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Research Article

Digital Twin-Based Modeling of Real-World Objects Utilized in the Senior Housing Project

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ABSTRACT

The rapid advancement of digital technologies has significantly transformed various sectors, including urban development and elderly care. Among these innovations, Digital Twin technology emerges as a revolutionary tool that bridges the physical and digital worlds by creating dynamic virtual representations of real-world entities. This study explores the integration of Digital Twin technology in senior housing projects to improve the quality of life for the elderly while enhancing operational efficiency. By leveraging the Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing, this research demonstrates how Digital Twin models can facilitate real-time monitoring, predictive analysis, and efficient resource management. The implementation of IoT sensors within a senior housing environment enables proactive safety measures, optimized energy usage, and enhanced healthcare interventions. Through simulations and real-time data analytics, the study validates the model's effectiveness in fostering a safer, smarter, and more responsive living environment for aging populations. The findings contribute to the growing discourse on smart city technologies and highlight Digital Twin technology as a scalable and sustainable solution for elderly care and urban infrastructure management.

Keywords: Digital Twin, Internet of Things (IoT), Infrastructure, Smart City, Cloud Computing

INTRODUCTION

In the areas of urban development, healthcare, and aged care services, the growing older population creates considerable obstacles. Traditional methods of managing elder housing sometimes face challenges in providing care that is both individualized and effective, which may lead to living circumstances that are less than ideal and inefficiencies in the use of resources. Evolving digital technology offers innovative ways to enhance care for the elderly and optimize facility operations in response to this matter. The capacity of one such technology, known as Digital Twin, to generate virtual reproductions of physical systems in real-time has garnered a lot of interest. This ability enables extensive monitoring, analysis, and modeling of the systems.

Digital Twin technology is primarily driven by IoT, AI, and cloud computing, allowing for real-time data collection and predictive analytics. In the context of senior housing, these capabilities enable proactive decision-making, resource optimization, and enhanced safety measures. By continuously updating digital replicas with sensor-generated data, Digital Twin systems provide valuable insights into environmental conditions, resident behaviors, and facility operations. This results in improved living standards, reduced operational costs, and enhanced emergency preparedness.

This study aims to investigate the application of Digital Twin technology in senior housing projects, focusing on its potential to enhance quality of life and operational efficiency. The research explores how IoT-enabled Digital Twin models can address the unique needs of elderly residents, ensuring personalized care, safety, and sustainability. This study adds to the field of smart cities by using real-time data analytics and simulation techniques. It also gives a scalable framework for future use in infrastructure for caring for the elderly.

LITERATURE REVIEW

IoT and Smart City

The Internet of Things (IoT) is a critical technology that enables the development of smart cities by facilitating the communication and exchange of data between interconnected devices, including mobile phones, actuators, and sensors (Niaky & Tahami, 2021). This connectivity enables efficient monitoring, automation, and administration of urban resources, thereby improving residents' quality of life and fostering sustainable city operations.

The fast expansion of IoT significantly influences Information and Communication Technology (ICT). Forecasts suggest that the quantity of linked IoT devices will attain 29.4 billion by 2030 (Melibari, Baodhah, & Akkari, 2023). This expansion enhances smart city infrastructure by incorporating advanced technologies that enable fluid interaction among people, structures, and other urban systems.

IoT technologies, such as wireless sensor networks, RFID, and barcodes, provide intelligent detection, tracking, and real-time data processing. These abilities enable communities to streamline operations, increase services, and advance industrial growth. The IoT is essential for updating urban infrastructure and promoting long-term sustainability by automating operations and facilitating device-to-device connectivity without human involvement.

Cloud Computing

The evolution and widespread acceptance of cloud computing has significantly transformed the information technology environment by establishing a novel paradigm for distributing and accessing computer resources over the internet. This paradigm shift transitions from conventional on-premises IT infrastructure to a more dynamic, adaptable, and scalable model. Cloud computing includes several services, such as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS), each of which provides different levels of control, flexibility, and administration to meet the distinct requirements of enterprises and individuals.

