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Article

The Microverse: A Task-Oriented Edge-Scale Metaverse

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Abstract: Over the past decade, there has been a remarkable acceleration in the evolution of smart cities and intelligent spaces, driven by breakthroughs in technologies such as the Internet of Things (IoT), edge–fog–cloud computing, and machine learning (ML)/artificial intelligence (AI). As society begins to harness the full potential of these smart environments, the horizon brightens with the promise of an immersive, interconnected 3D world. The forthcoming paradigm shift in how we live, work, and interact owes much to groundbreaking innovations in augmented reality (AR), virtual reality (VR), extended reality (XR), blockchain, and digital twins (DTs). However, realizing the expansive digital vista in our daily lives is challenging. Current limitations include an incomplete integration of pivotal techniques, daunting bandwidth requirements, and the critical need for near-instantaneous data transmission, all impeding the digital VR metaverse from fully manifesting as envisioned by its proponents. This paper seeks to delve deeply into the intricacies of the immersive, interconnected 3D realm, particularly in applications demanding high levels of intelligence. Specifically, this paper introduces the *microverse*, a task-oriented, edge-scale, pragmatic solution for smart cities. Unlike all-encompassing metaverses, each microverse instance serves a specific task as a manageable digital twin of an individual network slice. Each microverse enables on-site/near-site data processing, information fusion, and real-time decision-making within the edge–fog–cloud computing framework. The microverse concept is verified using smart public safety surveillance (SPSS) for smart communities as a case study, demonstrating its feasibility in practical smart city applications. The aim is to stimulate discussions and inspire fresh ideas in our community, guiding us as we navigate the evolving digital landscape of smart cities to embrace the potential of the metaverse.

Keywords: metaverse; digital twins (DT); blockchain; Internet of Things (IoT); smart public safety surveillance (SPSS)

1. Introduction

The proliferation of Internet of Things (IoT) technology combined with evolving artificial intelligence (AI) and machine learning (ML) promote unprecedented advancements in ubiquitous and seamless services for human activities [1]. The technical evolution in internet technology has made smart cities a reality for the foreseeable future. Over the past decade, since the concept of "smart cities" was officially defined by the National Institute of Standards and Technology (NIST) in 2014, more than 200 smart city projects have been launched [2]. Many experiences and lessons were learned, preparing society for a more intelligent, efficient, and sustainable future [3].

Many open questions are yet to be addressed in designing, creating, managing, and living in a smart city. One of the top challenges is the *scalability* of today's smart city

solutions to an enormous amount of sensors. Not only does the amount of data being generated continuously and drastically grow but also the complexities increase significantly as more intelligent functions are added. For example, IoT network infrastructures are often under different administrations when initially built, but more novel applications or services require resources across domain boundaries. Network slicing (NS) technology has been identified as an acceptable approach to address cross-domain services [4,5]. NS allows users to create logical networks for individual applications using network devices belonging to different domains. However, creating and managing a network slice that involves sensing, computing, communicating, and data-storing devices deployed across domains is nontrivial. There is a compelling need for a holistic solution that enables full-spectrum smart city operation monitoring, analyzing, decision making, and the taking of actions dynamically in real time.

Recently, the metaverse has attracted interest from both academia and industry [6]. Many expect the metaverse to redefine how people live, work, and socialize by enabling a seamless interweaving of the physical world with a virtual cyberspace [7]; while the dawn of a new era of the immersive, interconnected 3D world appears possible thanks to a wave of revolutionary technologies like augmented reality (AR), virtual reality (VR), extended reality (XR), and virtual digital twins (DTs), these technologies also bring many new challenges and open problems before the comprehensive digital landscape of the metaverse becomes ubiquitous in daily life. Concerns exist for privacy and security that might be addressed with blockchain technology. Meanwhile, scalability is still among the top concerns [8].

Inspired by the vision of the metaverse and the hierarchical edge–fog–cloud computing paradigm, a task- or application-oriented, local-scale, immersive, interconnected 3D world is envisioned. In this paper, the *microverse*, a task-oriented, edge-scale, pragmatic solution for smart city applications, is proposed, which involves IoT resources under multiple administration network domains. Instead of creating a metaverse that mirrors the entire smart city in one digital world, each microverse instance is a manageable digital twin of an individual network slice for a specific task. Following the edge–fog–cloud computing paradigm, the microverse enables on-site/near-site data collection, processing, information fusion, and real-time decision making.

This paper's primary contributions are outlined as follows:

- A hierarchical microverse framework is proposed. The microverse approach redefines the metaverse into a dynamic, purpose-built ecosystem that streamlines task completion, enhances collaboration, and offers immersive professional settings.
- Using smart public safety surveillance (SPSS) for smart communities as a case study, a microverse instance is designed and created that contains unmanned aerial vehicles (UAVs), ground units, and sensing networks. Leveraging technologies such as DTs and AI, the SPSS prototype mirrors objects in virtual space and is capable of surveillance tasks.
- The feasibility of the microverse is validated through a preliminary experimental study on the proof-of-concept prototype of the SPSS microverse system in which we are continuously constructing the microverse for further research.

The rest of this paper is structured as follows: Section 2 provides a brief overview of the crucial enabling technologies. Section 3 presents the rationales and architecture of the microverse, emphasizing the hierarchical, layered architecture. Section 4 describes SPSS as an instance of the microverse, including experimental results on the prototype and lessons learned from the case study. Finally, Section 5 concludes this paper with a summary and some discussions on ongoing efforts.

2. Background and Related Work

This section commences with an exploration of the challenges yet to be surmounted by metaverse developers, which are crucial for actualizing this new digital era in our everyday lives. Following the challenges, this paper describes three pivotal enabling technologies:

digital twins, network slicing, and lightweight blockchain, each playing a vital role in the metaverse's evolution.

2.1. The Metaverse in the IoT: Challenges

In the context of smart cities, the fusion of the metaverse with the IoT—an expansive network of interlinked devices and sensors—heralds a transformative era in urban interaction, blending the digital with the physical [9]. The digital–physical synergy enriches the smart city landscape with immersive, interactive, and data-intensive environments. Yet, integrating the metaverse within the complex IoT infrastructure of smart cities presents a set of formidable challenges that need to be addressed [10,11].

The primary challenge lies in bandwidth and *latency* constraints [12]. Applications within the metaverse necessitate substantial data rates and minimal latency to facilitate seamless, immersive experiences. However, IoT environments usually function on limited networks, which are potentially inadequate for these high demands. Addressing the communication gap to guarantee fluid and responsive interactions in the metaverse, especially within the confines of IoT infrastructures, is a pivotal technical hurdle necessitating the development of inventive approaches in network infrastructure and data transmission strategies.

Scalability emerges as a critical issue [13] in integrating the IoT and the metaverse. The IoT landscape, characterized by a continuously growing assortment of devices, sensors, and data sources, presents a complex data and network interaction volume challenge. Adapting the metaverse to efficiently manage the immense amount of data while maintaining scalability parallel to the IoT's expansion is a sophisticated engineering endeavor. It is crucial to achieve scalability without sacrificing performance quality.

Interoperability remains a significant challenge in IoT environments [14,15]. Devices produced by various manufacturers frequently employ distinct communication protocols and data formats, complicating their integration. Establishing a cohesive metaverse ecosystem that incorporates these heterogeneous devices while preserving interoperability is a challenging yet crucial task to ensure a seamless user experience.

Security and *privacy* are paramount concerns within the IoT realm, and integrating the metaverse into an ecosystem significantly escalates these risks [9]. The potential for unauthorized access to sensitive IoT data via metaverse applications poses serious threats. Ensuring the security of data and devices in this converged environment is a critical challenge. Notably, the amalgamation of IoT data with the metaverse could create comprehensive user profiles, triggering ethical and privacy issues. Striking an appropriate balance between offering personalized experiences and maintaining user privacy is an intricate and necessary task.

Integrating the metaverse into the real world presents additional challenges [9,16]. The ambitious endeavor to adopt a metaverse aims to connect digital and physical domains seamlessly, requiring accurate location tracking, sophisticated object recognition, and advanced sensor fusion [17]. These sensor exploitation technologies could ensure precise alignment with IoT data and devices, yet they represent complex and intricate tasks that must be meticulously addressed for a digital metaverse.

