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MetaLung: Towards a Secure Architecture for Lung Cancer Patient Care on the Metaverse

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***Abstract*—The interest in metaverse applications by existing industries has seen massive growth thanks to the accelerated pace of research in key technological fields and the shift towards virtual interactions fueled by the Covid-19 pandemic. One key industry that can benefit from the integration into the metaverse is healthcare. The potential to provide enhanced care for patients affected by multiple health issues, from standard afflictions to more specialized pathologies, is being explored through the fabrication of architectures that can support metaverse applications. In this paper, we focus on the persistent issues of lung cancer detection, monitoring, and treatment, to propose *MetaLung*, a privacy and integrity-preserving architecture on the metaverse. We discuss the use cases to enable remote patient-doctor interactions, patient constant monitoring, and remote care. By leveraging technologies such as digital twins, edge computing, explainable AI, IoT, and virtual/augmented reality, we propose how the system could provide better assistance to lung cancer patients and suggest individualized treatment plans to the doctors based on their information. In addition, we describe the current implementation state of the AI-based Decision Support System for treatment selection, *I3LUNG*, and the current state of patient data collection.**

***Index Terms*—metaverse, healthcare, IoT, security, XAI, architecture, digital twin, cancer**

I. INTRODUCTION

The metaverse, a rapidly growing concept, offers significant potential for the evolution of Internet and next-generation applications [1] in diverse fields such as gaming, social media, industry, and healthcare [2]. Characterized by immersive, hyper-spatiotemporal, and self-sustaining qualities, the metaverse envisions virtual avatars representing humans, objects, and other entities from the physical world, interacting in real-time within a simulated environment. This environment may emulate the physical world or be entirely synthesized. The recent Covid-19 pandemic has accelerated the development of virtual presence due to restrictions on physical interactions, bringing healthcare and its future advancements to the forefront of research. Consequently, the intersection of the metaverse and healthcare has emerged as a hot topic, with the integration of fundamental technologies such as Digital Twins (DTs), Virtual/Augmented/Mixed Reality (VR, AR, MR), 5G and beyond, IoT devices and sensors, Artificial Intelligence (AI), and distributed ledgers poised to revolutionize and personalize care for patients afflicted by various pathologies [3]. One such pathology is lung cancer, a leading cause of cancer-related mortality among men and women worldwide, accounting for approximately 18% of all cancer deaths in 2020 [4]. The prevalence and lethality of lung cancer have driven extensive research efforts to better understand the disease and develop effective treatments. In this context, the I3LUNG [5] project is at the forefront of developing an AI-based Decision Support System (DSS) to assist clinicians in treating patients with Non-Small-Cell Lung Cancer (NSCLC)[1]. Within this project, establishing a flexible environment that facilitates the exchange of ideas among physicians, analysis of data from previous clinical studies and the real world, and storage of patient information has emerged as a priority. In this paper, following the I3LUNG use case, we propose a fully distributed reference architecture for intelligent lung cancer patient care, namely *MetaLung*. By leveraging existing technologies, we discuss possible applications ranging from virtual consultations, to cancer diagnosis, disease monitoring, and remote treatment planning. Our contributions are threefold:

- We provide *MetaLung*, a novel architecture for doctor-patient interaction, patient monitoring, and remote care within the metaverse.
- We illustrate a use case of our architecture for lung cancer treatment, encompassing detection, monitoring, and tailored treatment selection based on individual patient needs.
- We present the current state of the I3LUNG system implementation and provide security considerations for ensuring data privacy and system integrity.

The remainder of this paper is organized as follows. Section II explores the intersection between metaverse and healthcare applications. Section III provides an overview of existing metaverse architectures and applications. In section IV we

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[1] More information about the project is available at https://i3lung.eu/.

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present the reference architecture for a lung cancer patient care system and analyze the interplay of key technology enablers for the realisation of three virtual services. Section V outlines the current state of the I3LUNG platform, while Section VI discusses essential security aspects arising during the design and implementation of the system in the metaverse. Finally, Section VII concludes the paper and proposes future research directions.