IaaS offers a virtualized computing infrastructure available over the internet, allowing customers to rent virtual computers, storage, and networking resources on a pay-as-you-go model. This concept relieves enterprises of the capital and operating costs related to the maintenance of physical servers and data center equipment. PaaS provides a development environment as a service, providing developers with the essential tools and frameworks to create and deploy applications without the intricacies of overseeing the underlying hardware and software layers. SaaS, undoubtedly the most dominant approach, delivers software programs over the internet, thereby obviating the need for installation, maintenance, and patch management by end users (Golightly, Chang, Xu, Gao, & Liu, 2022).

Cloud computing deployment methods include public, private, hybrid, and community clouds, each addressing distinct organizational needs related to data governance, security, and regulatory compliance. The public cloud offers internet-based services to multiple clients, whereas the private cloud is exclusive to a single firm. The hybrid cloud amalgamates public and private environments, providing the adaptability to transfer workloads between them according to changing demands and expenses. Community clouds cater to companies with similar goals and operational or regulatory requirements.

The intrinsic value of cloud computing, apart from its structural models, is in its scalability, enabling organizations to modify resources based on demand, and its cost-effectiveness, which diminishes entry hurdles for small enterprises and startups. Organizations may boost operational agility, stimulate creativity, and promote sustainable corporate success by using cloud technology in an increasingly digitalized environment.

Using JSON for Data Exchanging in Web Service Applications

JavaScript Object Notation (JSON) is a lightweight, language-independent data format widely used in web development for effective communication between clients and servers. Its simplicity and human-readable syntax make it an ideal choice for data transfer across several platforms, including a web application created in JavaScript and a backend server running on PHP. Developers like JSON for its capacity to provide efficient data transmission, allowing for dynamic processing and response to user input. The simplicity of integration improves the entire user experience, facilitating rapid and engaging online applications (Erickson, 2024).

In addition to its applicability in web development, JSON is often employed for the management of application settings. Storing settings, such as database connection parameters or API keys, in JSON format allows developers to change application functionality without altering the source code. The straightforward nature of these configuration

files enhances readability and simplifies updating, making JSON a viable choice for managing both dynamic data and static settings inside an application or IT system.

Interpreting and comprehending JSON data is crucial in web service applications, facilitating the retrieval of pertinent information from the server's response. This dynamic data analysis enables seamless integration with web APIs and external services. Employing dynamic Data Mapping Templates (DMTs), developers may efficiently transform JSON data into the host programming language at runtime. This method improves interoperability and ensures optimal data management and use, hence enhancing the performance and flexibility of web services (Peng, Cao, & Xu, 2011).

Digital Twin Concept

The concept of digital twins has revolutionized the management of physical systems in the digital era. A digital twin is a dynamic, digital representation of a tangible object or system that mirrors the physical world by utilizing real-time data throughout its lifecycle as a representation. This concept is capable of transcending the boundaries between the physical and virtual domains, thereby facilitating the detailed analysis, simulation, and optimization of systems in previously unimaginable ways (Liu, Fang, Dong, & Xu, 2021).

The implementation of digital twins is revolutionizing conventional operational processes in a variety of sectors, such as manufacturing, healthcare, and urban planning. For instance, in the manufacturing sector, digital twins facilitate the virtual testing of production lines and processes, thereby identifying and resolving potential issues before their occurrence in the real world. This predictive capability leads to increased productivity and cost savings by substantially decreasing downtime and improving efficiency.

In a controlled virtual environment, digital twins of human organs can simulate physiological responses to treatments in the healthcare sector. By predicting outcomes before actual procedures, this innovative approach has the potential to personalize healthcare, thereby reducing the risk of treatment and enhancing its efficacy.

The integration of IoT devices is crucial for the enhancement of the accuracy and utility of digital twins and the provision of real-time data. Digital twins are constantly updated with real-time data, which provides insights that enable more informed decision-making. Nevertheless, the increasing popularity of these systems has brought about a variety of challenges, such as the necessity for a significant amount of computing power, concerns regarding data privacy, and the collaboration of experts from a variety of fields to construct and maintain these intricate systems.