Last but not least, *energy efficiency* is paramount in IoT environments, especially those dependent on distributed battery-operated devices. The persistent data demands from metaverse applications can rapidly exhaust device batteries, underscoring an urgent need for energy-efficient communication strategies. Three emerging technologies that could provide efficiency include digital twins, network slicing, and blockchains.

2.2. Digital Twins

The concept of the digital twin was initially introduced in 2002 and subsequently documented by the National Aeronautical and Space Administration (NASA) [18]. A digital twin (DT) is a digital model that accurately represents the components and behaviors of a physical object or system [19]. Unlike a traditional simulation, a DT is not restricted

to one particular process and can contain different procedures. Moreover, establishing the DT system ensures that data communication between virtual and physical objects is bidirectional and real-time. These characteristics of DTs enable simulation, analysis, and optimization in a broader range of system areas compared to a simulation.

At first, industrial manufacturing adopted DT technology mainly to enhance different stages of production through simulation, optimization, and the incorporation of machine learning technologies. An example is an event-driven simulation focusing on manufacturing and assembly jobs, utilizing digital twin technology and human–robot collaboration [20–22]. A proposed framework employs digital twin technology to enable accurate and multidisciplinary integration in assembly processes, particularly in industries that deal with high-precision products (HPPs) [23]. The HPP also develops a prediction and enhancement framework and a practical examination to validate its efficacy and practicality. The case study illustrates an ice cream machine as an application instance of a digital twin (DT) in the food industry [24], with a particular focus on the utilization of virtual reality (VR) and augmented reality (AR) technology for visualization and interaction purposes. The framework employs secure data transmission by implementing a secure gate between the computer and the cloud.

Recently, efforts have been demonstrated focusing on many facets of smart cities, such as intelligent transportation, intelligent energy distribution, and intelligent educational institutions. An example is the optimization problem in self-driving cars' electric propulsion drive systems (EPDSs) [25]. The suggested framework utilizes a DT-based approach to establish a connection between the logical twin in the control software and the propulsion motor drive system, enabling the estimation of EPDS performance. Nevertheless, the platform concepts are offered without any supporting experimental data. In another aspect of smart driving, a driver digital twin system was proposed that focused more on simulating and predicting the behavior mode and status of the drivers [26]. Compared to other work, the DT framework covers various aspects such as drivers' distraction detection, attention estimation, drowsiness detection, emotional state prediction, etc. Although the architecture is innovative, the paper did not provide any case studies or feasibility tests.

DT methods are also proposed to support environmental energy sustainability. The DT simulation methods and digital representation of the world mirror those of the dynamic data-driven applications systems (DDDAS) paradigm from the National Science Foundation in 2000 [27]. A DDDAS combines a digital simulation model with a physical estimation model to ensure runtime performance. The big data challenge is mitigated with the reduced order modeling and ensemble methods that afford systems-level performance and analysis. DDDAS methods were used to control wind turbines [28] and wind turbine farms [29]. Hence, for over a decade, there have been approaches to manage wind power plants by integrating DTs and cloud technologies with extensive data analysis to set up remote control stations [30].

DT techniques have been combined with blockchain; for example, a research team built a prototype of a smart campus [31,32]. With the help of a modeling engine, their system enables users to create their avatars inside the virtual campus. Users' location and primary status are reflected in real time. Moreover, an ecosystem with some simple functions, like a market, is established with the help of blockchain technology. As the purpose of the work mainly focused on social good, the authors did not further investigate the potential of the system.

In recent years, several healthcare applications have reconsidered the concept of DTs by incorporating living beings [33,34]. For example, a healthcare framework based on DTs is presented to monitor and predict an individual's health condition by utilizing wearable devices [35]. In addition, an innovative remote surgical prototype using VR, 4G, and AI is demonstrated, generating a patient's digital twin and enabling live surgery over a mobile network [36].

2.3. Network Slicing

Network slicing (NS) is an innovative and transformative idea within the telecommunications field, with the potential to significantly reshape the deployment and management of networks. Network slicing is a fundamental concept that entails the establishment of several virtual networks, referred to as *slices*, within a solitary physical network architecture [37]. Every individual slice is customized to fulfill distinct criteria, including bandwidth, latency, security, and other performance metrics, to accommodate the wide-ranging demands of different applications and services.

An NS strategy enables network operators to effectively manage resources and tailor services according to the distinct requirements of various use cases [38], such as massive machine-type communication (mMTC), ultrareliable low-latency communication (URLLC), and enhanced mobile broadband (eMBB). As an illustration, a network slice specifically designed for Internet of Things (IoT) devices may emphasize minimizing power consumption and ensuring extensive coverage. Conversely, a network slice tailored for augmented reality applications may prioritize minimizing latency and providing ample bandwidth.

Implementing network slicing plays a crucial role in facilitating the establishment of 5G networks, wherein various distinct and high-demand scenarios may operate together [39]. Operators can enhance network speed and responsiveness through the dynamic creation and management of slices, guaranteeing a smooth user experience across various applications.

Furthermore, network slicing facilitates the advancement of novel ideas and concepts by offering a dedicated environment for external developers and enterprises to generate and launch their services. The ability to adapt and change the network quickly facilitates the rapid progress of novel applications and services, stimulating economic expansion and technical innovation.

Ensuring security and isolation between slices are of utmost importance in network slicing. The NS architectural design integrates robust security procedures to mitigate interference and safeguard data privacy. The inclusion of NS into the metaverse is of utmost importance, mainly due to the coexistence of vital services like healthcare or autonomous cars with conventional mobile services inside the same network architecture.

2.4. Lightweight Blockchain

As the underlying technology of cryptocurrency, like Bitcoin [40], blockchain has been recognized as a critical technology to guarantee the assurance, security, and resilience of networked systems [41]. Blockchain is a distributed ledger technology (DLT) that utilizes cryptographic mechanisms, consensus protocols, and peer-to-peer (P2P) networks to ensure verifiable and auditable transition data storage. All participants in a blockchain network can agree on a transparent and immutable distributed ledger without relying on any third-party authority. Thanks to the system's properties like decentralization, immutability, and transparency, blockchain promises to improve security issues of centralized IoT frameworks, which are prone to single-point failures. Thus, shifting from centralized IoT systems to decentralized and secure IoT systems becomes realistic. Blockchain has been applied to IoT scenarios for security enhancement, like identity authentication [42], access control [43] and trust storage [44], and IoT data transacting [45]. Nevertheless, integrating cryptocurrency-oriented methods into IoT networks encounters challenges to performance, security, and scalability.

Various IoT–blockchain solutions have been reported recently by adopting lightweight blockchain design for IoT scenarios. By utilizing lightweight consensus protocols, like proof of stake (PoS) and practical Byzantine fault tolerance (PBFT), IoTChain [46] relies on a three-tier blockchain-enabled IoT architecture to guarantee security and efficiency. To improve scalability and interoperability, HybridIoT [47] leverages a hybrid blockchain architecture that allows a BFT-based mainchain framework to interconnect many proof-of-work (PoW) subchains. By combining a round-robin scheduling algorithm with consensus protocol, MultiChain has been implemented on a fog network to guarantee secure communication management for the Internet of Smart Things (IoST) [48]. As a lightweight blockchain

architecture for general IoT systems, microchain [49] has been applied to diverse IoT applications, like federated learning atop hierarchical IoT networks [50] and urban air mobility (UAM) systems [41]. By dividing a blockchain into multiple vital components that can integrate with a lightweight consensus protocol and network model and optimize storage, microchain promises to handle the dynamicity and heterogeneity of the microverse.

3. The Microverse: Rationale and Architecture

The concept of a hierarchical microverse framework entails structuring the virtual environment into distinct, organized tiers, each providing unique functions that contribute to a larger digital ecosystem [51]. Adopting a tiered structure is instrumental for a microverse's deployment, fostering a multifaceted environment that supports various applications, services, and user interactions. Employing a hierarchical approach offers numerous benefits, such as a systematic method for creating and organizing virtual spaces. Moreover, it allows the microverse to scale and adapt to changing needs seamlessly, ensuring its continuous growth and diversification.

