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DESIGN REQUIREMENTS FOR METAVERSE-BASED SMART HEALTHCARE SYSTEMS

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ABSTRACT

This is a multidisciplinary approach, integrating advanced technologies, clinical expertise, and ethical principles utilization in designing Metaverse-based smart healthcare systems. Prioritizing user-centric design, interoperability and immersive technologies in the design requirement definitions, a typical Metaverse-based smart healthcare systems can revolutionize healthcare delivery. The rapid evolution of digital technologies has paved the way for innovative healthcare delivery models, with the Metaverse emerging as a transformative platform for smart healthcare systems. This paper delineates the comprehensive design requirements for developing Metaverse-based smart healthcare systems, which integrate virtual environments, advanced technologies, and healthcare services to enhance patient care, medical training, and operational efficiency. These systems aim to create immersive, secure, and scalable healthcare ecosystems that address the needs of patients, healthcare providers, and stakeholders while overcoming technological, ethical, and operational challenges. A cornerstone of Metaverse-based healthcare systems is their user-centric approach, ensuring accessibility, usability, and personalization. Interfaces must be intuitive, accommodating diverse user groups, including patients with varying levels of technical proficiency, elderly populations, and individuals with disabilities. Customizable avatars, multilingual support, and adaptive user interfaces enhance engagement and inclusivity. Systems should support personalized healthcare journeys, enabling tailored treatment plans, virtual consultations, and patient education through immersive experiences. Usability testing with diverse cohorts is essential to ensure interfaces meet the needs of all stakeholders, including healthcare professionals requiring efficient workflows. Seamless interoperability with existing healthcare infrastructures, such as electronic health records (EHRs), clinical decision support systems, and wearable devices, is critical. Metaverse systems must adopt standardized protocols to enable real-time data exchange, ensuring continuity of care and accurate patient information across virtual and physical environments. Integration with Internet of Medical Things (IoMT) devices facilitates continuous monitoring, enabling real-time health data updates within the Metaverse. This ensures that virtual consultations and interventions are informed by comprehensive, up-to-date patient data, enhancing clinical decision-making.

Keywords: Immersive Technologies, Interoperability, Internet of Medical Things (IoMT), Metaverse Healthcare, Smart Healthcare Systems, User-Centric Design.

1.0 INTRODUCTION

The advent of the metaverse has opened new horizons for delivering interactive healthcare solutions (Wolko, 2024). It is a digital, immersive, and interconnected virtual environment where people interact with one another and digital entities using technologies like augmented reality (AR), virtual reality (VR), artificial intelligence (AI), blockchain, and 3D modeling. It's a collective space that merges the physical and virtual worlds, allowing for activities such as gaming, socializing, commerce, education, and professional collaboration. The metaverse represents a significant opportunity to reshape healthcare by improving patient outcomes, optimizing medical training, and creating more inclusive care environments (Wang et al., 2024). Its continued evolution will depend on technological advancements, ethical considerations, and collaborative efforts between industries and governments.

1.1 Relevance to HealthCare

The metaverse holds transformative potential for the healthcare industry, enabling advancements in how care is delivered, accessed, and experienced. Key areas of relevance include: **medical training and education**, **patient care and treatment**, **mental health support**, **personalized and preventive care**, **health equity and accessibility**, **research and innovation**, and **healthcare marketplaces. Medical training and education is related directly to virtual simulations, anatomy and pathology exploration, and remote collaboration.** The metaverse provides realistic simulations for medical students and professionals to practice surgical procedures, patient care, and diagnostics without risking patient safety. AR and VR tools enable immersive exploration of human anatomy and pathological processes in 3D, and professionals worldwide can convene in virtual environments for training, conferences, or case discussions (Turab & Jamil, 2023).

Through metaverse-enabled telemedicine, patients can meet physicians in virtual clinics, enhancing accessibility and patient engagement. **Personalized and preventive care are hinged more on digital twins and wearables integration.** A virtual replica of a patient's anatomy or health data can allow healthcare providers to simulate outcomes, plan interventions, and predict disease progression. Devices can stream real-time health data to the metaverse, enabling continuous monitoring and proactive interventions (Yaqoob et al., 2023).

1.2 Importance of Architectural Design

This paper explores architectural design requirements essential for implementing such systems, supplemented by case studies and use cases to demonstrate their practical applications (Ishtaiwi et al., 2024). A robust architecture is essential for metaverse-based healthcare systems to ensure they deliver safe, reliable, and effective services while meeting the unique demands of the healthcare industry. It can pave the way for future innovations, making healthcare delivery more accessible, personalized, and effective (Vetrivel & Mohanasundaram, 2024). Metaverse-based healthcare often involves real-time interactions, such as virtual consultations, surgery simulations, and therapy sessions; a robust architecture can minimize latency for smooth, real-time communication, and can also ensure high availability and fault tolerance to prevent downtime.