II. BACKGROUND

Over the past decade, the healthcare industry has undergone a significant transformation with the emergence of novel technologies. These innovations encompass the proliferation of wearable devices, big data, as well as the advancements in AI and edge-cloud computing, enabling healthcare organizations to digitalize their services for patients. From the development of data analytics and AI to the introduction of wearable devices and edge-cloud-based services, healthcare organizations have been able to digitalize their services for patients. IoT devices, such as wearables, medical sensors, and telemedicine equipment, have facilitated the provision of tele-health services and the advent of the Internet of Medical Things (IoMT) [6], [7]. Moreover, edge computing has enabled data processing and analysis tasks to be performed at the source, offering substantial potential for more accurate diagnoses and informed treatment selection for both physicians and patients. The metaverse promises to disrupt healthcare by addressing clinical workflow bottlenecks, such as the need for physical patient-clinician interactions during diagnoses, treatment prescriptions, and surgeries. By extending tele-health services through virtual spaces, the Metaverse aims to enable more efficient and accessible care. Interactive simulations can empower patients to understand their conditions and treatments, facilitating informed decision-making. Augmented interfaces may also support clinicians in diagnostic and treatment procedures, while also providing immersive educational experiences for medical students [8], [9].

III. RELATED WORK

In recent years, there has been an increase in research studies exploring the potential of the metaverse in the healthcare industry. For instance, Bansal et al. [10] provide a comprehensive overview of metaverse applications in the healthcare industry, acknowledging important challenges for their practical implementation. They explore the use of eXtended Reality (XR) technologies to enable immersive and interactive training experiences and discuss existing hardware and software for the metaverse, including Mixed Reality (MR) headsets, virtual manipulation hardware with haptic feedback, and applications that facilitate the development of XR services. This study also examines the potential of telemedicine for remote care, supplementing patient-doctor visits in a virtual space. Moreover, the study analyzes how the metaverse can be used to enhance clinical care in various medical fields. Another study by [11] investigates the potential of a virtual healthcare application to provide access to personalized care for the specific needs of ophthalmology, including telemedicine, telesurgery, and telementoring. This study discusses using immersive user interfaces –such as Virtual Reality (VR) headsets and haptic feedback gloves– to enhance the sense of realism in a virtual world, as well as the development of avatars and Digital Twins (DTs) to enable more realistic consultations and personalized care. Potential applications to diagnostics, therapeutics, and medical education were also examined. Ali et al. [12] introduce a metaverse architecture for healthcare dividing the doctor, the patient, and the metaverse environments. Their proposed solution integrates blockchain to guarantee safety, security, and data privacy, while eXplainable AI (XAI) is used to provide logical reasoning for disease prediction, ensuring the transparency of AI models used in clinical settings.

In [13], a general metaverse architecture framework is proposed. This study focuses on big data processing, assessing the requirements for storage, computation, scalability, privacy, and security for specific industries. Additionally, countermeasures for ensuring privacy and security are suggested. A reference architecture for the metaverse is proposed in [14], which extends cloud-based architectures and separates the following layers for generic metaverse applications: infrastructure, service components, service store, business scenarios, and user interactions. Five vertical layers have been identified to cover cross-cutting aspects: security and privacy, integration, data and intelligence, governance, and quality of service.

Lim et al. [15] propose a metaverse reference architecture based on edge computing to provide a solid foundation for the realization of interoperable, immersive, and decentralized virtual ecosystems. Their architecture comprises four distinct layers: infrastructure, metaverse technology enablers, virtual worlds for immersive interactions, and the physical world, consisting of users, sensors, actuators, virtual service providers, and physical service providers. Similar considerations are provided in [16], which explores the enabling technologies and challenges to practical implementations of generic metaverse applications. A layered reference architecture dividing infrastructure components –communication, computation, and blockchain–, metaverse engine, and virtual and physical worlds is provided. In a similar work, Wang et al. [17] discuss metaverse enabling technologies, proposing a general reference architecture that separates infrastructure aspects of hardware, networking, processing, and storage from metaverse engine, digital world, and human world, similarly to [15]. Additionally, they focus on security and privacy threats across the architecture's layers, suggesting appropriate countermeasures. Finally, Musamih et al. [7] explore the potential of healthcare applications in the metaverse and propose a framework leveraging technology enablers such as distributed computing, AI, DTs, distributed ledger, 5G, and 6G, and the IoMT. Similarly to other works, the physical infrastructure, virtual world, and human world are separated layers. Via interfaces and accessibility devices, users can access metaverse services, which in turn are maintained by enabling technologies.