Using a microverse underscores the importance of crafting a cohesive and interconnected digital landscape, which is essential for spurring innovation and enriching the user experience in the ever-evolving world of digital interconnectivity. The layered architecture presents a holistic design strategy that categorizes the diverse components of the metaverse into specific levels, each serving distinct roles. Given the metaverse's growing complexity and wide array of applications, adopting a layered architecture is essential for effectively managing the intricacies inherent in virtual environments [52,53].

3.1. A Hierarchical Architecture View

Figure 1 shows a layered architectural view of the envisioned microverse framework. The physical layer contains multiple pervasively deployed IoT networks under different administration domains that are run by different service providers. Each IoT network consists of variant sensing, computing, communication, and storage devices, either as fixed infrastructure or mobile nodes. A given application or task may need resources from multiple domains to accomplish the job collaboratively. All the devices appointed to conduct the task form a network slice (NS) or a dedicated logic network. Because of the complexities and challenges of network heterogeneity and cross-domain management, a microverse is created using digital twins technology. Essentially, the microverse mirrors the IoT devices and the working environment in the digital space, enabling an immersive, interconnected 3D working environment. Following the edge–fog–cloud computing paradigm [54], the microverse functions at the edge, using the fog layers to support real-time on-site/near-site operations.

The *physical layer* forms the cornerstone of the microverse, offering essential technological and network support for its comprehensive functionality [55]. The edge network is central to the physical layer, incorporating key assets such as computational power, communication pathways, and storage capabilities that align with the contemporary shift towards decentralized and distributed computing architectures. By prioritizing edge resources in the physical layer, the microverse aims to bolster the availability and efficiency of computational processes, facilitate seamless interaction among entities, and ensure robust storage solutions. The strategic concentration on the edge network within the physical layer not only underscores the growing relevance of edge computing in modern tech landscapes but also highlights its pivotal role in crafting a resilient and flexible framework for the microverse.

The *slicing layer* (SL) is integral to the microverse, serving as a critical regulatory component that dictates the norms and guidelines governing communication and interaction within the intricate digital realm. The SL's primary function is establishing a structured system that ensures smooth and efficient data flow management, aligning with quality-of-service (QoS) requirements. The slicing layer is responsible for setting up protocols and standards that aid in the fluid exchange of information within the microverse. It aims to

enhance data transmission and reception efficiency by judiciously allocating resources and bandwidth and leveraging its regulatory authority. The commitment of the SL system to QoS is evident in its ability to minimize congestion, reduce latency, and give precedence to essential data streams, thereby enhancing the overall efficiency and responsiveness of the microverse. Essentially, the slicing layer is pivotal in molding the communication dynamics within this complex framework, ensuring that digital interactions adhere to set standards and facilitating an environment that adeptly manages data traffic for high performance and reliability.

The concept of a *microverse layer*, particularly within the digital twin (DT) service layer framework, introduces a model where distinct virtual realms represent and sustain each domain. The microverse layer aims to equip the metaverse with semantic models and intelligent services, forming the essential infrastructure for the application layer above. By creating separate virtual worlds for specific areas, the microverse layer offers a nuanced and contextually dense mirroring of real-world phenomena. The microverse layer integrates semantic models to capture spatial features and a holistic understanding of objects and their interplay. Incorporating intelligence into this layer significantly enhances its capacity to provide advanced services, catering to the diverse needs of applications operating at a higher level. The microverse framework positions the microverse layer as the custodian of domain-specific virtual spaces, delivering crucial metaverse services. The microverse layer has the potential to amplify the functionality of digital twin ecosystems and foster a more sophisticated, intelligent convergence of the virtual and physical worlds.

The *application layer* of the microverse comprises the components that users directly engage with and access. It serves as a platform enabling individuals to immerse themselves in simulated environments, participate in social interactions, enjoy recreational content, and partake in commercial activities. This layer includes VR applications, AR experiences, and diverse digital content through information fusion systems [56].
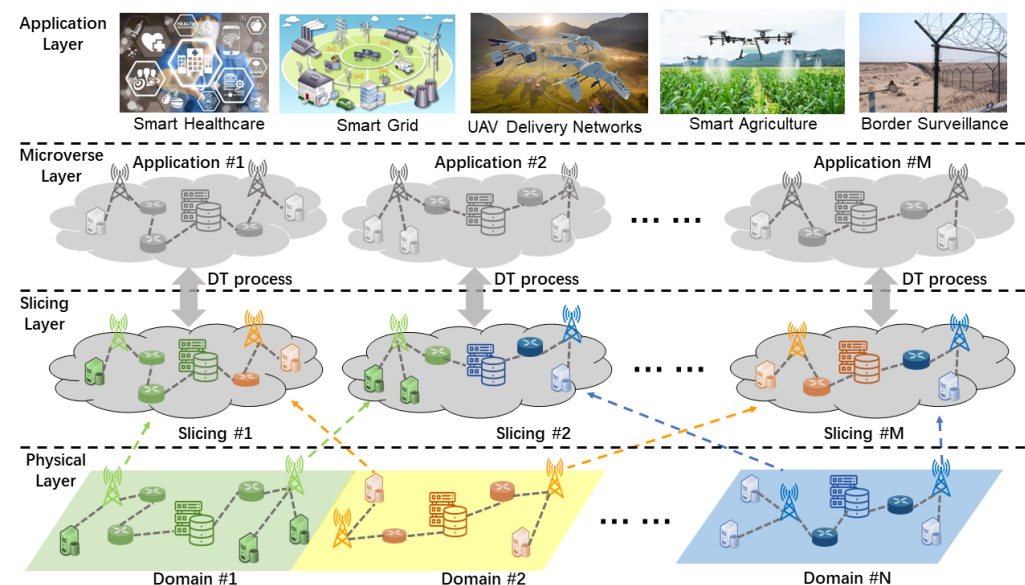

Figure 1. Microverse: a hierarchical view.

3.2. Microchained IoT Networks

Microchained IoT networks are an innovative paradigm within the Internet of Things (IoT) connections, which introduces a novel age characterized by enhanced efficiency, security, and scalability [41,49]. In contrast to conventional IoT topologies, which frequently depend on centralized servers for data processing and management, microchained networks spread these functionalities over a decentralized network of microcontrollers or microprocessors integrated into IoT devices.

The fundamental principle underlying microchained IoT networks revolves around utilizing blockchain technology, which offers a robust and transparent infrastructure for managing data transactions [50]. Every IoT device in the network is equipped with its microcontroller, establishing a node inside the blockchain system. These nodes collectively contribute to the maintenance and operation of the distributed ledger. The decentralization process minimizes the presence of singular points of failure, bolstering the network's ability to withstand disruptions and diminishing its susceptibility to cyber-attacks.

The term *microchained* highlights the incorporation of blockchain technology at a smaller scale, explicitly emphasizing its deployment at the device level. The micro-blockchain methodology facilitates effective and tamper-proof data storage and retrieval, as each data transaction is cryptographically interconnected and chronologically recorded inside the blockchain. Implementing security measures in IoT devices plays a crucial role in upholding the reliability and authenticity of the generated data, hence cultivating a sense of confidence and trust among the many parties involved. In addition, microchained IoT networks effectively tackle issues of scalability. The decentralized structure of the design facilitates the smooth integration of supplementary devices without imposing excessive load on a central server. The importance of scalability becomes increasingly significant as the size and complexity of IoT networks continue to grow.

Security issues hold significant importance in the IoT environment since they frequently involve the interaction of devices with sensitive data. Microchained Internet of Things (IoT) networks offer a resilient security architecture utilizing blockchain's immutability. Illicit modifications to data pose significant difficulties, and the blockchain's inherent transparency guarantees responsibility and the capacity to track any security violation.