Healthcare systems must be user-friendly and accessible to patients, caregivers, and professionals; a strong architecture therefore is necessary to optimizes AR/VR environments for intuitive navigation and interaction, and to ensure compatibility across diverse devices and platforms. Healthcare providers and patients will only adopt metaverse-based systems if they are perceived as trustworthy and dependable; a strong architecture ensures consistent performance and reliability. A flexible and scalable architecture fosters innovation, allowing healthcare providers to adapt to new technologies and trends.

2.0 RELATED WORK

Lakshmi et al., (2024) stated clearly how metaverse facilitates rapid and efficient decision-making by enabling connections with multiple experts simultaneously (Turab & Jamil, 2023). The growing landscape of emerging wireless applications is a key driver toward the development of novel wireless system designs (Khan et al., 2024). Such a design can be based on the metaverse that uses a virtual model of the physical world systems along with other schemes/technologies. Clear definition of requirements capable of integrating optimization theory, machine learning, and virtual models will enable proactive performance and intelligent analytics in metaverse systems especially for efficient management of wireless system resources (Aditya & Mohan, 2024).

Lifelo et al., (2024) introduced artificial intelligence-enabled metaverse for sustainable smart cities. Their study reveals that Artificial Intelligence (AI)-enabled metaverse offers transformative potential for developing sustainable smart cities (Wolko, 2024). Chen and Ruan, (2024) opined that in the complex landscape of healthcare supply chains it is now necessary to adopt innovative solutions that align with the evolving technological landscape. The emphasis was on the emergence of metaverse as a compelling solution by offering the potential for significant enhancements in efficiency and traceability (bin Zainuddin et al., 2024). The metaverse gained a lot of popularity particularly due to the emergence of Cloud computing, and remote communications (Ismail & Buyya, 2023). It is quite evident that the requirements of realizing the metaverse in real-time and at a large-scale need yet to be examined for the technology to be usable (Yaqoob et al., 2023).

To address this limitation, Ismail and Buyya (2023), further presented the temporal evolution of metaverse definitions and captures its evolving requirements. Ullah et al., (2023) focused their study on the exploration of applications of metaverse in various health care systems and elaborate on how it can efficiently improve the clinical management of patients (Stary, 2023). A substantial scientific contribution illuminating the foundational concepts underlying the emergence of the metaverse was accessible in (Rawat & Hagos, 2024). The architecture was analyzed by defining key characteristics and requirements, thereby illuminating the nascent reality set to revolutionize digital interactions (Kang et al., 2023). The scrutiny was extended to critical technologies integral to the metaverse, including interactive experiences, communication technologies, ubiquitous computing, digital twins, artificial intelligence, and cybersecurity measures (Vetrivel & Mohanasundaram, 2024). Li et al., (2024) defined the next generation of interoperable healthcare ecosystem in the Metaverse (Sujatha et al., 2025). Metaverse is the buzz technology of the moment raising attention both from academia and industry (Abilkaiyrkyzy et al., 2023). Many stakeholders are considering an extension of their existing applications into the metaverse environment for more usability (Mozumder et al., 2023). Metaverse is a virtual realm that improves the efficiency and cost of smart power system operation and development in various ways that are rarely considered in the literature (Tightiz et al., 2024). Alam (2024), explored the advantages, uses, and transformative outcomes of the MoT in smart cities. It encompasses sustainability, urban planning, citizen participation, infrastructure management, and more (Wang et al., 2024).

Recently, significant research efforts have been initiated to enable the next-generation, namely, the sixth-generation (6G) wireless systems (Khan et al., 2024). They Khan et al., (2024) presented a vision of metaverse towards effectively enabling the development of 6G wireless systems (Liu et al., (2023). Shardeo et al., (2024). Pointed out clearly that the emergence of novel innovations has disrupted multiple service sectors, and healthcare is one such sector that has seen significant changes since the inception of Internet (Ishtaiwi et al., 2024). The aim currently, is to identify the factors that drive the adoption of metaverse in the healthcare industry using an architecture with the needed healthcare defined requirements. Such definitions will complement the future trend and eliminate identified bottlenecks with the metaverse implementation in healthcare services. Kim et al. (2023) examined and categorized the key technologies and advancements that have spearheaded the metamorphosis of metaverse wearables (Qu et al, 2023).