IV. PROPOSED SYSTEM ARCHITECTURE

While not exclusive to this domain, the integration of Internet of Things (IoT), edge computing, Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), and eXtended Reality (XR) technologies have been proposed to offer improved and immersive experiences for patients, such as virtual visits and remote care. We provide a short overview of each technology's roles in enabling metaverse healthcare services [7], followed by a description of our proposed architecture.

A. Metaverse Enabling Technologies

1) Edge Computing and Internet of Things: Edge computing is a form of distributed computing that involves pushing data processing and computing tasks to the network's edge closer to the data source. By processing data locally, edge computing can reduce latency, improve performance and make data private and secure. In combination with IoT devices and sensors to collect, store and transfer data over the network, edge computing represents a key infrastructure paradigm to support the requirements of metaverse applications [15].

2) Augmented Interfaces: A ubiquitous concept in the metaverse is the *avatar*, a virtual embodiment of a physical body that can be controlled by an individual to interact with other avatars, virtual objects, and virtual spaces. The existing technologies supporting this kind of interaction are represented by XR hardware (VR headsets with stereo display screens or AR glasses), haptic wearables (haptic gloves or vests), and Brain-Computer Interfaces (BCI) [18]. XR and haptic wearables are combined to enable immersive first-person experiences in a simulated world which, in the healthcare domain, may support diverse applications for remote robotics, telemedicine, rehabilitation, and remote care, beyond standard patient-doctor interactions. For example, the integration of VR can complement traditional care methods, providing the patients with an immersive experience for understanding the diagnosis, reviewing medical images and test results, discussing the available treatment plans, or inspecting the disease progression.

3) Digital Twins: Digital Twins (DTs) are high-fidelity digital replicas of real-world objects and actors, like patients, healthcare professionals, medical infrastructure, and medical facilities, that replicate the physical characteristics of their analogues. DTs are increasingly gaining attention due to their potential to revolutionize healthcare services, such as real-time patient monitoring and forecasting of the patient response to simulated treatments and clinical procedures. A class of DTs is provided by the Patient DT (PDT), representing a testbed for clinicians to simulate the biological processes associated with the tumor initiation, growth, and metastasis, as well as the interplay with the surrounding environment to plan adaptable treatments, incorporating factors such as tumor size, location, genetic makeup, growth patterns and response to treatment. Creating a PDT is a complex process, and fully digitalizing the human body is currently a distant goal [19], [20].

4) Artificial Intelligence: Artificial Intelligence (AI) in patient care has become increasingly important in recent years, with its applications ranging from disease detection and treatment recommendation to drug discovery. Despite the clear potential of AI, its adoption in clinical practice remains limited due to the challenge of interpreting and verifying the accuracy of AI predictions. Deep learning models, which have achieved remarkable results in medical-related problems, typically act as black boxes, making it difficult to trace the relationship between the patient's characteristics and the treatment outcome. To address this, eXplainable AI (XAI) has emerged in recent years [21], providing tools to interpret the workings of AI models and empower clinicians to make informed decisions. By interpreting AI predictions, the trustworthiness of these models can be increased, ensuring that clinicians are making optimal decisions for their patients.

5) Distributed Ledger Technology: A Distributed Ledger Technology (DLT) is a decentralized peer-to-peer network used to store and transfer data without relying on centralized servers. This layer is a distributed and secured ledger system that records and stores data in a decentralized manner.

B. The MetaLung Architecture

We propose the **MetaLung** conceptual architecture, designed considering the current technological advancements to support common use cases of lung cancer patient care: communication, remote care, and active monitoring. The necessary components and services of the proposed MetaLung reference architecture are shown in Figure 1, which distinguishes four layers that bridge the physical and the virtual world.