3.3. The Microverse: A Task-Oriented Metaverse

The microverse, as an application- or task-oriented metaverse, marks a significant shift in virtual environments, moving beyond traditional digital spaces to prioritize goal-driven interactions and efficiency [57]. The microverse approach redefines the metaverse into a dynamic, purpose-built ecosystem that streamlines task completion, enhances collaboration, and offers immersive professional settings. Diverging from the typical entertainment-centric virtual worlds, the task-oriented metaverse focuses on developing specialized functionalities tailored to specific goals, including professional and educational pursuits. It features virtual workspaces meticulously designed to mirror real-life scenarios, seamlessly incorporating the necessary tools and resources to support a broad spectrum of activities.

Collaboration plays a fundamental role in the task-oriented metaverse [58], enabling users to participate in real-time and spatially aware interactions. The microverse enables significant interaction by reproducing the intricacies of the actual world, fostering a more immersive and authentic collaboration experience across many settings, such as virtual conference rooms, collaborative creative studios, and educational environments. The microverse exhibits a broad scope that extends beyond a specific industry, demonstrating its ability to transcend borders and find practical applications in many disciplines, including but not limited to remote work, education, healthcare, and several others.

As illustrated by the top layers in Figure 1, each microverse instance mirrors an application task, such as overseeing the daily operations on a smart farm, monitoring the safety and security of a smart grid [59], or enabling remote border surveillance to reduce the risk for law enforcement officers. Each microverse instance is the digital twin of the task space, including the network slice and the application's working environment. For example, a microverse instance created for a smart healthcare service that monitors the safety and health of a senior resident living alone in her home mirrors wearable medical sensors and networking devices along with the layout of the rooms and the pieces of furniture [60]. Real-time sensing data are transferred to the microverse, where the senior's position, gesture, and health condition are displayed, recorded, and analyzed. When signs of dangerous actions are identified, i.e., falling, an alert is generated and sent to service providers instantly [61,62].

In addition, the microverse utilizes technologies such as augmented reality (AR) and virtual reality (VR) to enrich users' immersive experiences in a 3D virtual–physical interwoven space. These technologies enhance the perception of presence and immersion, making the perceptual experience of tasks more palpable and participatory. For instance, in the microverse, the healthcare service provider can "see", "hear", and "sense" the senior's status just as they are physically in the same room.

4. Case Study: A Smart Public Safety Surveillance Microverse for Smart Communities

The microverse framework, while acting as a universal, task-oriented, edge-scale metaverse, manifests differently across specific instances, as its application heavily dictates its structure. To demonstrate its feasibility, a proof-of-concept prototype, the SPSS microverse, is developed within smart public safety surveillance (SPSS) systems for smart communities [63]. The SPSS prototype exemplifies the microverse framework's capability to seamlessly integrate the physical world with its digital counterpart, offering an innovative approach to bolstering public safety. A detailed description of the SPSS system architecture and main function blocks is beyond the scope of this paper, and interested readers are referred to our earlier publication [63].

4.1. Design Rationale

The SPSS microverse system employs a sophisticated network of surveillance cameras strategically deployed throughout the town to gather real-time data from multiple vantage points. These cameras are connected to an advanced data processing and analysis server infrastructure. Furthermore, the SPSS infrastructure serves as a gateway to a virtual environment, accessible through a metaverse application developed using the Unreal Engine 5 (UE5) platform.

Following the hierarchical microverse framework architecture, the physical layer functions as the principal repository of data, whereby surveillance cameras are employed to oversee and watch various public areas, thoroughfares, and crucial sites. The entire SPSS network is under one administration that manages physical devices, logical networks, and users. The gathered data, including live video feeds and sensor information, are delivered to the server nearly instantaneously. The server processes the data that the user provides. Then, it saves them in a structured database, which guarantees the establishment of a complete repository containing various community activities and events. Furthermore, the sensor and video content are available for user queries such as forensic analysis [64].

The metaverse layer, constructed using the Unreal Engine, functions as a dynamic reflection that accurately represents the current state of the community in real-time. Instantaneous replication of observed occurrences or deviations inside the tangible realm is promptly reflected within the digital domain. The synchronization of various elements not only serves to improve the situational awareness of public safety personnel but also establishes a framework for effective decision-making and coordination of response efforts.

The SPSS microverse surpasses traditional monitoring methods by leveraging the immersive capabilities of the metaverse. Law enforcement agencies and emergency responders can virtually traverse a digital depiction of the community, allowing them to gather valuable insights into existing crises and enhance their methods for real-world interventions.

This case study illustrates the capacity to integrate the physical and virtual realms to augment public safety in smart communities. Integrating data from the metaverse and the physical world, this novel methodology lays the groundwork for a forthcoming epoch in intelligent urban governance. In this microverse paradigm, amalgamating up-to-the-minute data and virtual observations culminates in developing safer and more adaptable urban settings. As a small-scale, proof-of-concept prototype considering one network domain, this case study does not involve the network slicing layer and microchained security networks. We leave them to our future work.

4.2. SPSS Microverse Prototype Architecture

Figure 2 shows the architecture of the SPSS microverse prototype. It was carefully built to connect the real world to the virtual world of the metaverse in a groundbreaking experiment. The innovative technology consists of multiple layers that smoothly integrate physical and digital components. A group of drones serves as an intermediary between the physical environment and the virtual world, representing the physical layer. An Android device acts as the intermediary layer, enabling smooth connections between drones and servers over Wi-Fi networks. It manages the regulatory framework that governs the data flows inside the system. The microverse, which serves as the core of the SPSS design, is located on a server and faithfully replicates the complexities of the actual world in a digital realm. Ultimately, a software layer created using the Unreal Engine completes the SPSS framework by offering a visually captivating setting, granting users an unmatched experience as they explore the intersection of the physical and digital worlds. The SPSS microverse showcases the incorporation of advanced technologies and highlights the capability of these systems to connect the gap between real life and the immersive environments of the metaverse.
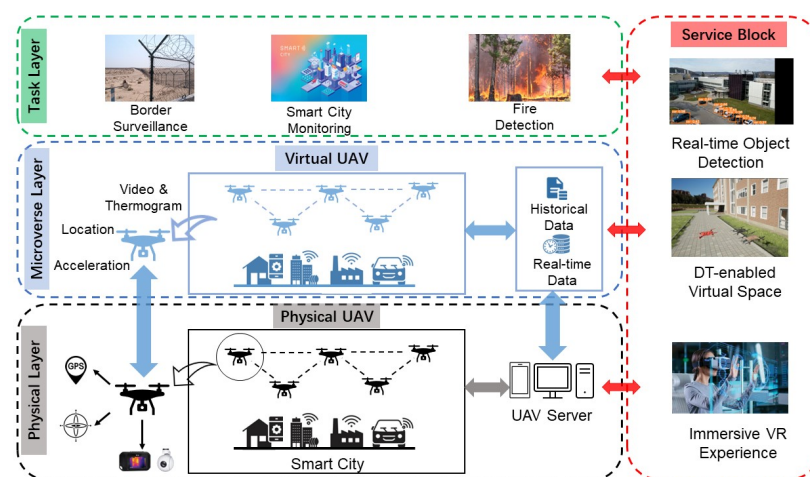

Figure 2. SPSS microverse prototype architecture.

Integrating the SPSS comprehensive system marks a paradigm shift in the representation of physical-world activities within the metaverse. Leveraging the capabilities of Unreal Engine, the development team created a visually immersive application to mirror real-world data in the virtual realm. Using the innovative microverse approach enabled the metaverse to serve as a dynamic reflection of the physical world, with any activity in the tangible realm instantly replicated in the digital landscape. For example, as the drone embarked on its real-world missions, navigating landscapes and collecting data, the metaverse faithfully mirrored every move, creating a synchronized parallel experience.

4.3. Workflow and System Settings

The SPSS microverse prototype incorporates a range of key technologies. Table 1 outlines the system's configurations, while the workflow of our experimental setup is depicted in Figure 3. In this setup, operators pilot drones in the building's parking area, utilizing the same wireless local area network (WLAN) that connects to the surveillance room inside the building. A specially developed Android application enables the smartphone to relay real-time video and data from various sensors to the digital twin (DT) in the virtual environment. As demonstrated in Figure 4a, vital parameters such as longitude, latitude, altitude, and the drone's rotation (yaw spin) are transmitted as JavaScript Object Notation (JSON) packets, ensuring the virtual replica's location in the microverse is synchronized. Furthermore, the camera's live feed is streamed to the server via Wi-Fi, employing the Real-Time Streaming Protocol (RTSP).

