiple physical actuators and sensors, such as electric lights, motors, temperature sensors, etc., which can interact with virtual objects, as shown in Figure 5. For example, when a virtual person enters the living room, the light automatically turns on as the context manager processes the event data and updates the smart home environment. The context manager then relays this data to the AR-based user experience layer, which interacts with the relevant virtual objects. Additionally, virtual objects can interact with one another; for instance, if a virtual person turns on the TV and changes channels, the virtual TV responds by displaying the selected program. This setup allows users to experience and control various aspects of smart home environments, providing a dynamic and immersive interaction.

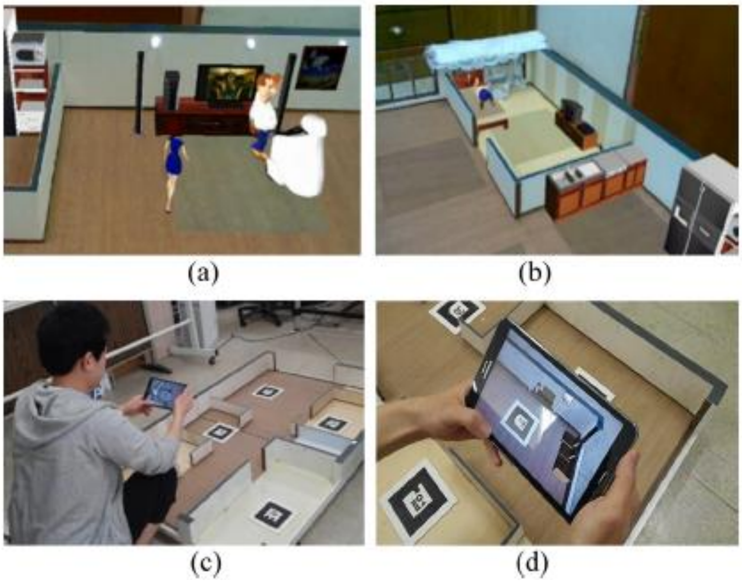

Figure 5 User experiences through AR environment: (a) and (b) virtual-physical interaction, (c) AR in the WIM, (d) mobile AR interaction

By adding, replacing, and modifying physical objects and virtual objects and their associated contexts and states in the environment. Although previous researches mostly focused on VR-based simulation methods, they did not provide an effective communication method between virtual objects and physical objects.

Simulation

The paper presents a study on a reality-based hybrid method combining immersive VR and exocentric AR for smart home interactions. The method uses head-mounted display (HMDs) and Leap Motion sensors to enable gesture-based interaction in VR and AR environments. In the first experiment, participants experienced VR and AR prototypes, with the order of experiences randomized. In the VR setup, users wore HMDs and interacted with simple virtual scenarios, practicing gestures for object manipulation. In the AR setup, participants used a AR system to navigate smart home environments and interact with virtual objects. The second experiment involved pairs of participants experiencing synchronous VR and hybrid reality methods to assess coordination and shared experiences in a smart home context. The study involved 20 case aged 20-32. Participants reported feeling less psychological and physical stress in AR compared to VR, where HMDs contributed to discomfort despite a higher sense of immersion. Both VR and AR were found to be effective in providing usability and usefulness for interaction tasks, though AR provided a more natural experience. The hybrid method showed better integration between virtual and physical objects and offered more detailed perspectives on smart home environments. Feedback highlighted the need for improvements in gesture-based interactions due to occasional inaccuracies with the Leap Motion sensor. Participants also noted limitations with mobile AR's narrow field of view. Suggestions for future research include developing a mobile VR system for seamless switching between VR and AR, enhancing the combined experience of both realities.

