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UbiMeta: A Ubiquitous Operating System Model for Metaverse

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ABSTRACT

The metaverse signifies the amalgamation of virtual and tangible realms through human-computer interaction. The seamless integration of human, cyber, and environments within ubiquitous computing plays a pivotal role in fully harnessing the metaverse's capabilities. Nevertheless, metaverse operating systems face substantial hurdles in terms of accessing ubiquitous resources, processing information while safeguarding privacy and security, and furnishing artificial intelligence capabilities to downstream applications. To tackle these challenges, this paper introduces the UbiMeta model, a specialized ubiquitous operating system designed specifically for the metaverse. It extends the capabilities of traditional ubiquitous operating systems and focuses on adapting downstream models and operational capacity to effectively function within the metaverse. UbiMeta comprises four layers: the Ubiquitous Resource Management Layer (URML), the Autonomous Information Mastery Layer (AIML), the General Intelligence Mechanism Layer (GIML), and the Metaverse Ecological Model Layer (MEML). The URML facilitates the seamless incorporation and management of various external devices and resources. It provides a framework for integrating and controlling these resources, including virtualization, abstraction, and reuse. The AIML is responsible for perceiving information and safeguarding privacy and security during storage and processing. The GIML leverages large-scale pre-trained deep-learning feature extractors to obtain effective features for processing information. The MEML focuses on constructing metaverse applications using the principles of Model-as-a-Service (MaaS) and the OODA loop (Observation, Orientation, Decision, Action). It leverages the vast amount of information collected by the URML and AIML layers to build a robust metaverse ecosystem. Furthermore, this study explores how UbiMeta enhances user experiences and fosters innovation in various metaverse domains. It highlights the potential of UbiMeta in revolutionizing medical healthcare, industrial practices, education, and agriculture within the metaverse.

KEYWORDS

metaverse; ubiquitous operating system; federated computing; OODA loop

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The metaverse, as a prominent example of the next generation of the Internet, is expected to enhance information density and data value in higher dimensions[1,2]. Its primary feature lies in enabling individuals to embody digital avatars in the virtual world and facilitating the integration of virtual and real worlds through human-computer interaction techniques like Augmented Reality (AR) and Virtual Reality (VR). Towards this goal, operating systems play a crucial role in realizing the metaverse[3]. There have been significant advancements in previous successful operating systems. In the era of personal computers, notable operating systems include Microsoft's Windows, Apple's Macintosh, and open-source Linux. Similarly, in the era of mobile internet, we have operating systems like Google's Android, Apple's iOS, and Huawei's HarmonyOS. However, in the era of the metaverse, economic and political barriers of the current Internet will be further overcome[4]. With the all-encompassing extension of the Internet into human society and the physical world, as well as the emergence of new technologies such as cloud computing, big data, and artificial intelligence, various new application models and scenarios have emerged. The integration of human, cyber, and environments in ubiquitous computing will bring about new models and scenarios. Facing these new challenges, operating system-related technologies are facing numerous critical changes.

In recent advancements, the Ubiquitous Operating System (UOS) has been designed to support all entities operating within this ubiquitous environment[5,6]. It serves as the exclusive gateway to access the trusted collaborative network and facilitates interactions between entities and objects. However, as the metaverse emerges, the UOS faces new challenges. The metaverse environments require a further extended UOS that functions as the operational system for conducting all economic and social activities, while also serving as a management platform for autonomous and controllable information. The extended UOS supports flexible and diverse resource virtualization and heterogeneous bridging capabilities, enabling application development and operational support under new computing models. The fundamental paradigm lies in the characteristics of natural interaction among human, cyber, and environments.

This paper proposes the UbiMeta model, which defines a ubiquitous operating system for the metaverse. UbiMeta serves as a generalized extension of the UOS, with a specific focus on adapting business models and operational capacity to function effectively in the metaverse. It integrates the novel technologies of

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UOS and incorporates new technologies that cater to the unique ecosystem of the metaverse. UbiMeta consists of four critical progressive hierarchies.

Ubiquitous Resource Management Layer (URML): This layer forms the theoretical foundation for other key technologies within UbiMeta. It involves modeling the behaviors of various entities participating in the system and facilitates the management and control of ubiquitous resources. This includes external virtualization, abstraction, and reuse of resources.

Autonomous Information Mastery Layer (AIML): This layer encompasses a range of activities guided by information technologies. It includes planning, organizing, storing, retrieving, transmitting, applying, and protecting personal information. AIML enables the perception of personal data through gestures, speech, visuals, and other means while ensuring the security of the data. Additionally, it proposes the restriction that the processing of personal data should adhere to the federated learning schema.

General Intelligence Mechanism Layer (GIML): It serves as a fundamental and efficient deep learning engine, providing powerful capabilities for a wide range of downstream applications. By utilizing large-scale pre-trained deep-learning feature extractors, GIML efficiently converts raw data into meaningful and effective features.