In the surveillance room, a desktop personal computer (PC) operates as the server for the microverse system, which is developed using Unreal Engine 5 (UE5). This system processes incoming data, encompassing sensor readings and camera footage, to ensure synchronization of DTs and support advanced analytical capabilities. Utilizing live feeds from surveillance drones in RTSP, learning methodologies are employed to execute various algorithms, including object detection, tracking, and trespassing alerts. In the SPSS prototype, the lightweight YOLOv8 model is integrated for object detection on the video stream. Figure 4b showcases a real-time demonstration of object detection using YOLOv8, which is integrated into the UE system. Furthermore, to enhance the user experience with immersive interactivity, a VR device is incorporated to enable real-time first-person perspectives from the drones.

Table 1. Configuration of SPSS microverse prototype.

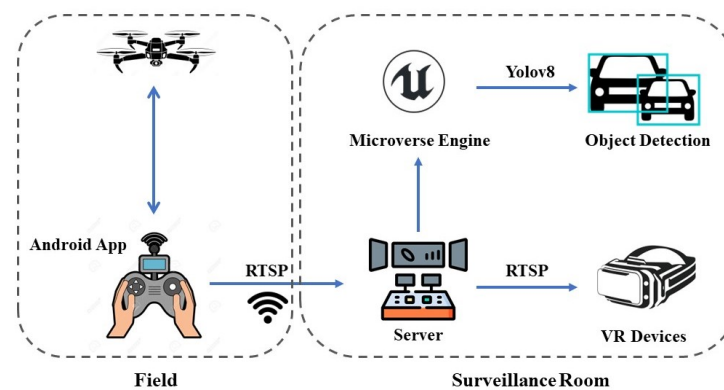| Device	DJI mini 3	Pixel 4	Desktop	Quest Meta 3
CPU	Ambarella H6M Image SOC	Octa-core	i5-13600K, 5.1 GHz	Snapdragon XR2 Gen 2
GPU	N/A	Adreno 640	RTX 3090ti	N/A
Storage	64 GB (SD)	128 GB	2 TB	512 GB
OS	Designed App	Android 6.0	Win10	Android 12

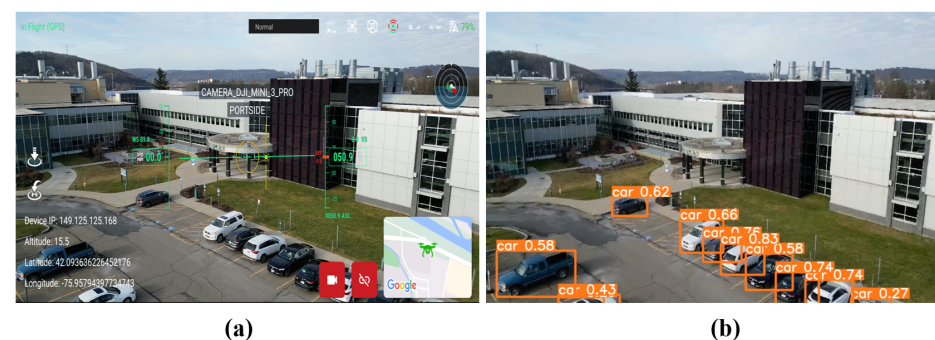**Figure 3.** SPSS microverse prototype workflow.

Figure 4. Screen shots. (**a**) Designed Android app. (**b**) Real-time object detection output.

4.4. Experimental Results

To validate the feasibility of our proposed microverse SPSS (MSPSS) framework, a prototype was developed using Unreal Engine, accurately modeling an actual engineering building from our testbed premises. The MSPSS prototype included virtual representations of several drones, as shown in the red circles in Figure 5, which reflected their real-world conditions in real time. The prototype achieved swift object detection within this virtual

setting by leveraging efficient deep learning (DL) algorithms. In addition, employing Meta software allowed for an immersive, first-person view from the drone cameras, as demonstrated in Figure 6.
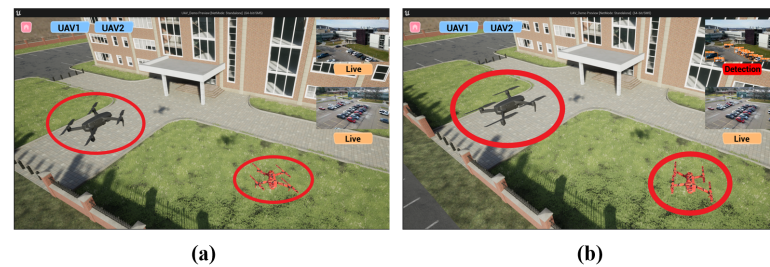

Figure 5. Screenshots of UE5-based microverse prototype. (**a**) Both drones are in live-stream mode. (**b**) The first drone switches to detection mode.

Figure 6. Screenshots of immersive VR experience.

Figure 7 presents the experimental results regarding the delay and throughput, the essential performance factors. Essential benchmarking tests were conducted, focusing on RTSP-based transmission throughput and the end-to-end latency for live streams in UE virtual spaces and VR headsets. Using a bespoke Android application, the video stream was configured at 30 frames per second with a bit rate of 3 Mbps, aiming to reduce latency while maintaining a fluent streaming experience. By calculating the difference between timestamps, the end-to-end delays were evaluated, which refers to the latency between the drone-carrying camera and the live streaming the user experiences in the surveillance room from either the live cast in UE5 or VR headsets.
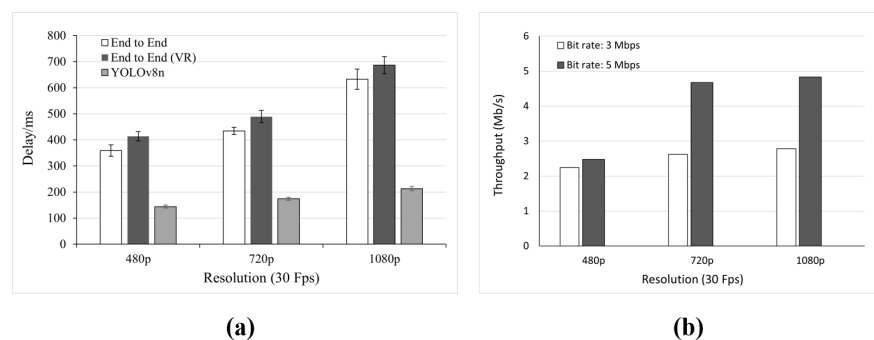

Figure 7. (**a**) Delay in different resolutions at 30 Fps. (**b**) Streaming throughput in different resolutions at different bit rate settings.

The tests executed five streaming sessions, each lasting five minutes, at various resolutions. The streaming was considered stable after five minutes for each session, and the end-to-end latency was recorded. A reasonable increase was observed in latency in all categories when the resolution was higher. Notably, the Meta software introduced additional processing time after receiving the stream on the PC, which escalated delays in VR device usage. A potential solution could be developing a specialized streaming app for Meta Quest 3, though it remains a task for the future due to current time limitations. Considering the drone's versatility in supporting different streaming bit rates, tests were conducted at 3 Mbps and 5 Mbps.

Therefore, the user would not experience high latency (less than one second) either when watching a live feed of cameras in the UE platform and VR goggles or when inspecting the results of an AI-enabled object-tracking procedure. The results validate the feasibility of the microverse system, as the low latency meets the requirements for most scenarios in real-world SPSS applications.