III. EXPERIMENT AND RESULTS

The application of a virtual smart home system. it begins with an introduction to the system, followed by a detailed examination of its various functions. The system's performance is evaluated in terms of its roaming capabilities, 3D client control functions, mobile control terminal operations, and virtual monitoring features. In the roaming function test, key aspects such as role control and collision detection are assessed to ensure smooth navigation within the virtual environment. The 3D client control and mobile control terminal functions are then tested, with particular attention to the control of various nodes, including the TV, air conditioner, water heater, and desk lamp. Finally, the evaluates the virtual monitoring function within the 3D client, conforming its effectiveness. the test results demonstrate that the virtual smart home system operates as expected, validating the successful integration of 3D technology into smart home systems.

User description

Assessing the health status of family residents typically requires clinical intervention. However, alternative methods can estimate Cardiorespiratory Fitness (CRF) indirectly by measuring the subject's heart rate (HR). another crucial factor during CRF assessment is ensuring the safety of the individual being tested. When configuring and testing smart home systems for users, data collected during the user evaluation phase is crucial. Smart home designers can analyze this information to create a mixed reality environment tailored to meet the specific needs of users. There are several benefits to utilizing hybrid or virtual reality in this context. Firstly, it allows for real-time testing of communication between different devices. Secondly, it enables users to directly interact with thee virtual environment, helping them become familiar with their newly designed smart homes. This interaction also provides valuable feedback to designer for further improvements.

However, when implementing virtual reality technology, special consideration must be given to the target users, particularly the frail elderly. The risks associated with using a head-mounted display for these individuals are significant, potentially leading to adverse events. Therefore, less immersive solutions should be prioritized, even if it means sacrificing some degree of presence. Non-immersive environments should be favored, and stricter standards should be implemented to prevent critical situations for vulnerable users. Conditional test interruptions should be considered in cases of chest pain, ischemic ECG changes, excessively high heart rates, blood pressure abnormalities, severe arterial oxygen saturation drops, or symptoms such as dizziness, blurred vision, difficulty breathing, or confusion. By validating the system in a mixed reality environment and observing user behavior during simulations, designers can assess whether the implemented solutions effectively address user's limitations in daily activities. To further validate these concepts, two actual use cases are presented: one involving a kitchen designed for the elderly with impaired vision and another focused on a broader elderly population.

Creation of kitchen living environment

In this model, he / she places the most suitable equipment and sensors. For this user, the smart home system retrieves two induction cooktops: one that produces high contrast on its surface (with a black panel) and a textured button surface; the other is a black surface with high contrast controls and digital and Backlit display; two convection oven models with digital and backlit display and a set of control lights; four high-contrast backlit digital display dishwashers; two refrigerators with digital backlight interface, showing the current internal temperature and internal light. According to the user's preferences, the designer selects home appliances and sets them into a virtual model of the kitchen, as show in Figure 6 – 9. They will introduce scenarios and smart home simulator applications during the first training phase of approximately 15 minutes. To facilitate and speed up their work, digital models of empty kitchens will also be provided as a starting point. During the configuration phase, task times, errors, potential software errors, and user comments are recorded. At the end of the trial, a system availability score questionnaire will be issued to each tester. Free reviews will also be collected and considered to improve the software based on user needs.

Figure 6 A snapshot of the Smart Home Simulator application: the designer selects the user for who he/she con7gures the kitchen.

Figure 7 A snapshot of the configurable appliances (for a selected user) in the kitchen.

Figure 8 The designer places the dishwasher, choosing from the appliance models retrieved from the KBHome.

Figure 9 The designer places the suitable sensors in the kitchen.