Digital twins have a promising future, despite these obstacles. They present a vision of a world in which the distinctions between the real and the digital are blurred, resulting in more efficient, sustainable, and personalized solutions in all facets of life. The potential applications of digital twins are anticipated to expand as technology advances, thereby introducing a new era of digital transformation (Mihai, Yaqoob, Hung, Davis, Towakel, Raza, Karamanoglu, Barn, Shetve, Prasad, Venkataraman, Trestian, & Nguyen, 2022).

Digital Twin Agent for Super-Aged Society

In the context of a rapidly aging global population, the implementation of digital twin technology offers an innovative and disruptive solution to the complex difficulties encountered by a super-aged society. This innovative use of digital twins aims to elevate the quality of life for the elderly by integrating technology and care to customize and enhance healthcare results and living situations (Kobayashi, Fukae, Imai, & Arai, 2022).

In the setting of a super-aged society, digital twin technology operates by generating virtual clones of old humans. Real-time health information from diverse IoT devices and sensors continuously refreshes these copies. This ongoing flow of data facilitates the surveillance of health issues, enabling preemptive treatments and tailored healthcare strategies. The digital twin is a platform for managing a person's health that combines information from medical records, wearable tech, and environmental sensors to provide a holistic view of an individual's health status.

This technology also expands its application beyond healthcare to assisted living settings. Digital twins can model and evaluate the living situations of the elderly, detecting possible threats or opportunities for enhancement in their environment. This guarantees that living environments are both safer and more supportive of independence and well-being.

The customization features of digital twins facilitate the development of more customized healthcare services. Getting to know each person's unique health history and needs helps doctors give senior patients better treatments and

interventions that are more likely to work for their specific health conditions. This degree of customization is essential for controlling chronic diseases and averting acute health events.

The use of digital twin technology in a super-aged society constitutes a progressive approach to the intricate issues associated with aging. Utilizing real-time data with virtual simulation provides a means to improve healthcare, offer safer living conditions, and ultimately increase the quality of life for the elderly. The incorporation of technology into aged care represents a substantial advancement toward more empathetic, effective, and individualized care for elderly people globally.

METHODS

Research Design

This study aims to develop and evaluate a digital twin model for senior housing projects through a systematic methodology that incorporates both qualitative and quantitative research methods. The approach is designed to ensure a comprehensive analysis, encompassing the integration of digital twin technology within the context of smart city development and elderly care. The digital twin model will be conceptualized, outlining its architecture, components, and functionalities. This phase includes designing the physical layout of the senior housing facility, incorporating essential utilities, and resident areas, and the integration of IoT devices. In the data integration stage, real-time data from IoT devices within the housing facility will be incorporated into the model. These devices, including sensors monitoring utilities, resident activities, and environmental conditions, will enable real-time data capture and analysis. The simulation will be employed to replicate real-world scenarios, allowing for the testing of emergency responses, utility management, and daily operations, facilitating the identification of potential improvements.

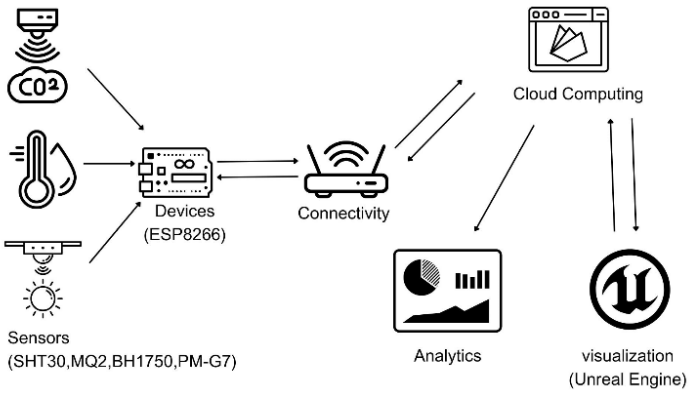

Figure 1. Digital Twin Platform framework

Data Collection and Integration

The study will employ both primary data and secondary data sources. IoT devices embedded in the senior housing project will collect primary data, which will focus on energy usage, water consumption, and resident movement patterns. This real-time data will be essential for monitoring facility operations and ensuring the effectiveness of the digital twin model. Along with the primary data that is collected, secondary data will also be gathered from records, reports, and relevant studies that already exist. This will give historical and contextual information that supports and adds to the primary data that is collected. The integration of both data types will enhance the model's ability to reflect real-world conditions and improve predictive capabilities.