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3.0 DESIGN ELEMENTS FOR METAVERSE-BASED SMART HEALTHCARE SYSTEM

The metaverse is a new computing era where the internet becomes a shared, persistent, immersive and interoperable space, where interactions become possible as if the players are in the physical world. One critical consideration in the technological trend of healthcare in the metaverse is designing a framework with all the necessary elements contained in the virtual environment. The core design components of such typical virtual environment are the user interface layer, the application layer, data management layer, networking layer, and the integration layer (see fig. 1).

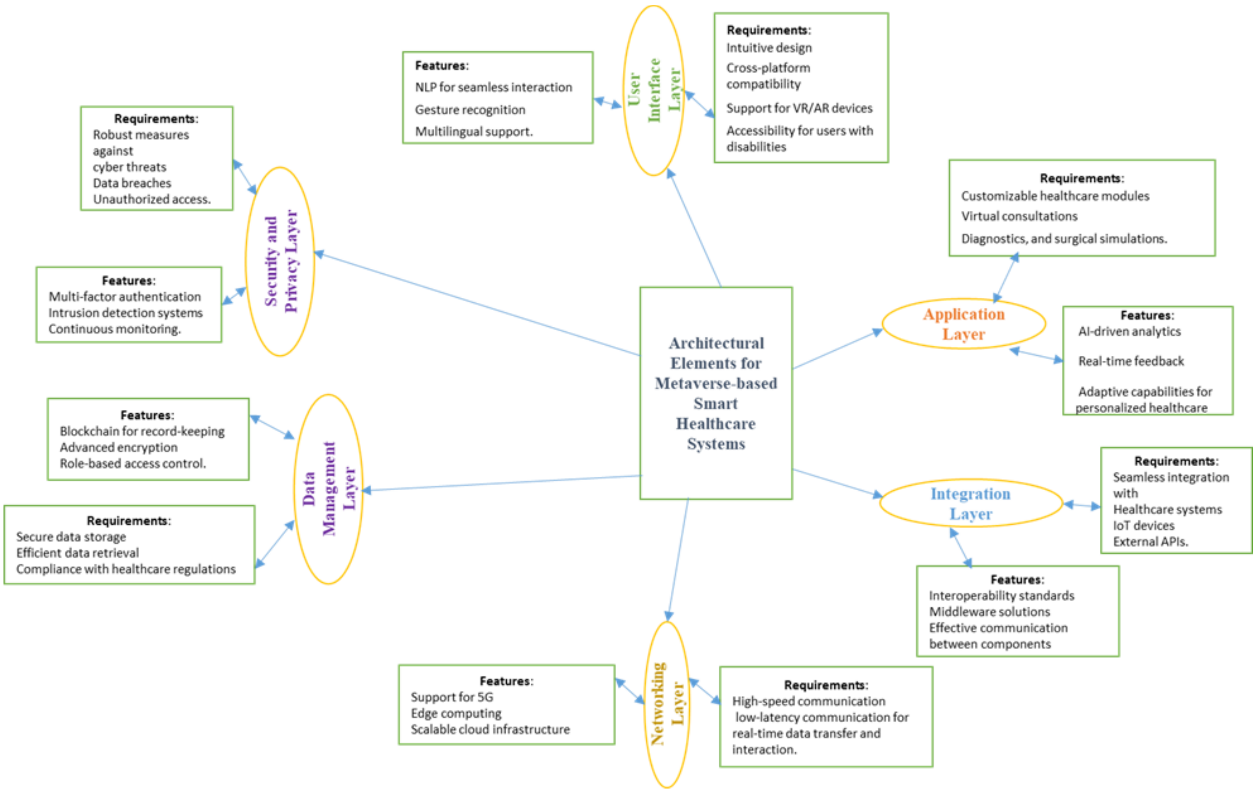

Fig. 1: Design Features of Healthcare in the Metaverse

Figure 1 depicts the virtual environment, which is necessary to identify the requirements and features for the proper actualization of healthcare in the metaverse. The virtual environment can be composed by recognizing and rendering the requirements and features and as well utilize them to facilitate the component enablers for the immersive and multisensory experience.

3.1 Healthcare Requirements in the Metaverse Layered Architecture

The Metaverse layered architecture, which usually consists of the infrastructure, distributed computing, platform, and application layers as shown in figure 2 enables an immersive experience for users in different application domains such as smart healthcare, smart mobility,

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smart education, business, manufacturing, gaming and entertainment, and social media (Ismail & Buyya, 2023). Figure 2 depicts the design requirements of the applications of healthcare in the metaverse. Metaverse can enhance patient care and treatment through virtual consultations therapy in virtual spaces and rehabilitation. Doctors and patients can meet in virtual clinics with realistic 3D avatars, offering a more engaging experience than video calls. Virtual environments can treat conditions like anxiety, or phobias using exposure therapy in controlled digital spaces.