Metaverse Ecological Model Layer (MEML): Building upon the abundant personal data collected by URML and AIML, this layer focuses on constructing the downstream metaverse ecosystem. MEML adopts the Model-as-a-Service (MaaS) approach to standardize the access and composition of models while managing their usage following the principles of the OODA loop (Observation, Orientation, Decision, Action).

We summarize the major characteristics of UbiMeta as follows:

Four-layer architecture: The paper proposes a four-layer hierarchy, consisting of URML, AIML, GIML, and MEML. This architecture provides a comprehensive framework for managing ubiquitous resources, ensuring privacy and security, processing information efficiently, and fostering application innovation within the metaverse.

Privacy and security considerations: UbiMeta ensures the protection of ubiquitous information privacy by adhering to the federated computing schema. This schema safeguards privacy and security during data processing, addressing concerns associated with handling sensitive data within the metaverse. UbiMeta integrates large-scale pre-trained deep-learning foundations, supporting hetero-capability, hetero-modality, and hetero-functionality federated computing.

Metaverse ecosystem construction: UbiMeta focuses on constructing metaverse applications using the principles of MaaS and the OODA loop. By leveraging the information collected by the URML and AIML layers, UbiMeta builds a robust metaverse ecosystem, fostering innovation and enhancing user experiences across diverse domains.

These contributions collectively advance the development of operating systems tailored for the metaverse, paving the way for enhanced user experiences and innovation within this emerging virtual realm.

The following sections will illustrate the progress of the metaverse and the ubiquitous operating system (Section 1), condense the challenges of ubiquitous operating system for metaverse (Section 2), discuss the four hierarchies of the proposed UbiMeta (Section 3), outline the typical scenarios of the UbiMeta (Section 4), and finally summarize the entire paper (Section 5).

1 Background

This section begins by introducing the history of the term metaverse, which was first proposed in a science fiction novel *Snow Crash*[7]. However, the understanding of this term has evolved significantly[1], and it seemed to be the next generation of the Internet. Subsequently, the section proceeds to describe the basic concept of UOS and provides an overview of recent studies in this field.

1.1 Concept of metaverse

The science fiction *Snow Crash*[7] outlines a collapsing postmodern civilization in which people transition into a virtual Internet. While the realization of this concept is hindered by limitations in computing infrastructure technology, various novel multimedia technologies have emerged that partially fulfill this vision[8–10]. During periods, several standards have attempted to standardize the metaverse. ISO/IEC 23005 (MPEG-V)[11] is the first standardized framework for Networked Virtual Environments (NVEs) in the metaverse. As a supplement to this pioneer, IEEE 2888[12] aims to define standardized interfaces for the synchronization of cyber and physical worlds. In recent views, the metaverse is described as a self-sustaining, hyper spatiotemporal, and 3D immersive virtual shared space, created by the convergence of physically persistent virtual space and virtually enhanced physical reality[10].

The metaverse is considered to be human-centric. With the assistance of intelligent wearable devices such as VR/AR helmets[13], individuals possess the capability to actively engage and manage their digital avatars within the metaverse. These interactions are facilitated through the utilization of multimodal human-computer interaction[14]. To enhance the engagement of humans and create vivid metaverse avatars, wearable technologies play a crucial role[15]. For instance, wearable resistive sensors are employed to characterize joint movements in the metaverse[16], while brain-computer interfaces are adopted to enhance seamless human-computer interaction[17]. Moreover, the integration of Internet of Things (IoT) devices is of great importance to enhance the capabilities of metaverse applications[18, 19].

In this paper, we propose UbiMeta as a solution to address the specific challenges of integrating multiple IoT devices and generating virtual digital avatars within the metaverse. UbiMeta formalizes the AIML, as well as the GIML, to directly tackle these challenges.

1.2 Concept of ubiquitous operating system

The concept of ubiquitous computing is capable of addressing the computational challenges discussed in the previous section on the metaverse. An Operating System (OS) serves as a layer of system software that sits between applications and computer hardware, managing resources. In the context of ubiquitous computing, the UOS goes a step further by adapting to the new patterns and scenarios that arise from the integration of human, cyber, and environments, which is a primary focus.

There are several early successful UOSs developed in various fields and domains. The HomeOS[20] already has dozens of applications and supports a variety of devices. It implements cross-device tasks through abstract interfaces. Afterward, the CampusOS[21] aims at managing the network resources of a university campus and providing flexible campus applications. More recently, the CrowdOS[22] is designed for crowdsourcing and mobile crowd sensing. It is an abstract software layer running between the native OS and application layer[22]. Parallel Driving OS

(PDOS)[23] achieves heterogeneous hardware support, ubiquitous resource management, and ubiquitous application development in the context of autonomous driving.

Nowadays, the development of UOS is still in progress. While there are various prototypes available, the implementation of UOS in the metaverse is yet to be realized. This paper proposes UbiMeta as a solution to adapt UOS for the metaverse. UbiMeta aims to provide a high level hardware abstraction layer that offers interfaces for a variety of device types while integrating machine learning based algorithms for realizing assisted decision-making. The following section will present the prototype of the proposed UOS for the metaverse.