1) Physical World: This layer consists of two distinct realms: the human world includes healthcare providers and patients, and the infrastructure, which enables the metaverse engine to model tangible assets such as medical devices, facilities, and patient data for data transformation. On the other hand, the infrastructure includes physical devices, communication, computation, and storage components: sensing and control functions are operated through pervasive *physical devices*, such as IoT sensors and actuators, wearables, augmented peripheral devices for visual and haptic feedback, and medical devices (e.g., scanners and medical intervention tools). A reliable data-intensive *communication* infrastructure is required to support the massive data generation and transmission between devices. We identify the hybrid Cloud-Edge-Computing paradigm to meet strict ultra-low latency requirements, local caching, and animation rendering at the edge, while cloud servers are involved in data synchronisation and cyber-physical mapping [22]. *Collaborative computation* capabilities are offered at the device, edge nodes, and cloud servers, depending on their capabilities [23]. In this scheme, smart devices can perform less-intensive tasks, offloading demanding tasks to edge nodes and cloud servers. For instance, edge nodes can be used for 3D avatar rendering and data aggregation, while cloud servers can be used for metaverse synchronisation. Finally, local, edge, and cloud caching mechanisms are in place to support *storage* requirements.

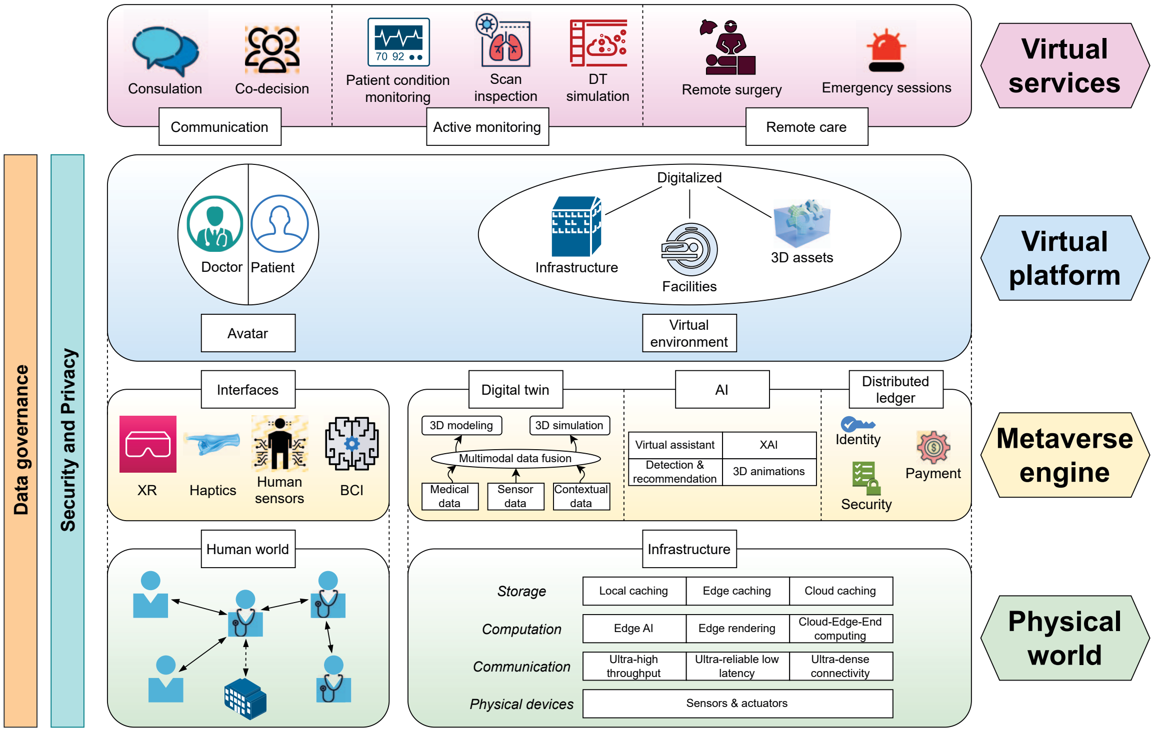

Fig. 1. *MetaLung*: metaverse healthcare architecture for lung cancer care.