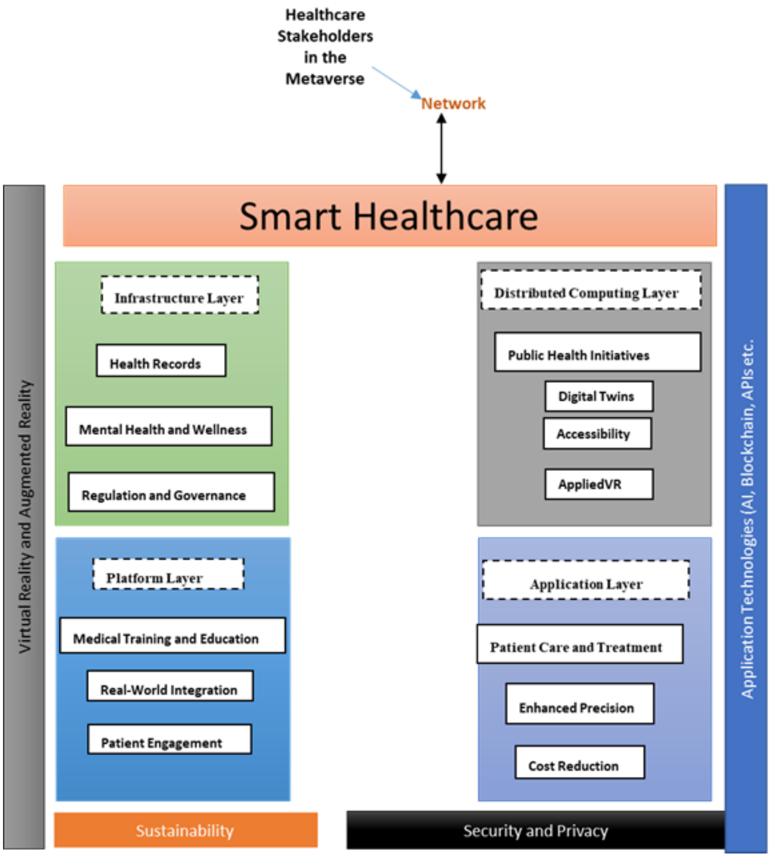

Fig. 2: Applications of Healthcare in the Metaverse

Patients recovering from strokes or injuries can engage in gamified physical therapy in VR, making exercises more interactive. Metaverse can revolutionize the healthcare industry by providing medical training and education. Surgeons can practice complex procedures in VR environments, improving skills without risking patient safety. Medical students across the globe can join virtual anatomy labs, explore 3D models, and work together in the Metaverse. Trainees can interact with realistic AI-powered avatars that simulate various symptoms and conditions.

Mental health and wellness via the metaverse involves meditative environment and support groups. Virtual spaces designed for relaxation and stress relief can improve mental health and promote mindfulness. Patients with chronic conditions or mental health challenges can meet in secure virtual spaces for peer support. While digital twins in smart healthcare are concerned with personalized medicine and surgical planning, health records and public health intitiatives are focused on data security, decentralized health economies, virtual health fairs and public health initiatives and pandemic preparedness.

4.0 DESIGN TRENDS AND DEFINITIONS

Metaverse-based interactions and intervention tools are available, our envisioned architectural design requirements for metaverse-based smart healthcare systems are new scenarios that will bring additional openings and operational simplicity. Eventually, healthcare frameworks will be realized, and these, combined with the immersed environments will create identified advantages for a successful workflow. It is yet to be seen how the ecosystem will evolve of carefully gathered requirements of healthcare components design platform with the needed requirements capable of capturing system logic for any diagnosis, treatment or other patient management scenarios. Therefore, with this trend a well-defined and highly desirable component of the metaverse for smart healthcare can easily be developed.

4.1 Infrastructure Design Requirements

The adoption of many technologies to enable metaverse-based smart healthcare systems will need to be developed by stakeholder companies and corporate bodies Due to its immediate value and potential incentives; the infrastructure design requirements adoption is typically centered on health records, mental health and wellness, and regulation and governance. Health records infrastructure are particular about patient-centered smart healthcare and medical service systems, augmented and virtual reality-based remote patient monitoring and individualized treatments, and medical and metaverse operating system technologies in 3D internet of things healthcare and virtual clinical settings. Medical and metaverse operating system technologies use 3D anatomical images of the human body structure in virtual environments. Metaverse healthcare data and systems can be harnessed for optimized remote patient monitoring and long-term digital health data management in cloud computing environments. Mental health and wellness infrastructure requirements should define the transformative platform offering new dimensions of interaction and engagement that can possibly represents an entirely new medium for improving telemedicine. These definitions can now offer novel methods to improve resource optimization, patient care, and operational efficiency in the healthcare sector. In addition, the power in the combination of meta and universe in the word "Metaverse" will be harnessed to open a new era in mental health, mainly in psychological disorders, where the creation of a full-body illusion via digital avatar could promote healthcare and personal well-being. Technology is a driving force of the metaverse that can be guided, in part, by governments.