2 Challenge of Ubiquitous Operating System for Metaverse

The ubiquitous operating system, following the principles of ubiquitous computing, is designed to manage ubiquitous computing resources and support ubiquitous application development and runtime. It encompasses novel features such as ubiquitous sensing, ubiquitous connectivity, lightweight computing, lightweight cognition, feedback control, and natural interaction. Fundamentally, the ubiquitous operating system adheres to the essential functions of an operating system by providing flexible and diverse resource virtualization and bridging capabilities for heterogeneous resources. It facilitates application development and runtime support within the framework of emerging computing paradigms. The ubiquitous operating system is usually a loosely coupled system that involves various heterogeneous computers, nodes, and sites interconnected through network connections.

The current emphasis in the development of ubiquitous operating systems lies in accessing and controlling external devices, while also providing support systems for various network applications. In the context of the metaverse, which encompasses the convergence of human, cyber, and environments, and where individuals aspire to embody digital avatars, the following challenges for a general UOS arise:

Challenge 1: Constructing flexible and changeable system structure for ubiquitous environments.

The typical characteristics of ubiquitous computing scenarios of human, cyber, and environment integration include complex and diverse application scenarios and massive heterogeneous resources in ubiquitous resources, which require the operating system to have a flexible and changeable system structure. It is necessary to establish a new basic theory and architecture of operating systems for ubiquitous computing environments, as well as a software-defined operating system construction method.

The integration of human, cyber, and environments encompasses a wide range of components, including not only processors, memories, and storage devices, but external environments, each with its own unique performance and functionality. It is crucial to explore general methods for abstracting and managing heterogeneous hardware resources. This involves developing a universal access and driver framework that can effectively handle the diverse hardware resources.

The UOS is designed to be compatible with a wide range of heterogeneous devices, based on ARM, x86, RiscV, and LoongArch architectures. However, for end users, UOS functions as a standard centralized operating system. It can share various heterogeneous processors, such as CPUs, GPUs, NPUs, and MCUs, as well as all resources like disks, network interfaces, nodes, and computers across different locations. This enables the system to enhance data availability throughout the entire network. The processors are interconnected using efficient communication media, such as high-speed buses, wired and wireless connections, and mobile networks.

In addition, the abstraction and management of heterogeneous resources should be adaptable to the evolution of novel resources and platforms. Establishing a general driver model will enable the ubiquitous operating system to effectively support the evolving capabilities of devices and efficiently manage the dynamic access and migration of device resource capabilities.

Challenge 2: Establishing a secure computing environment for information perception and processing.

In the context of information perception and processing, a significant challenge lies in ensuring a secure computing environment. This challenge has become increasingly important in light of regulations such as the General Data Protection Regulation (GDPR)[24]. The GDPR imposes strict guidelines and requirements for the protection of personal data, emphasizing the need for robust security measures.

To address this challenge, it is significant to implement comprehensive security protocols and mechanisms within the computing environment. This includes measures such as encryption, access control, authentication, and auditing. By establishing a secure computing environment, organizations can safeguard sensitive information and ensure compliance with regulatory frameworks like the GDPR.

Challenge 3: Developing natural and effective ubiquitous human, cyber, and environments convergence.

The integration of human, cyber, and environments in the ubiquitous computing environment expands the space and modalities of general human-computer interaction. A new requirement arises for abstracting multimodal human-computer interaction and proposing a simple interactive instruction set that facilitates system operation. Addressing this challenge involves establishing behavioral abstraction, structured description, multimodal perception, and understanding models and methods for human-computer interaction. Furthermore, it requires the development of a natural and efficient ubiquitous interactive instruction set, optimizing interactive performance and system cost, and meeting individual needs through quantifiable system scheduling and resource integration.

In response to the challenges discussed above, the following section provides a detailed introduction to UbiMeta, a proposed model for a ubiquitous operating system specifically designed for the metaverse.

3 Architecture of UbiMeta

In response to the aforementioned challenges, we have developed a model, UbiMeta, that harnesses the fundamental behavior of the ubiquitous operating system to further enhance the metaverse environment. Figure 1 illustrates the proposed model, which comprises four layers: the URML, the AIML, the GIML, and the MEML.

The URML plays a critical role in abstracting and managing ubiquitous resources. It employs a multi-core heterogeneous distributed model, enabling applications to run on multiple computers and expanding the capabilities of network operating systems to support advanced levels of communication and integration. The AIML encompasses a range of management activities that encompass planning, organizing, storing, retrieving, transmitting, applying, and protecting information resources from external devices. Lastly, the MEML involves the integration of