Data Analysis and Validation

Statistical and computational methods will be applied to analyze the collected data, aiming to identify patterns, trends, and inefficiencies within the system. To make sure the digital twin model is accurate and reliable, it will be tested to see if it accurately represents the real world and how well it works in different operational situations. Following testing, feedback incorporation will be implemented, where insights from stakeholders, including facility managers and residents, will be used to refine and enhance the model. This iterative process will help address any identified issues and optimize the model’s effectiveness.

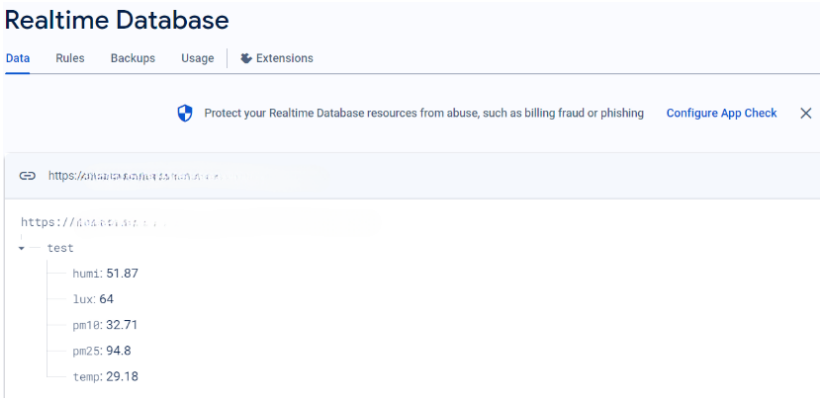

Figure 2. Realtime Database on Firebase

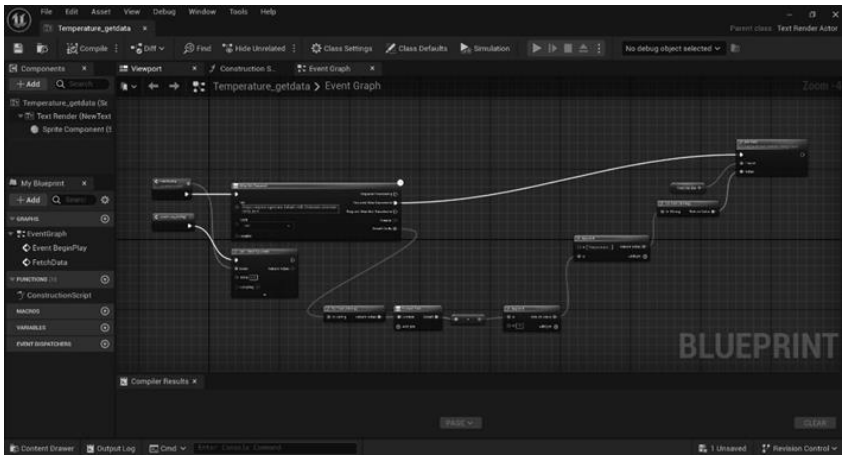

Figure 3. Unreal Engine 5 Blueprint base on C++

Evaluation and Ethical Considerations

The model will be assessed using predefined performance metrics, including resource optimization, resident satisfaction, and operational efficiency, to measure its overall impact and value. Additionally, a comparison study will be carried out between the digital twin model and the usual ways of running senior housing facilities to show the model's advantages and possible enhancements. Ethical considerations will be central to the study, ensuring that data collection and analysis methods adhere to stringent privacy and consent protocols. The research will prioritize the protection of resident information and compliance with ethical standards.