Creation of kitchen living environment for sports activities

This scenario describes a 72-year-old frail woman who must perform daily exercise on a cycling ergometer in her bedroom, with monitoring and assistance provided by a smart home system. This system is equipped with various sensors to track heart rate, respiration rate, and blood pressure, ensuring her safety during exercise. The smart home environment includes automated features like temperature control and air quality monitoring, all managed through a virtual tablet. Room preparation: Upon entering the bedroom, a presence sensor activates, triggering the monitoring of air quality and temperature. If the carbon dioxide levels are too high, a warning appears on the tablet, prompting her to open the window. The windows can be controlled via the tablet, ensuring the environment reaches the optimal conditions (20°C) before she begins exercising. Exercise Setup: Once the environment is ready, the tablet notifies her to start the exercise. The system automatically adjusts the exercise workload based on her health condition. Instructions on how to wear the necessary sensors are provided through the tablet. During Exercise: As she exercises, wearable devices continuously monitor her blood pressure, breathing rate, and pulse. Any abnormalities trigger alerts on the tablet, guiding her to adjust or stop the exercise if necessary. Data Recording: After completing the exercise, all relevant Data including blood pressure, pulse rate, and exercise duration are automatically stored in the system. This data is made available to caregivers or clinicians to assess her health and monitor her progress over time. The smart home system ensures the user's safety and well-being during physical activity by providing real-time monitoring, feedback, and environmental control, all while recording essential health data for ongoing assessment.

Fall detection

The smart home system ensures the user's safety and well-being during physical activity by providing real-time monitoring, feedback, and environmental control, all while recording essential health data for ongoing assessment. The test examines three common types of falls experienced by the elderly in daily life. Due to the risks involved are selected to replace the elderly for the fall detection test, with safety measures in place to protect the experimenters. Scenario A: Slipping in the bathroom, Toilet, or kitchen in this scenario, user wear HMD devices and wearable sensors to simulate fall in environments like bathrooms, toilets, and kitchens, where tile floors and liquids such as water, oil, or detergent can cause. The fall typically involves leaning backward, and sensors detect changes in head posture, acceleration, body posture, and pulsed to determine the fall. The smart home system then promptly generates an alarm. Scenario B: Falling After Standing Up suddenly here, user simulate a scenario where elderly individuals, due to poor blood circulation or weak legs, may fall after standing up too quickly. The fall posture is generally upright or slightly leaning forward or backward. In this case, head and body posture detection may not be highly sensitive, so acceleration and pulse changes are primarily relied upon to detect the fall and trigger an alarm in the smart home system. Scenario C: Falling Due to Mood Swings, Medical Emergencies, or Overexertion. In this scenario, user simulate falls that occur due to heightened emotions, medical emergencies like a stroke, or excessive physical exertion. The elderly's heart rate and blood pressure often spike, potentially leading to serious issues like cerebral hemorrhage or infarction. Falls in this scenario can vary in posture, but pulse change detection is the most sensitive, followed by body posture, head posture, and acceleration detection. At least two of these factors are used to determine the fall, prompting the smart home system to sound and alarm. Additionally, elderly individuals are prone to tripping on stairs or falling due to poor vision. While these situations were not separately tested, the detection principles are similar to the three scenarios above. This study demonstrates that the virtual reality-based smart home system is effective at detecting falls and promptly issuing alarms.

IV. Conclusion and Future Works

The research detailed in this paper focuses on the development of a virtual reality smart home system using Unity3D, incorporating technologies such as context-aware systems, 3D modeling, VR/AR, and fall detection. The study successfully demonstrated the application of these technologies in creating an immersive and interactive smart home environment, particularly catering to the needs of the elderly. By integrating advanced sensing and detection algorithms, the system enhances safety, especially in fall detection, and improves user interaction through a combination of virtual and augmented reality. The key achievements include the design and development of a comprehensive virtual smart home system that allows for realistic simulations and user testing before physical implementation. The research also highlights the importance of making smart home technologies accessible and easy to use for the elderly, ensuring that the system not only enhances their quality of life but also monitors their health effectively. Overall, the study presents a promising approach to combining 3D technology with smart home systems, offering new insights and directions for the future of smart home systems is increasingly focused on enhancing both intelligence and user-centric design. Integrating 3D technology represents a key trend for various industries, including smart homes. The virtual smart home system explored in this paper is a step toward incorporating 3D technology into these environments. However, there are areas for improvement in practical applications. Without integration with real hardware systems, this research serves more as an innovative exploration rather than a fully practical solution. Future efforts should focus on developing smart home systems that combine 3D technology with real-world hardware to achieve more practical and impactful results.

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