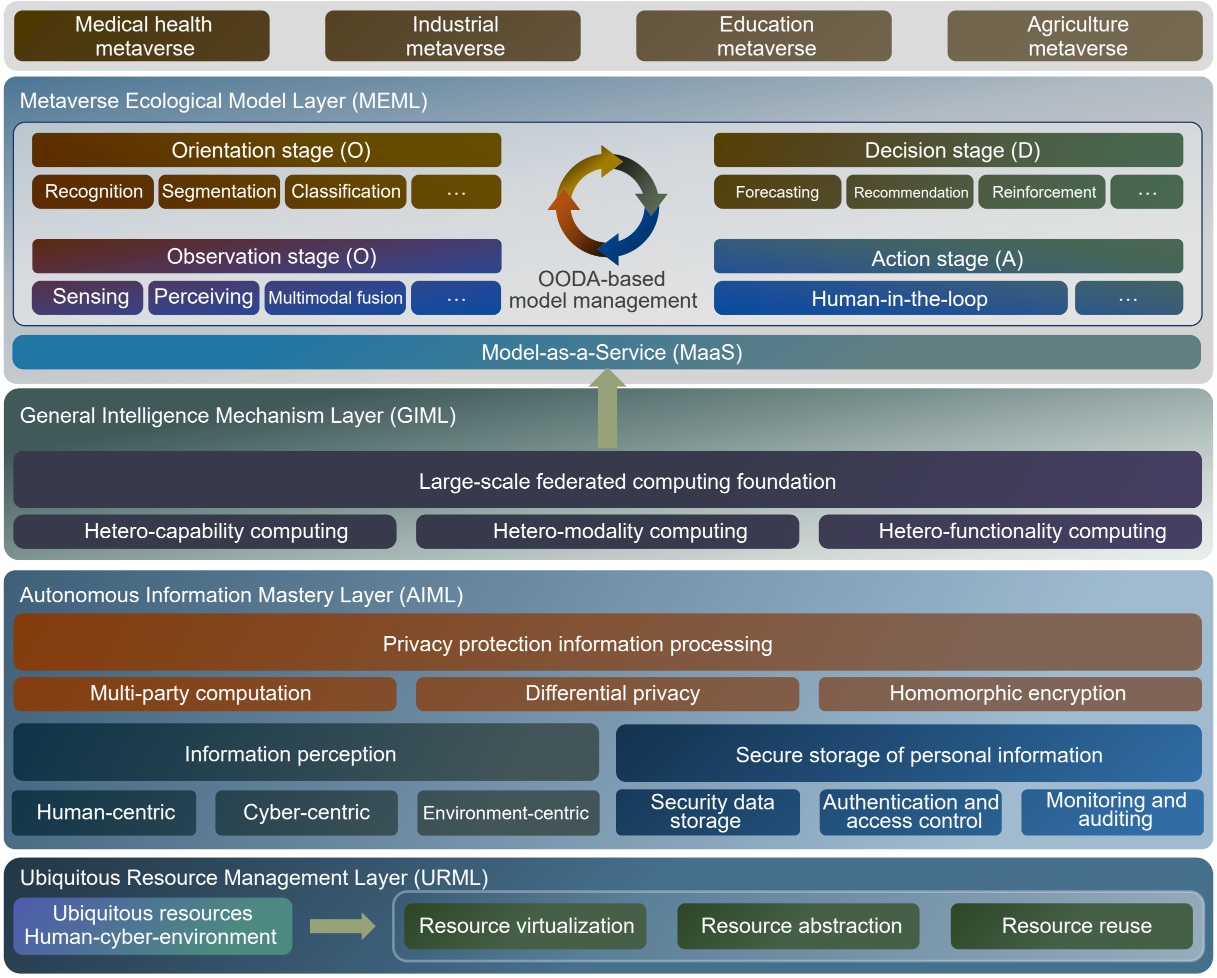

Fig. 1 Architecture of UbiMeta.

advanced information technology to provide assistive decision-making support.

3.1 Ubiquitous resource management layer

We first clarify the concept of ubiquitous resources in UbiMeta. In contrast to the resources found in traditional operating systems, such as computer-centric hardware, peripheral devices, or software, the resources in the metaverse are distributed and surrounding the ubiquitous existence of humans, cyberspace, and the environment. Figure 2 showcases various examples of resources within UbiMeta.

One of the key innovations introduced by UbiMeta is the concept of distributed resource access. This feature enables effective utilization of resources across different nodes and devices within the metaverse ecosystem. By leveraging distributed resource access, UbiMeta empowers applications and processes to access and utilize resources from multiple sources, regardless of their physical location. This distributed approach to resource access significantly enhances the scalability and flexibility of the metaverse environment.

By incorporating distributed resource access within its framework, UbiMeta revolutionizes the way resources are accessed and utilized in the metaverse. This not only optimizes resource allocation, but also enables the realization of complex and resource-intensive applications. The distributed nature of resource access in UbiMeta contributes to the overall efficiency and effectiveness of the metaverse ecosystem.

The URML in UbiMeta has the similar functional objectives to ubiquitous operating systems. Its primary aim is to optimize the management of diverse resources while promoting application compatibility. However, it is important to note that UbiMeta is primarily focused on supporting ubiquitous resources rather than only computer-centric hardware, peripheral devices, or softwares. While UbiMeta does provide a framework for integrating and managing resources, its main objective is to enable seamless incorporation and management of various resources within the metaverse.