4.5. Discussion

The metaverse, a collective virtual shared space created by the convergence of virtually enhanced physical and digital reality, relies on computer vision, including object detection, to create seamless and interactive virtual environments [65,66]. Exploring the metaverse through a theoretical approach is very complicated. To date, there is no widely accepted standard definition for the metaverse, let alone a mathematical model capable of covering such a highly heterogeneous and diverse design space. In this work, the microverse is introduced as a case study to explore the new frontier from a practical point of view. A microverse is an open framework created following the philosophy of envisioning an immersive future where the physical and virtual/digital worlds are interwoven. The spectrum of applications that fit in the big picture is vast; while technologies like digital twins, VR/AR/XR, and AI have been recognized as essential components of the future metaverse, specific devices, functions, and algorithms are highly application-dependent.

Real-time object detection can be a critical component for metaverse applications, depending on the specific use case and the level of interactivity required. Today, we are witnessing the growing adoption of object detection and tracking technologies in emerging state-of-the-art VR/AR devices. For example, the Apple Vision Pro is equipped with six world-facing tracking cameras and four eye-tracking cameras to support an immersive VR/AR experience [67]. In this paper, based on our prior research, public safety was selected as a case study to showcase the potential of the future microverse. Object detection and identification are core functions for public safety surveillance in smart cities. Therefore, YOLO was adopted in this proof-of-concept microverse prototype.

The experimental results are merely a preliminary study on a proof-of-concept platform. The system settings, like the frame rate, are configured to accommodate the SPSS. Considering the variety of tasks the system may be applied to, these configurations could be different under other scenarios.

The Real-Time Streaming Protocol (RTSP) was adopted over other streaming protocols like HTTP Live Streaming (HLS) and Real-Time Messaging Protocol (RTMP) due to the RTSP's superior low-latency streaming capabilities, which are particularly beneficial in video surveillance and closed-circuit television (CCTV) systems. Various system configurations were tested to meet the specific demands of SPSS, including different bit rates and resolutions, as well as a range of plugins and software tailored for the RTSP pull stream. By optimizing the buffer size, the overall delay was successfully constrained to under one second, ensuring smooth and uninterrupted streaming.

Due to available technology, our microverse prototype and VR system remain nascent. The entire environment and infrastructure, including buildings, trees, and real landscapes, have not been wholly mirrored in the virtual realm. With further effort in 3D modeling, the microverse world is expected to provide a more vivid experience for multiple users. Apart from the virtual content in the current version, the operators should be able to

create specific content, like their avatars, inside the microverse. Thus, a more immersive virtual experience including VR/AR-enabled human–computer interaction (HCI) would be realized.

The current efforts demonstrate the integration of the AR, DDDAS, DT, and information fusion technologies essential to the microverse. Future endeavors could extend beyond object detection using RGB streams to incorporate more sophisticated algorithms applicable to RGB and thermal live feeds, such as tracking and sensitive alerts. Employing 360-degree cameras alongside compatible VR headsets could significantly enhance the user's first-person-view (FPV) experience, making it far more immersive.

Limited by the selection of devices and software, the current version of the prototype requires enhancement for interoperability issues. The microverse needs to leverage the full capabilities of UE5 to create a cross-platform application that provides an interface for different IoT devices like drones and VR headsets. To accommodate various tasks, more investigations and iterations of design are required to ensure the system's compatibility with other standards, such as streaming protocols.

5. Conclusions and Future Work

The exciting dawn of an immersive, interconnected 3D digital world is expected to reshape the entire human society, particularly in applications demanding high levels of intelligence. Considering the challenges and constraints yet to be tackled to enable a fully functional metaverse, this paper introduces the *microverse*, a task-oriented, edge-scale, pragmatic solution for smart cities, and validates it through a case study. The prototype of a smart public safety surveillance microverse for smart communities demonstrated that the task-oriented microverse is promising as enterprises progressively adopt remote work and digital collaboration [68]. The potential of the microverse technology to significantly alter our methods of work, education, and digital communication situates it as a catalyst for transformation within the continuing development of the metaverse. The microverse represents a significant advancement toward a more efficient, integrated, and purpose-driven digital realm rather than a simple look into the future. The authors hope this vision paper will stimulate discussions and inspire fresh ideas in the community, guiding us to navigate the evolving digital landscape of smart cities and embrace the potential of the metaverse.

On reporting the current vision of the microverse, our ongoing efforts will be focused in several directions. First of all, a complete vision of the microverse platform that reflects not only critical elements of the DT system but also other infrastructures in the real world will be constructed to provide a vivid vision and a more immersive user experience. Functionalities such as user-generated content (UGC) will be added to enhance the human–computer interface (HCI) through avatars. A more comprehensive evaluation of different transmitting protocols will be conducted to test more benchmark analyses in various scenarios of smart surveillance. To simplify the observation of camera footage, other push-streaming protocols will be investigated to optimize the streaming latency for AI results, both for VR and other usages. Moreover, the current VR function is limited to the cinematic vision of live streaming. With new devices such as 360-degree cameras and VR goggles, applications will be developed to provide an FPV experience with a low-latency live feed directly from the drones, as well as an interactive VR user interface (UI) inside the microverse virtual space and direct control from VR rather than the remote control panel. Last but not least, considering the limited sensor capability and restriction on fog-level servers for AI functionalities of commercial drones, a customized fleet of drones carrying various sensors and edge-computing units will be designed to satisfy different tasks such as delivery, smart agriculture, fire detection, etc.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
AR	Augmented reality
CCTV	Closed-circuit television
DDDAS	Dynamic data-driven applications systems
DL	Deep learning
DLT	Distributed ledger technology
DT	Digital twin
EPDS	Electric propulsion drive system
FPV	First-person view
HLS	HTTP live streaming
HPP	High-precision product
IoST	Internet of Smart Things
IoT	Internet of Things
JSON	JavaScript Object Notation
ML	Machine learning
mMTC	Massive machine-type communication
MSPSS	Microverse SPSS
NASA	National Aeronautical and Space Administration
NIST	National Institute of Standards and Technology
NS	Network slicing
P2P	Peer-to-peer
PBFT	Practical Byzantine fault tolerance
PC	Personal computer
PoS	Proof of stake
PoW	Proof of work
QoS	Quality of Service
RTMP	Real-Time Messaging Protocol
RTSP	Real-Time Streaming Protocol
SL	Slicing layer
SPSS	Smart public safety surveillance
UAM	Urban air mobility
UAV	Unmanned aerial vehicle

UE5	Unreal Engine 5
UI	User interface
URLLC	Ultrareliable low-latency communication
WLAN	Wireless local area network
VR	Virtual reality
XR	Extended reality