2) Metaverse Engine: Abstracting from the physical infrastructure and the physical world, the metaverse engine is a collection of the technological enablers as listed in Section IV-A, bridging physical and virtual worlds together. We briefly elaborate on each technology for lung cancer patient care: *Digital Twins* of patients and medical infrastructures are generated and maintained by aggregating data from physical devices through multimodal data fusion strategies for the primary support of medical monitoring and treatment simulation tasks. We identify three data sources that can be harnessed to build the PDT: medical, sensor, and contextual or non-health data. Medical data refers to information collected by healthcare professionals during exams and patient visits. Sensor data includes data from medical sensors used to capture clinical parameters and from wearables, such as fitness trackers and smartwatches, to capture measurements related to the patient's health status. Finally, contextual data provides additional information about the patient's environment, lifestyle, and quality of life, e.g., data from questionnaires, surveys, or other forms of self-reporting. Clinical and medical data provide snapshots of a patient's status, serving as crucial inputs for training diagnostic and prognostic AI models that form the core of a PDT. A key aspect of DT development is distinguishing between healthy and diseased states, enabled by continuous monitoring and medical exam updates. Through *augmented interfaces*, doctors can interact with patients and AI-based avatars, supporting remote consultations and remote care services. *AI* can be applied for a number of different purposes: machine learning and deep learning models can be trained using aggregated data from patients, along with monitoring data to diagnose lung cancer and provide personalized medical advice and treatment plans. XAI is used to support clinicians by providing explanations for the model's predictions. AI can power virtual assistants to guide healthcare professionals through Natural Language Processing (NLP) models by analyzing voice data used during consultation services and instructing doctors in remote surgical procedures. Finally, AI can animate 3D avatars, environments, and simulation rendering. As part of the metaverse engine, the *Distributed Ledger Technology* (DLT) provides secure transaction record-keeping and ensures the integrity of digital identities, patients, and doctors alike.

3) Virtual World: A platform comprises user (patient and medical professionals) avatars and virtual replicas of environments, simulated medical facilities, and infrastructures. To generate and maintain the virtual world, a pool of 3D assets must be made available to doctors and patients alike.

4) Virtual services: This layer comprises the MetaLung healthcare services. In this paper, we elaborate on three key services for lung cancer patient care, namely communication, active monitoring, and remote care, further described in Sections IV-C, IV-D, and IV-E, respectively.

5) Verticals: Verticals represent common properties to the layers previously described and concern aspects related to data governance, privacy, and security, the latter further detailed in Section VI.

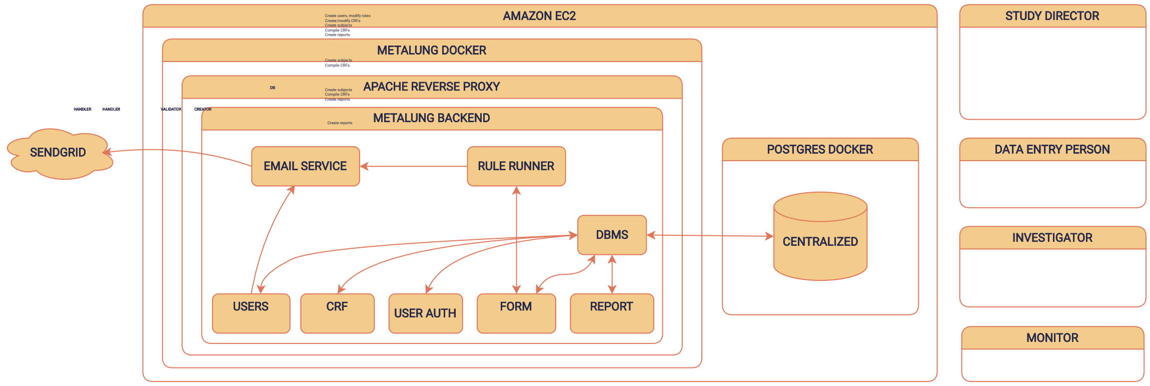

Fig. 2. Scheme of the current implementation of the *MetaLung* platform.