An essential responsibility of the URML is to efficiently handle the allocation, utilization, and recycling of software and hardware resources among applications, thereby enabling resource sharing among multiple metaverse programs. Given the multitude of applications contending for resources in the metaverse, it is crucial to address the challenge of resource allocation rationally.

To ensure the usability of resources, only system-provided functions or other facilities can be controlled and utilized. At a higher level, the URML enhances the functionalities of hardware devices to make them metaverse-compatible, featuring a user-friendly interface, robust capabilities, high efficiency, and ease of use. Metaverse applications solely perceive resources without direct interaction with specific hardware. Therefore, it is imperative for the operating system to achieve resource virtualization, resource abstraction, and resource reuse. The following paragraphs introduce these critical aspects, respectively.

3.1.1 Ubiquitous resource virtualization

Resource virtualization refers to the technologies used to

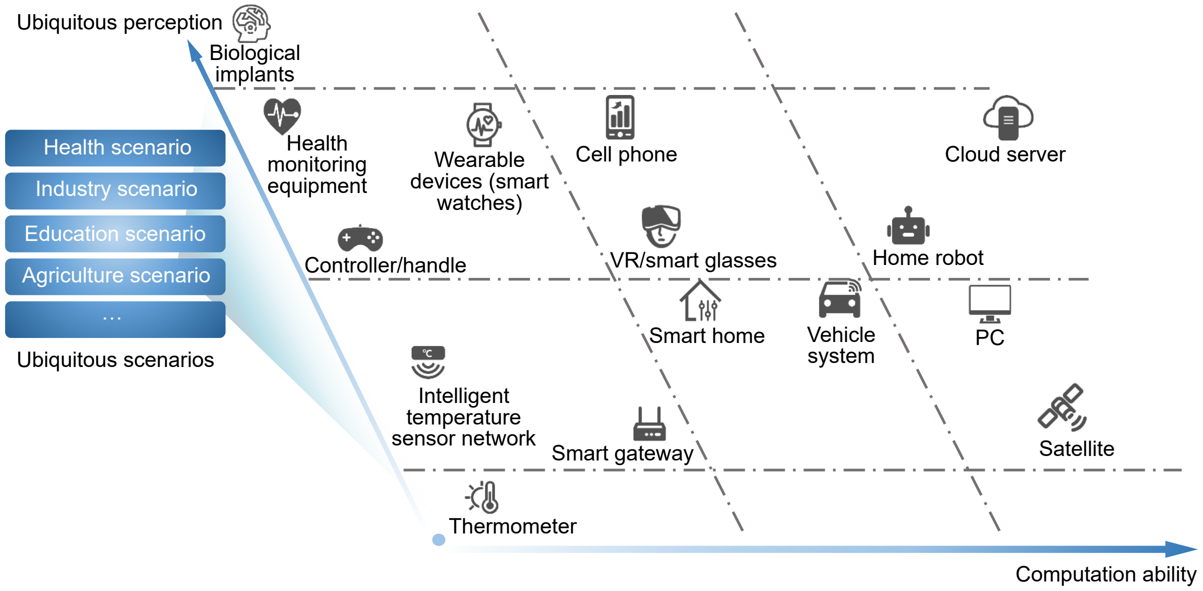

Fig. 2 Ubiquitous resources in UbiMeta.

effectively manage computer software and hardware resources within an operating system. It enhances the ability and level of the operating system to serve users. Virtualization involves transforming, simulating, and integrating resources. It can convert a physical resource into multiple logical counterparts or combine multiple physical resources into a single logical counterpart. This creates the illusion of multiple exclusive resources that do not require sharing or virtual resources that are easy to use and exceed the actual number of physical resources. The goal is to enable multiple users to share a set of physical resources.

Virtualization technology can be applied to external devices, which are in high demand in the metaverse where many applications are not oriented towards specific physical memory but rely on memory virtualization, which is mapped to physical memory. Additionally, virtualization technology can be used for file systems, allowing the operating system to support multiple specific file systems simultaneously under the control of a virtual file system.

3.1.2 Ubiquitous resource abstraction

The primary objective of resource virtualization is to enhance the efficiency of physical resource utilization. On the other hand, resource abstraction is employed to address system complexity and improve resource usability. Resource abstraction involves creating software that shields the physical characteristics and implementation details of hardware resources. It simplifies the operation, control, and utilization of hardware resources. The software encapsulates the implementation details internally and provides application interfaces externally. The aim is to make abstraction as simple as possible. Well-designed abstraction not only facilitates user understanding and utilization but also provides robust support for low-level hardware usage.

Abstraction techniques can also be utilized to define and construct multiple layers of software abstraction. Each layer hides the implementation details of the subsequent layer, resulting in a multi-level resource abstraction. Data Input/Output (I/O) also relies on multiple layers of abstraction.