References

1. Xu, R.; Nikouei, S.Y.; Chen, Y.; Blasch, E.; Aved, A. Blendmas: A blockchain-enabled decentralized microservices architecture for smart public safety. In Proceedings of the 2019 IEEE International Conference on Blockchain (Blockchain), Atlanta, GA, USA, 14–17 July 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 564–571.
2. Global Community Technology Challenge. Available online: https://www.nist.gov/ctl/smart-connected-systems-division/iot-devices-and-infrastructures-group/smart-americaglobal-0 (accessed on 26 December 2023).
3. Lai, C.M.T.; Cole, A. Measuring progress of smart cities: Indexing the smart city indices. *Urban Gov.* **2023**, *3*, 45–57. [CrossRef]
4. Wu, Y.; Dai, H.N.; Wang, H.; Xiong, Z.; Guo, S. A survey of intelligent network slicing management for industrial IoT: Integrated approaches for smart transportation, smart energy, and smart factory. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 1175–1211. [CrossRef]
5. Xu, R.; Chen, Y.; Li, X.; Blasch, E. A secure dynamic edge resource federation architecture for cross-domain IoT systems. In Proceedings of the 2022 International Conference on Computer Communications and Networks (ICCCN), Honolulu, HI, USA, 25–28 July 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–7.
6. Kusuma, A.T.; Supangkat, S.H. Metaverse fundamental technologies for smart city: A literature review. In Proceedings of the 2022 International Conference on ICT for Smart Society (ICISS), Bandung, Indonesia, 10–11 August 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–7.
7. Cheng, R.; Wu, N.; Chen, S.; Han, B. Will metaverse be nextg internet? vision, hype, and reality. *IEEE Netw.* **2022**, *36*, 197–204. [CrossRef]
8. Cheng, R.; Wu, N.; Varvello, M.; Chen, S.; Han, B. Are we ready for metaverse? A measurement study of social virtual reality platforms. In Proceedings of the 22nd ACM Internet Measurement Conference, Nice, France, 25–27 October 2022; pp. 504–518.
9. Mozumder, M.A.I.; Sheeraz, M.M.; Athar, A.; Aich, S.; Kim, H.C. Overview: Technology roadmap of the future trend of metaverse based on IoT, blockchain, AI technique, and medical domain metaverse activity. In Proceedings of the 2022 24th International Conference on Advanced Communication Technology (ICACT), Pyeongchang, Republic of Korea, 13–16 February 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 256–261.
10. Jha, M.K.; Yogeshwari, A.; Rubini, P.; Singh, M. Converge of IoT and AI in Metaverse: Challenges and Opportunities. In Proceedings of the 2023 5th International Conference on Inventive Research in Computing Applications (ICIRCA), Coimbatore, India, 3–5 August 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 1462–1467.
11. Lin, H.; Wan, S.; Gan, W.; Chen, J.; Chao, H.C. Metaverse in education: Vision, opportunities, and challenges. In Proceedings of the 2022 IEEE International Conference on Big Data (Big Data), Osaka, Japan, 17–20 December 2022; IEEE:Piscataway, NJ, USA, 2022; pp. 2857–2866.
12. Yaqoob, I.; Salah, K.; Jayaraman, R.; Omar, M. Metaverse applications in smart cities: Enabling technologies, opportunities, challenges, and future directions. *Internet Things* **2023**, *23*, 100884. [CrossRef]
13. Ismail, L.; Buyya, R. Metaverse: A Vision, Architectural Elements, and Future Directions for Scalable and Realtime Virtual Worlds. *arXiv* **2023**, arXiv:2308.10559.
14. Jaimini, U.; Zhang, T.; Brikis, G.O.; Sheth, A. iMetaverseKG: Industrial Metaverse Knowledge Graph to Promote Interoperability in Design and Engineering Applications. *IEEE Internet Comput.* **2022**, *26*, 59–67. [CrossRef]
15. Rawal, B.S.; Mentges, A.; Ahmad, S. The Rise of Metaverse and Interoperability with Split-Protocol. In Proceedings of the 2022 IEEE 23rd International Conference on Information Reuse and Integration for Data Science (IRI), San Diego, CA, USA, 9–11 August 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 192–199.
16. Aloqaily, M.; Bouachir, O.; Karray, F.; Al Ridhawi, I.; El Saddik, A. Integrating digital twin and advanced intelligent technologies to realize the metaverse. *IEEE Consum. Electron. Mag.* **2022**, *12*, 47–55. [CrossRef]
17. Blasch, E.; Pham, T.; Chong, C.Y.; Koch, W.; Leung, H.; Braines, D.; Abdelzaher, T. Machine learning/artificial intelligence for sensor data fusion–opportunities and challenges. *IEEE Aerosp. Electron. Syst. Mag.* **2021**, *36*, 80–93. [CrossRef]
18. Grieves, M.; Vickers, J. Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*; Springer: Cham, Switzerland, 2017; pp. 85–113.
19. Park, K.T.; Yang, J.; Noh, S.D. VREDI: Virtual representation for a digital twin application in a work-center-level asset administration shell. *J. Intell. Manuf.* **2021**, *32*, 501–544. [CrossRef]
20. Malik, A.A.; Brem, A. Digital twins for collaborative robots: A case study in human-robot interaction. *Robot. Comput. -Integr. Manuf.* **2021**, *68*, 102092. [CrossRef]
21. Bilberg, A.; Malik, A.A. Digital twin driven human–robot collaborative assembly. *CIRP Ann.* **2019**, *68*, 499–502. [CrossRef]
22. Maruyama, T.; Ueshiba, T.; Tada, M.; Toda, H.; Endo, Y.; Domae, Y.; Nakabo, Y.; Mori, T.; Suita, K. Digital twin-driven human robot collaboration using a digital human. *Sensors* **2021**, *21*, 8266. [CrossRef]

23. Sun, X.; Bao, J.; Li, J.; Zhang, Y.; Liu, S.; Zhou, B. A digital twin-driven approach for the assembly-commissioning of high precision products. *Robot. Comput.-Integr. Manuf.* **2020**, *61*, 101839. [CrossRef]

24. Karadeniz, A.M.; Arif, İ.; Kanak, A.; Ergün, S. Digital twin of eGastronomic things: A case study for ice cream machines. In Proceedings of the 2019 IEEE International Symposium on Circuits and Systems (ISCAS), Sapporo, Japan, 26–29 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–4.

25. Rassõlkin, A.; Vaimann, T.; Kallaste, A.; Kuts, V. Digital twin for propulsion drive of autonomous electric vehicle. In Proceedings of the 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 7–9 October 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–4.

26. Hu, Z.; Lou, S.; Xing, Y.; Wang, X.; Cao, D.; Lv, C. Review and perspectives on driver digital twin and its enabling technologies for intelligent vehicles. *IEEE Trans. Intell. Veh.* **2022**, *7*, 417–440. [CrossRef]

27. Darema, F. New software architecture for complex applications development and runtime support. *Int. J. High Perform. Comput. Appl.* **1999**, *13*, 180–190. Available online: https://journals.sagepub.com/doi/abs/10.1177/109434209901300302?download=true&journalCode=hpcc (accessed on 2 February 2024).

28. Bazilevs, Y.; Korobenko, A.; Deng, X.; Tippmann, J.; Hsu, M.C. Wind turbine simulation: Structural mechanics, fsi and computational steering. In Proceedings of the COUPLED V: Proceedings of the V International Conference on Computational Methods for Coupled Problems in Science and Engineering: CIMNE, Ibiza, Spain, 17–19 June 2013; pp. 229–240.

29. Pérez, E. A Simulation-Based Online Dynamic Data-Driven Framework for Large-Scale Wind-Turbine Farm Systems Operation. In *Handbook of Dynamic Data Driven Applications Systems: Volume 2*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 353–374.

30. Pargmann, H.; Euhausen, D.; Faber, R. Intelligent big data processing for wind farm monitoring and analysis based on cloud-technologies and digital twins: A quantitative approach. In Proceedings of the 2018 IEEE 3rd International Conference on Cloud Computing and Big Data Analysis (ICCCBDA), Chengdu, China, 20–22 April 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 233–237.

31. Roda-Sanchez, L.; Cirillo, F.; Solmaz, G.; Jacobs, T.; Garrido-Hidalgo, C.; Olivares, T.; Kovacs, E. Building a Smart Campus Digital Twin: System, Analytics and Lessons Learned from a Real-World Project. *IEEE Internet Things J.* **2023**, *11*, 4614–4627. [CrossRef]

32. Zaballos, A.; Briones, A.; Massa, A.; Centelles, P.; Caballero, V. A smart campus' digital twin for sustainable comfort monitoring. *Sustainability* **2020**, *12*, 9196. [CrossRef]

33. Erol, T.; Mendi, A.F.; Doğan, D. The digital twin revolution in healthcare. In Proceedings of the 2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Istanbul, Turkey, 22–24 October 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–7.