C. *Communication*

This service allows patients and physicians to interact and collaborate in a virtual environment. Represented as a co-decision aid platform, physicians of various medical specialties can provide consultations, virtual check-ups, and access a virtual PDT in combination with constant data monitoring. This enables them to provide relevant information to the patient, such as their current condition and possible disease progression. Clinicians can also suggest treatments based on the DT's simulated response. Additionally, speech recognition models and XAI are used to support lung cancer diagnoses by highlighting tumor regions and providing an accurate prognosis, helping patients understand medical procedures and potential outcomes.

D. *Active Monitoring*

By merging data from various sources, a comprehensive and up-to-date DT of the patient can be created to simulate treatment and surgery options. With the help of clinical sensors and wearables, vital metrics such as heart-rate, blood pressure, and temperature can be monitored in real-time and any deviations from normal levels can be quickly identified and responded to. Furthermore, non-health data related to the patient is stored in a separate database, providing additional insight into the patient's condition. By continuously tracking the patient's symptoms and vitals, medical professionals can be alerted of any emergencies or schedule exams and surgeries as needed.

E. *Remote Care*

Telemedicine applications such as surgical operations and remote treatments for lung cancer patients fall in this category. XR and haptic technologies create an immersive and interactive environment for clinicians to interact remotely with patients. The patient's DT allows a simulation of the treatment, suggesting the possible course of action, including the selection of appropriate medical infrastructures. However, advanced telemedicine services are available to patients with access to appropriate infrastructures, such as local hospitals or clinics.

V. PRELIMINARY SYSTEM SETUP

The foundation of MetaLung lies in the I3LUNG project, an international effort devoted to creating a Decision Support System that offers personalized and collaborative care for patients affected by lung cancer. One of the main objectives of I3LUNG is to investigate the individual response to a specific treatment type called immunotherapy and identify robust biological predictors through AI. In total, 2200 patients are expected to be enrolled during the course of the project, with 2000 patients from the retrospective phase providing data to create a preliminary model, while 200 prospective patients will provide multimodal data to validate the results obtained from the retrospective model and create the clinical DSS. At the current stage, part of the envisioned platform is already collecting multi-modal data from retrospective lung cancer patients. In particular, a total of 210 patients have been registered to participate in the study. The data collected by the I3LUNG platform is already anonymized and includes information about patients like the Informed Consent Form (ICF) signature that indicates their intention to participate in the project, basic clinical data like gender and age, a detailed section on all the therapies already undertaken, and quality of life questionnaires. The currently implemented platform is shown in Fig. 2 and illustrates the aggregation and collection of clinical data from lung cancer patients, referred to as subjects.

The current implementation is based on Libreclinica [24], an open-source electronic data capture software to store subjects' clinical data. The platform's backend and database are hosted in an EC2 image of Amazon AWS. Both are also contained in a Docker image, which makes the development lifecycle faster and easier and reduces the risk of conflicts. To prevent DDOS attacks, we adopt Cloudflare, which also provides a firewall for additional security. Additionally, to enhance efficiency and security, we use an Apache reverse proxy, which only redirects to the platform requests with TLS encryption. Clinical data about the patients are stored as an electronic Case Report Form (eCRF), an electronic questionnaire divided into sections to facilitate data entry by medical professionals. The platform

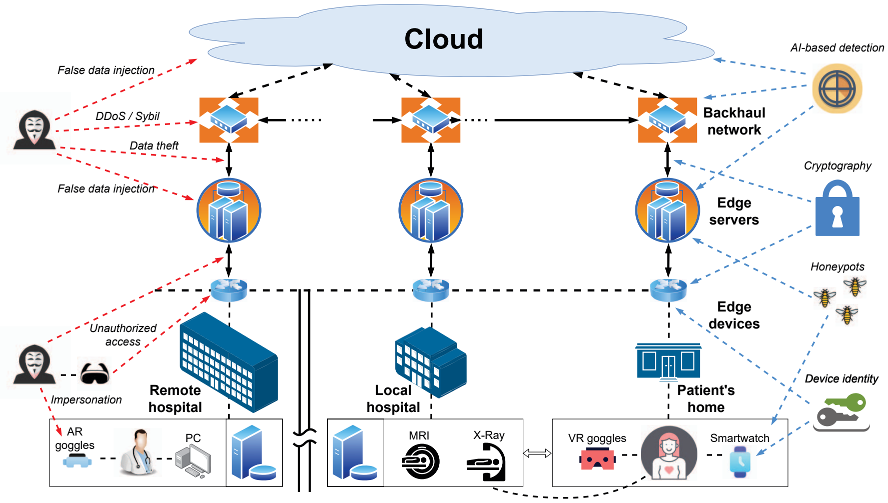

Fig. 3. Elements involved in the *MetaLung* architecture and their security considerations.