3.1.3 Ubiquitous resource reuse

Physical resources are inherently valuable and limited in supply. To address this limitation, the UbiMeta operating system facilitates the reuse of resources, allowing multiple processes to share and utilize them efficiently. This concept of resource reuse is crucial in the metaverse, where the demand for resources is constantly increasing. By enabling resource reuse, UbiMeta enables the creation of virtual resources and virtual machines to mitigate the scarcity of physical resources. This approach optimizes resource allocation and utilization, ensuring that available resources are effectively shared among different processes and applications within the metaverse. Through resource reuse, UbiMeta maximizes the efficiency and productivity of the metaverse ecosystem. It minimizes resource wastage and enables the creation of virtual environments that can effectively address the limitations of physical resources. This not only enhances the overall performance of the metaverse but also promotes sustainability by reducing the need for excessive resource consumption.

There are two fundamental approaches to sharing physical resources: time-division and space-division multiplexing sharing.

Time-division multiplexing sharing: As the name implies, time-division multiplexing involves dividing resources based on time. Resources are divided into smaller units for processes to use sequentially.

Space-division multiplexing sharing: As the name suggests, space-division multiplexing involves dividing resources based on space. This means that resources can be divided into smaller units for different processes to utilize simultaneously.

In comparison to virtualization, multiplexing divides the actual physical computer resources, while virtualization creates imaginary virtual homogeneous resources. Virtualization technology not only resolves the issue of insufficient physical resources, but also provides applications with user-friendly virtual resources, creating an enhanced operating environment.

3.2 Autonomous information mastery layer

The AIML in UbiMeta encompasses a range of management activities supported by information technologies that plan, organize, store, retrieve, transmit, apply, and protect data. It plays a crucial role in bridging the gap between the real world and the metaverse by enabling independent management and control of personal data. Due to the significant data privacy concerns associated with the metaverse, its widespread deployment can be hindered[25]. To address this issue, AIML is structured hierarchically to ensure the privacy-protected perception and storage of personal data. This section introduces the personal information perception methods employed in UbiMeta and the privacy constraints implemented to safeguard this data.

3.2.1 Ubiquitous information perception

In addition to fulfilling the operational and management functions of the operating system, UbiMeta surpasses expectations by providing flexible and diverse resource virtualization, abstraction, and reuse. To comprehensively achieve ubiquitous perception for humans, cyberspace, and the environment, AIML adopts various perceiving techniques.

To perceive human-centric information, AIML leverages abilities from human-computer interaction techniques:

Gesture interaction technology encompasses various techniques, including gesture recognition and gesture tracking, that enable users to control computer interactions using hand movements. This intuitive approach allows users to operate the metaverse and effectively manage and control information.

Speech interaction technology involves interacting through voice, which includes speech recognition and speech synthesis. These technologies utilize machine learning algorithms to accurately convert speech to text and generate natural-sounding speech. By leveraging this technology, users can manage and control information more intuitively, enabling functions such as voice assistants and natural voice dialogue. Users can issue commands to devices using their voice, and through consistent speech interaction, they can conveniently and efficiently manage information, perform searches, and input text using speech.

Visual interaction technology encompasses various forms of interaction using images and videos. This includes technologies such as face recognition and image recognition. Through visual interaction, users can engage with machines using cameras or other visual input devices. This enables the realization of functions such as face recognition, access control, image recognition, and intelligent security.

Eye tracking technology involves interaction through eye movements, including eye tracking and gaze tracking. This technology allows users to conveniently control the computer and perform functions such as controlling the cursor using their gaze. Furthermore, eye tracking serves as an alternative method for individuals with disabilities to connect to the metaverse, enabling them to engage in various activities and interactions.

Electroencephalogram (EEG) interface involves interaction through EEG signals, providing a method to sense human brain states within the metaverse. Advanced algorithms can extract information from brain waves, enabling actions such as typing and other cognitive tasks.

In terms of cyberspace-centric information perception, UbiMeta leverages advanced algorithms and technologies to process and analyze vast amounts of data from cyberspace. This includes techniques such as searching through web interfaces, web crawlers, or existing knowledge graphs. By harnessing these capabilities, UbiMeta can extract valuable insights, patterns, and knowledge from the digital realm, enabling intelligent decision-making and enhancing the overall user experience within the metaverse.

Furthermore, UbiMeta incorporates environmental perception to capture and understand the physical surroundings. This involves utilizing sensors, IoT devices, and environmental monitoring systems to collect data on temperature, humidity, light, sound, and other environmental factors. By integrating this information into the AIML, UbiMeta can adapt and respond to the physical environment, creating a more immersive and context-aware metaverse experience.

3.2.2 Secure storage of personal information

The perception of personal information in the metaverse gives rise to a significant amount of sensitive personal data[26]. Ensuring the security of data storage, implementing robust authentication and access control measures, and maintaining consistent monitoring and auditing of data are fundamental issues that require careful consideration.

Security data storage: This component is specifically designed to address the fundamental issue of ensuring the secure storage of personal data in the metaverse. It implements robust measures to protect the confidentiality, integrity, and availability of the stored data. To achieve secure data storage, encryption techniques are employed in conjunction with blockchain technology. Personal information is encrypted prior to storage, guaranteeing that even in the event of unauthorized access, the data remain unreadable and unusable. Furthermore, strong encryption algorithms and blockchain practices are implemented to further enhance the security of the stored data.