Using this thorough method, the study will carefully create, test, and rate a digital twin model for senior housing projects. This will give us useful information and useful ways to improve care for the elderly and facility management in the context of smart city development.

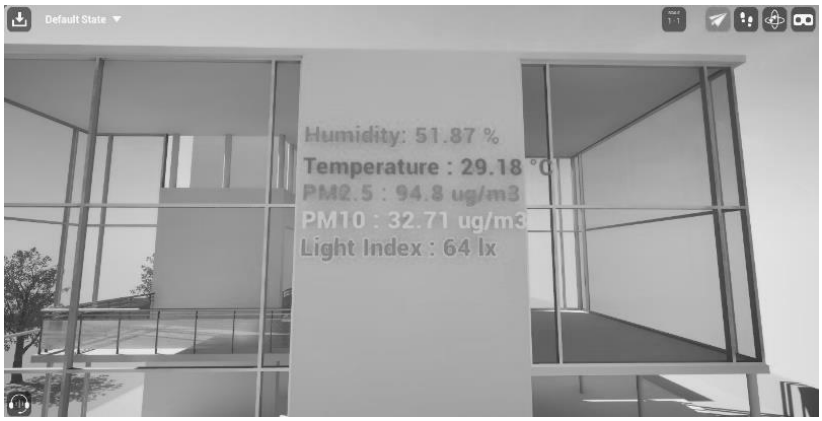

Figure 4. Digital Twins based on Unreal Engine 5

RESULTS

The Digital Twin model was successfully implemented in the senior housing facility by integrating a network of IoT devices, such as SHT30 (temperature and humidity sensors), MQ2 (gas sensors for smoke and hazardous gas detection), BH1750 (light intensity sensors), and PM-G7 (particulate matter sensors), with ESP8266 microcontrollers to facilitate rapid data collection. Strategically positioned throughout the facility, these devices continuously monitored environmental conditions, transmitting real-time data to Firebase and utilizing cloud computing for analytics. AI algorithms looked at the data to find patterns and outliers. This made it easier to plan for maintenance and make changes to the environment. By optimizing HVAC systems, fostering sustainability, and reducing energy consumption, the model significantly enhanced operational efficiencies. Emergency simulations achieved safety improvements by predicting potential risks, reducing response times, and enhancing preparedness. AI-driven proactive safety measures enabled real-time modifications to protect against hazards such as poor air quality and gas leakage. The immersive and interactive experience of Unreal Engine 5 enhanced user engagement, garnering positive feedback from both residents and staff. They appreciated its intuitive interface and real-time environmental data visualization. In contrast to conventional management methods, there were evident advantages, including reduced expenses as a result of more efficient resource utilization and increased satisfaction scores from residents, which indicated improved health and contentment. Overall, the findings indicate that the integration of digital twin technology into senior housing enhances the user experience, operational efficiency, and safety. It also provides proactive and cost-effective solutions for facility management.

DISCUSSION AND CONCLUSION

This study effectively created a digital twin model for senior housing initiatives by integrating IoT technology, data analytics, and simulation into a unified framework. This model has the potential to improve the quality of life and operational efficiency for the elderly. The model was able to provide in-depth insights into daily operations, resident interactions, and utility utilization by incorporating real-time IoT data. Additionally, it was able to accurately simulate both routine and emergency scenarios to ensure safety and comfort. By demonstrating the potential of digital twins to enhance emergency responses and optimize resource management, the research makes a substantial contribution to the development of smart cities and the care of the elderly. Nevertheless, ongoing refinements are necessary due to continued challenges, such as the complexity of accurately simulating real-world scenarios, data privacy, and security. Advanced AI algorithms should be integrated into future research to improve predictive accuracy, and ethical considerations regarding data acquisition in senior housing should be further investigated. The expansion of digital twin applications across broader smart city initiatives presents intriguing opportunities for urban development. In conclusion, this study highlights how digital twin technology has the potential to change the way living environments for older people are made smarter and more responsive. It provides scalable solutions that will influence the future of sustainable urban management and geriatric care.

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