is divided into four distinct user roles: study director, data entry person, investigator, and monitor. The study director has access to all the services, including creating and modifying users, sites, eCRFs, subjects, and reports. Data entry persons are restricted to creating subjects and entering data in the eCRF. Investigators also have the same capabilities as data entry persons, with the added ability to create and download reports (i.e., documents providing aggregated statistics on the enrolled subjects). Finally, the monitor can only create and download reports.

To avoid any clashes during data entry, each subject's access is locked so that no other user can enter data for the same subject. If any validation errors are detected, they are shown to the front-end so the user can rectify them. Additionally, any answers that deviate from the CRF's question trigger rules, which are managed by the Rule Runner service. These rules can modify the items that appear in the form, making it dynamic, and initiate notification emails, which are handled by a component that interfaces with SendGrid, an external platform that provides an API to deliver transactional emails.

In the future, the platform will be expanded to become a clinical Decision Support System for NSCLC detection and treatment selection, as well as have its database distributed through DLT.

VI. SECURITY ASPECTS

In this section, we provide some security considerations related to our architecture. We divide the analysis into (i) edge devices, and (ii) edge servers and networks, since their security concerns require separate solutions. While a full analysis of metaverse-related security challenges is outside the scope of this paper, we refer the reader to [17] for a full review of current concerns and countermeasures applicable to a general-purpose platform. A visual representation of the elements of our architecture with security-relevant challenges and countermeasures is shown in Figure 3.

A. Edge Devices

The edge devices in the system are composed of wearable devices (e.g., VR/AR goggles, smartwatches), terminals (e.g., PC, smartphone), and specialized hospital equipment (e.g., computed tomography scanner). On top of these, we can include the local hospital servers. We identify a set of three security features for this group of devices: authentication and access control, privacy assurance, and physical protection.

To start off, different security measures to provide authentication in metaverse-connected devices have been proposed that can fit our architecture. When talking about securing the edge devices of the architecture, we have to consider their constraints. Small wearable devices are likely to fall short on resources for security functions [25]. Thus a lightweight solution that establishes trust is required.

For strictly identity authentication, Srinivas et al. [26] present a cloud-based mutual authentication model in healthcare monitoring systems. Exploiting a Hidden Markov Model, Jan et al. [27] designed a mutual authentication model where the risk of data leakage is predicted. For short-range communication, Aksu et al. [28] study a fingerprinting method using an AI algorithm made for Bluetooth. Finally, a largely unexplored but promising solution is the use of Physical Unclonable Functions (PUFs) [29], where a PUF circuit is integrated into each device, enabling a form of remote attestation of the device's authenticity.

While authentication is a key feature for edge devices, it is not sufficient to guarantee data privacy. Some patient data (mainly for training AI models) can be anonymized, but this is not always acceptable. For that reason, other solutions specific to secure communications have been proposed. In Li et al. [30], a key establishment mechanism based on unique wireless channel characteristics based on the device's position is shown. A similar approach is taken in Sun et al. [31], where the noise produced by accelerometers is exploited for key generation. Another such solution was shown in Chen et al. [32] by utilizing gestures and motions through an accelerometer. Regarding specific medical equipment, Zheng et al. [33] proposed an electrocardiogram signal-based key distribution mechanism.

Overall, the previous security features protect the system from spoofing attacks, where malicious actors may attempt to inject false information, obtain unauthorized data access or impersonate a patient or doctor. By controlling access to the system's devices, attackers are also unable to control the physical operations of the devices, ensuring that harmful results are avoided. Were that not the case, it could cause physical harm to users through, e.g., overheating of wearables. Since some devices could be unable to provide security features with high overhead (e.g., cryptography) [25], the risk of attack has to be leveraged with countermeasures. In our architecture, most communications are performed with cryptography, with the few that do not only being performed on short-range links that require almost physical access to attack. Meanwhile, devices that communicate over longer ranges are secured with more advanced features.