Authentication and access control: Furthermore, access control mechanisms are put in place to restrict unauthorized access to the stored data. This involves implementing authentication protocols to verify the identity of users and granting access privileges based on predefined roles and permissions[27,28]. By enforcing strict access control measures, the risk of unauthorized individuals gaining access to sensitive personal data is significantly reduced.

Monitoring and auditing: To ensure the ongoing security of the stored data, consistent monitoring and auditing practices are implemented. This includes regularly monitoring access logs, detecting any suspicious activities, and conducting periodic audits to identify and address potential vulnerabilities or breaches. By maintaining a proactive approach to monitoring and auditing, any security incidents can be promptly identified and mitigated.

In conclusion, secure storage plays a crucial role in addressing the fundamental issues surrounding the secure storage of personal data in the metaverse. By implementing encryption, robust authentication and access control measures, and consistent monitoring and auditing practices, the security of personal information can be effectively safeguarded.

3.2.3 Information privacy protection

Finally, UbiMeta provides privacy protection methods for the later information exchange or processing since intermediate features can still be vulnerable to attacks[29]. To address this vulnerability, UbiMeta incorporates the use of Multi-Party Computation (MPC)[30], Homomorphic Encryption (HE)[31], and Differential Privacy (DP)[32] techniques.

MPC enables each participant in the metaverse to retain control over their personal information during usage. HE allows for computations to be performed on encrypted data without the need for decryption, thereby ensuring the security of sensitive information throughout the entire process. DP provides a mathematical framework for quantifying and managing privacy risks, ensuring that individual data points cannot be distinguished in the aggregated results.

By integrating MPC, HE, and DP, UbiMeta establishes a secure framework for data utilization in the metaverse. This framework imposes stringent requirements on downstream applications, guaranteeing the protection of personal information throughout the data utilization process. Figure 3 illustrates the data flow within the URML, AIML, and the following GIML. Participants can select the most suitable privacy technique based on the compatibility between the method and the downstream metaverse applications.

3.3 General intelligence mechanism layer

The GIML in UbiMeta plays a crucial role in providing artificial intelligence capabilities for downstream metaverse applications. Following the federated computing paradigm, GIML processes information using large-scale pre-trained deep-learning feature extractors. These extractors have demonstrated successful applications across various data modalities, including text[34], images[35], and sensor data[36]. Furthermore, some preliminary work[37] explore to adopt large-scale models for interaction and content generation within the metaverse.

UbiMeta incorporates a platform that supports secure data utilization through Federated Learning (FL)[38,39] techniques. FL serves as the foundation for enabling the interaction of features from different metaverse users' downstream models without compromising the privacy of raw data[40]. This ensures that sensitive information remains protected while still allowing for collaborative model training.

3.3.1 Federated hetero-capability computing

One key aspect of UbiMeta's FL implementation is the consideration of the heterogeneity of computational capabilities in metaverse devices. Different devices may have varying processing power and storage capacities[10]. UbiMeta addresses this challenge by providing a resource-constrained large-scale federated computing paradigm[41,42]. This paradigm ensures that the FL process is optimized for devices with limited resources, allowing for efficient model training and inference across a diverse range of devices.

3.3.2 Federated hetero-modality computing

UbiMeta further considers the modality heterogeneous issue among participants. While metaverse devices exhibit significant overlap in their sensing and interactive mechanisms, they also incorporate non-standardized sensing methods to optimize user experiences and cater to specific application scenarios.

The data captured by these non-standardized devices require some dedicated model structure for multimodal fusion. UbiMeta leverages the correlation-adaptive federated multimodal computing technique, enabling the aggregation of features extracted from different modalities across multiple devices. This allows for the creation of comprehensive and context-aware models that can effectively process and understand multi-modal input data.

3.3.3 Federated hetero-functionality computing

The downstream applications of UbiMeta involve the collaborative training of models for different perception and interaction tasks within the metaverse. Immersed in different scenarios, different users may have different tasks and objectives, and their model requirements are ever-changing. The aforementioned large-scale federated computing paradigm processes the ability to share the federated backbone among different tasks and facilitates the collaborative training of models for heterogeneous functionality within the metaverse.

This approach, known as federated hetero-functionality computing, enables users immersed in various scenarios to have different tasks and objectives, with their model requirements constantly evolving. By adopting federated hetero-functionality computing, UbiMeta promotes a collaborative and dynamic environment within the metaverse. Users can benefit from the collective knowledge and expertise of others, enhancing the accuracy and efficiency of their models.