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Metaverse standards can come from government bodies, such as government departments and standardization agencies, or market players, such as industry alliances and enterprises. Given the current development stage of the metaverse, its standards are developed in advance before the market matures. Regulation and governance infrastructure requirements definition therefore is based on technical and ethical standards. Without technical standards, the metaverse cannot be built. This digitalization transforms content production, the economic system of the concerned people, user experience, and scenes of the physical world with the support of technical standards. The virtual and the real worlds are closely integrated into the economic, social, and identity systems, and each user can produce content and edit the virtual world.

4.2 The Subject Oriented Layer Concept

This concept allows for structured and contextual refinement of digital designs and is open with respect to the number of layers as shown in figure 3. The structure is such that refinements can be implemented to the stage where the actual behavior can be encapsulated. This definition path way can enable specific category component application in both top down, middle-out or bottom-up approach. For example, in case a particular healthcare issue is identified to be inclusive, or several data are captured and need to be reflected in the design in the starting point of metaverse framework development, the scheme for layering the categories refinement in terms of the descriptions and the diagrammatic illustrations can be defined as part of the smart healthcare mataverse architecture design and operation.

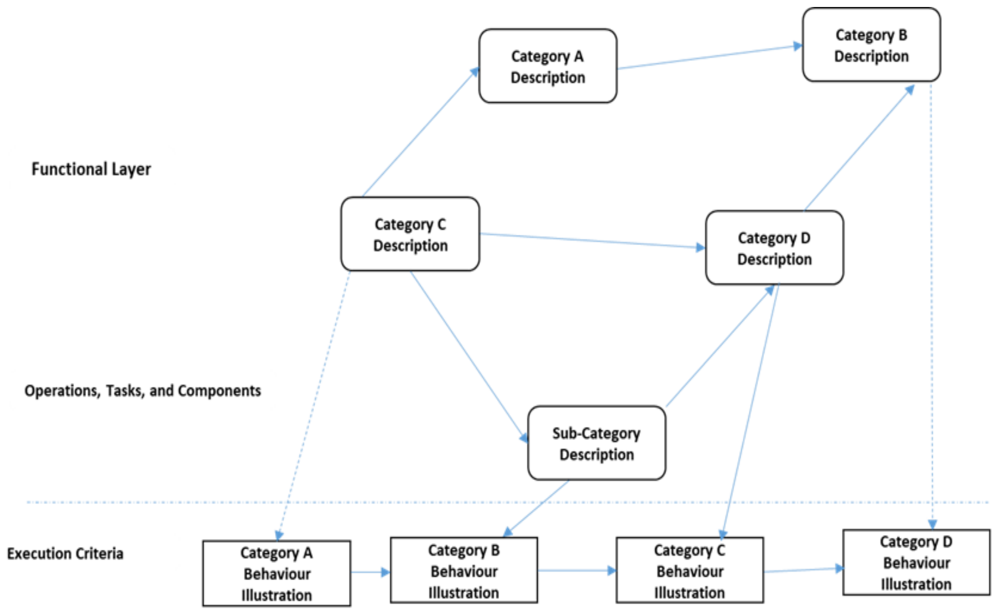

Fig. 3: Scheme of Refinement for Design Components

In the structure, a rectangle with rounded edges represents the realizable categories and a sub category for relevant inputs, a rectangles represents a category behavior illustrations, a line represents transmission of a message, and a dotted line represents decomposition. The subject-oriented layering concept aims to enrich the design space and follows guiding principles for design. Overall, the functional layer need to be specified, as it requires a category description representing value-generating subjects and their interaction. When a subject on this specific functional layer of abstraction is refined, the interactions such as passing of messages constrain its behavior on a lower layer. The next will be the operations, tasks and the components pertaining to the healthcare dynamics to accompany the functional layer for effective metaverse smart healthcare provision. The final refinement needs to be an execution criteria, as it contains run-time relevant behavior for validation. It also processes the messages exchanged between the components within one layer or across layers, depending on the level of refinement.

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