B. *Edge Servers and Network*

The edge devices are connected to the edge computing network through some routing device. For the patients' homes, this would be a router, while the hospitals also have their own servers. Either way, the edge devices can send and receive data from the edge computing servers. These communications are secured as previously described, and inter-server communications are cryptographically enabled. That said, the extensive attack surface of metaverse-based services enables numerous threats to data management, data privacy, and network operations.

To prevent these threats, security for the system is provided from a different perspective than for the edge devices. Theoretically, if attackers cannot access or impersonate devices in the system, they cannot do damage. However, this assumes that the network is not targeted (e.g., DDoS or Sybil attacks). To prevent these attacks, a fundamental approach is their detection. In recent years, multiple solutions that leverage AI-based detection have appeared. Shahsavari et al. [34] leverage a multi-class Support Vector Machine (SVM) classifier to detect malicious events. Another approach is shown in Krishnan et al. [35], where the use of a DT and Software Defined Network (SDN) is used to test security measures before deployment on real networks. Another technique to protect against network attacks is the use of honeynets (a.k.a. collaborative honeypots) as proposed by Zhang et al. [36] and Zarca et al. [37].

Regarding the integrity and privacy of data managed by the system, the most popular solution for metaverse is the use of Distributed Ledger Technology (DLT). While not prohibitively unusable, a centralized processing scheme has the disadvantage of creating a single point of failure and attack. By removing it, data integrity is improved. Additionally, since DLT is resilient against the injection of false information, it constitutes a reliable and robust solution. A good reference for how this can be achieved can be found in the recent work from Ali et al. [12]. They propose a general metaverse architecture for healthcare applications using blockchain technology which provides the desirable security features by making all relevant actors add their transactions to a personal blockchain.

VII. CONCLUSION

This paper presents MetaLung, an architecture for healthcare in the metaverse specifically designed for the purpose of providing care services to patients affected by lung cancer. We describe the architecture, its enabling technologies, and the current state of implementation of the I3LUNG platform, a Decision Support System for personalized lung cancer patient care.

Our solution draws inspiration from the I3LUNG project applied to the metaverse. MetaLung consists of the following layers: the physical infrastructure, metaverse engine, virtual world, and virtual services. We detail the device, networking, computing, and storage requirements needed to support metaverse applications. The metaverse engine integrates technologies such as augmented interfaces for avatar control and world navigation, Digital Twins for lung cancer patient monitoring and treatment simulations, clinical AI and XAI for DSSs, and DLT to address security, payment, and identity aspects. Patients and medical professionals can access virtual services on top of these layers, allowing them to interact in the virtual world with avatars and simulated spaces.

Despite being in its infancy, I3LUNG aims to achieve part of the objectives of MetaLung, namely, namely the clinical AI-powered DSS. At the current stage, the I3LUNG platform is expected to incorporate multimodal data from lung cancer patients, starting from clinical data captured during medical visits and exams, integrating other types of data to better understand the disease and its response to immunotherapy, thanks to the use of AI and XAI. At the time of writing, a platform for the I3Lung project is running, making up the data collection aspect of the overall architecture. Data from 2000 retrospective patients and 200 prospective patients are being collected for future use in other features, mainly the prediction of the efficacy of lung cancer treatments.

Security considerations have also been addressed, showing recent solutions for the main issues that can lead to the breakdown of the system. Dividing the relevant aspects of security features into those relevant to edge devices, edge servers, and network elements, we saw how access control and data integrity, and privacy could be accomplished. The way to do this is based on lightweight identifiable characteristics of small devices (e.g., accelerometer patterns and noise or PUFs) for authentications and key generations, while the backend leverages DLTs like blockchain and AI-based attack detection mechanisms.

Future work will see the further development of the platform to include other functions, including DTs, XAI predictive models, innovating doctor-patient communication, patient monitoring, and remote care services. Additionally, the centralized database will be replaced by a distributed ledger-based data management. All this will establish a secure and privacy-preserving architecture based on a metaverse where DTs and avatars are leveraged to improve the care of afflicted patients.

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