34. Elayan, H.; Aloqaily, M.; Guizani, M. Digital twin for intelligent context-aware IoT healthcare systems. *IEEE Internet Things J.* **2021**, *8*, 16749–16757. [CrossRef]

35. Liu, Y.; Zhang, L.; Yang, Y.; Zhou, L.; Ren, L.; Wang, F.; Liu, R.; Pang, Z.; Deen, M.J. A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access* **2019**, *7*, 49088–49101. [CrossRef]

36. Laaki, H.; Miche, Y.; Tammi, K. Prototyping a digital twin for real time remote control over mobile networks: Application of remote surgery. *IEEE Access* **2019**, *7*, 20325–20336. [CrossRef]

37. Khan, L.U.; Yaqoob, I.; Tran, N.H.; Han, Z.; Hong, C.S. Network slicing: Recent advances, taxonomy, requirements, and open research challenges. *IEEE Access* **2020**, *8*, 36009–36028. [CrossRef]

38. Pokhrel, S.R.; Ding, J.; Park, J.; Park, O.S.; Choi, J. Towards enabling critical mMTC: A review of URLLC within mMTC. *IEEE Access* **2020**, *8*, 131796–131813. [CrossRef]

39. Afolabi, I.; Taleb, T.; Samdanis, K.; Ksentini, A.; Flinck, H. Network slicing and softwarization: A survey on principles, enabling technologies, and solutions. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2429–2453. [CrossRef]

40. Nakamoto, S. Bitcoin: A peer-to-peer electronic cash system. *Decentralized Bus. Rev.* **2008**.

41. Xu, R.; Wei, S.; Chen, Y.; Chen, G.; Pham, K. LightMAN: A Lightweight Microchained Fabric for Assurance-and Resilience-Oriented Urban Air Mobility Networks. *Drones* **2022**, *6*, 421. [CrossRef]

42. Xu, R.; Chen, Y.; Blasch, E.; Chen, G. Exploration of blockchain-enabled decentralized capability-based access control strategy for space situation awareness. *Opt. Eng.* **2019**, *58*, 041609. [CrossRef]

43. Xu, R.; Chen, Y.; Blasch, E.; Chen, G. Blendcac: A smart contract enabled decentralized capability-based access control mechanism for the iot. *Computers* **2018**, *7*, 39. [CrossRef]

44. Xu, R.; Chen, Y.; Chen, G.; Blasch, E. SAUSA: Securing Access, Usage, and Storage of 3D Point CloudData by a Blockchain-Based Authentication Network. *Future Internet* **2022**, *14*, 354. [CrossRef]

45. Xu, R.; Chen, Y. Fed-ddm: A federated ledgers based framework for hierarchical decentralized data marketplaces. In Proceedings of the 2021 International Conference on Computer Communications and Networks (ICCCN), Athens, Greece, 19–22 July 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 1–8.

46. Bao, Z.; Shi, W.; He, D.; Chood, K.K.R. IoTChain: A three-tier blockchain-based IoT security architecture. *arXiv* **2018**, arXiv:1806.02008.

47. Sagirlar, G.; Carminati, B.; Ferrari, E.; Sheehan, J.D.; Ragnoli, E. Hybrid-iot: Hybrid blockchain architecture for internet of things-pow sub-blockchains. In Proceedings of the 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), Halifax, NS, Canada, 30 July–3 August 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1007–1016.

48. Samaniego, M.; Deters, R. Internet of smart things-iost: Using blockchain and clips to make things autonomous. In Proceedings of the 2017 IEEE International Conference on Cognitive Computing (ICCC), Honolulu, HI, USA, 25–30 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 9–16.

49. Xu, R.; Chen, Y.; Blasch, E. Microchain: A light hierarchical consensus protocol for iot systems. In *Blockchain Applications in IoT Ecosystem*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 129–149.

50. Xu, R.; Chen, Y. μDFL: A Secure Microchained Decentralized Federated Learning Fabric atop IoT Networks. *IEEE Trans. Netw. Serv. Manag.* **2022**, *19*, 2677–2688. [CrossRef]

51. Jiang, Y.; Kang, J.; Niyato, D.; Ge, X.; Xiong, Z.; Miao, C.; Shen, X. Reliable distributed computing for metaverse: A hierarchical game-theoretic approach. *IEEE Trans. Veh. Technol.* **2022**, *72*, 1084–1100. [CrossRef]

52. Bujari, A.; Calvio, A.; Garbugli, A.; Bellavista, P. A Layered Architecture Enabling Metaverse Applications in Smart Manufacturing Environments. In Proceedings of the 2023 IEEE International Conference on Metaverse Computing, Networking and Applications (MetaCom), Kyoto, Japan, 26–28 June 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 585–592.

53. Setiawan, K.D.; Anthony, A. The essential factor of metaverse for business based on 7 layers of metaverse–systematic literature review. In Proceedings of the 2022 International Conference on Information Management and Technology (ICIMTech), Semarang, Indonesia, 1–12 August 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 687–692.

54. Munir, A.; Kwon, J.; Lee, J.H.; Kong, J.; Blasch, E.; Aved, A.J.; Muhammad, K. FogSurv: A fog-assisted architecture for urban surveillance using artificial intelligence and data fusion. *IEEE Access* **2021**, *9*, 111938–111959. [CrossRef]

55. Cheng, S. Basic Infrastructure of the Metaverse. In *Metaverse: Concept, Content and Context*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 25–46.

56. Blasch, E.; Kessler, O.; Morrison, J.; Tangney, J.; White, F.E. Information fusion mangement and enterpise processing. In Proceedings of the 2012 IEEE National Aerospace and Electronics Conference (NAECON), Dayton, OH, USA, 25–27 July 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 204–211.

57. Wang, Z.; Deng, Y.; Aghvami, A.H. Task-oriented and Semantics-aware Communication Framework for Augmented Reality. *arXiv* **2023**, arXiv:2306.15470.

58. Dwivedi, Y.K.; Hughes, L.; Baabdullah, A.M.; Ribeiro-Navarrete, S.; Giannakis, M.; Al-Debei, M.M.; Dennehy, D.; Metri, B.; Buhalis, D.; Cheung, C.M.; et al. Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *Int. J. Inf. Manag.* **2022**, *66*, 102542. [CrossRef]

59. Blasch, E.; Xu, R.; Nikouei, S.Y.; Chen, Y. A study of lightweight dddas architecture for real-time public safety applications through hybrid simulation. In Proceedings of the 2019 Winter Simulation Conference (WSC), National Harbor, MD, USA, 8–11 December 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 762–773.

60. Qu, Q.; Sun, H.; Chen, Y. A Virtual Community Healthcare Framework in Metaverse Enabled by Digital Twins. In Proceedings of the International Congress on Communications, Networking, and Information Systems, Honolulu, HI, USA, 20–22 February 2023; Springer: Berlin/Heidelberg, Germany, 2023; pp. 27–46.

61. Qu, Q.; Xu, R.; Sun, H.; Chen, Y.; Sarkar, S.; Ray, I. A Digital Healthcare Service Architecture for Seniors Safety Monitoring in Metaverse. In Proceedings of the 2023 IEEE International Conference on Metaverse Computing, Networking and Applications (MetaCom), Kyoto, Japan, 26–28 June 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 86–93.

62. Qu, Q.; Sun, H.; Chen, Y. Light-Weight Real-Time Senior Safety Monitoring using Digital Twins. In Proceedings of the Proceedings of the 8th ACM/IEEE Conference on Internet of Things Design and Implementation, San Antonio, TX, USA, 9–12 May 2023; pp. 450–451.

63. Xu, R.; Nikouei, S.Y.; Nagothu, D.; Fitwi, A.; Chen, Y. Blendsps: A blockchain-enabled decentralized smart public safety system. *Smart Cities* **2020**, *3*, 928–951. [CrossRef]

64. Nikouei, S.Y.; Xu, R.; Nagothu, D.; Chen, Y.; Aved, A.; Blasch, E. Real-time index authentication for event-oriented surveillance video query using blockchain. In Proceedings of the 2018 IEEE International Smart Cities Conference (ISC2), Kansas City, MO, USA, 16–19 September 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1–8.

65. Arani, E.; Gowda, S.; Mukherjee, R.; Magdy, O.; Kathiresan, S.; Zonooz, B. A comprehensive study of real-time object detection networks across multiple domains: A survey. *arXiv* **2022**, arXiv:2208.10895.

66. Nalbant, K.G.; UYANIK, Ş. Computer vision in the metaverse. *J. Metaverse* **2021**, *1*, 9–12.

67. Apple Vision Pro. 2024. Available online: https://www.apple.com/apple-vision-pro/specs/ (accessed on 2 February 2024).

68. Camarinha-Matos, L.M.; Fornasiero, R.; Ramezani, J.; Ferrada, F. Collaborative networks: A pillar of digital transformation. *Appl. Sci.* **2019**, *9*, 5431. [CrossRef]