3.4 Metaverse ecological model layer

UbiMeta contributes to the thriving metaverse ecosystem by employing a diverse range of models, each designed to serve a specific purpose and provide unique functionalities. These models are instrumental in enhancing the overall metaverse experience and enabling a wide variety of downstream applications. One notable example is the utilization of large language models to

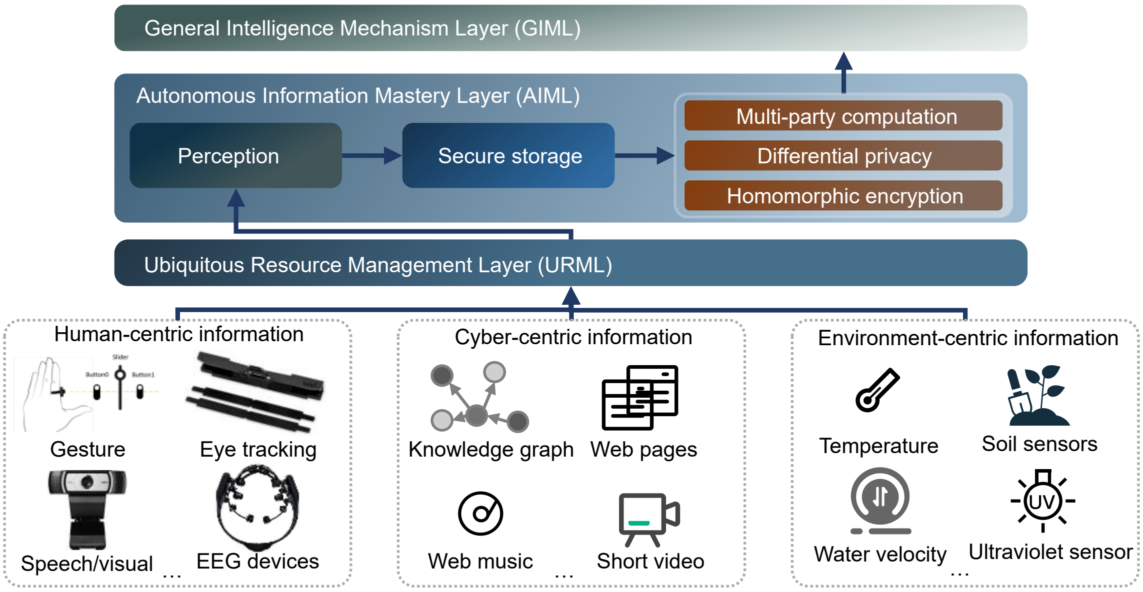

Fig. 3 Detailed data flow within URML, AIML, and GIML. The lower part showcases external devices that are responsible for collecting personal information. Specifically, the gesture interaction device utilized in this context is sourced from Ref. [33]. The URML facilitates a universal access interface for all connected devices, ensuring seamless connectivity. Furthermore, the GIML possesses the capability to process the data while adhering to the restrictions imposed by federated learning.

facilitate interactions between non-player characters and metaverse users. These models leverage techniques from the previously mentioned AIML. They are capable of recognizing user speech, processing it using advanced language models, and synthesizing speech for playback to the user. This enables more immersive and realistic interactions within the metaverse environment.

3.4.1 MaaS

MaaS revolutionizes the metaverse ecosystem by offering users the convenience of leveraging pre-trained models and algorithms without the need for extensive development or training. UbiMeta embraces the MaaS approach, providing a diverse range of pre-built models tailored to various metaverse applications. These models encompass a wide array of functionalities, including object recognition, natural language processing, sentiment analysis, and recommendation systems, among others. Through UbiMeta, users can effortlessly access and utilize these models, significantly reducing the time and effort required for model development.

The adoption of MaaS not only expedites the development process, but also fosters collaboration and innovation within the metaverse community. Developers can utilize existing models as foundational building blocks to create novel and distinctive applications, thereby nurturing a dynamic and rapidly evolving metaverse ecosystem. Moreover, the MaaS principle ensures scalability and flexibility in the metaverse environment. As the user base and demand for metaverse applications continue to grow, UbiMeta seamlessly scales its model infrastructure to accommodate the increasing workload. This scalability guarantees a seamless and uninterrupted user experience, even during peak usage periods.

3.4.2 OODA-based model management

The MEML focuses on incorporating metaverse features into models. Guided by the principles of OODA loop[43,44], MEML encompasses a comprehensive range of functionalities and capabilities. One key aspect of MEML is its OODA-based model management approach. While previous work has explored the combination of OODA with abstract metaverse design[45], UbiMeta presents a detailed alignment between models supporting metaverse application with the OODA loop. MEML leverages the four OODA stages to effectively manage and optimize metaverse models:

In the Observation stage, MEML collects and analyzes data from various media in AIML within the metaverse environment. These data include user interactions, environmental conditions, and other relevant information. By gathering and analyzing these data, MEML obtains valuable insights into the current state of the metaverse and identifies potential areas for improvement. This stage typically involves the utilization of specific models, such as recognition models, segmentation models, and classification models.

In the Orientation stage, MEML engages in the processing and interpretation of the collected data to develop a comprehensive understanding of the metaverse ecosystem. The utilization of multimodal data collected by AIML is essential in this stage, as it enables the integration of multiple sensory inputs to effectively perceive human thoughts. For example, accurately perceiving a user’s sentiment requires the consideration of both speech and facial expressions. The inclusion of additional physiological signals, such as EEG signals and skin temperature, can further enhance the robustness of this perception. By orienting itself to the current situation, MEML is able to make well-informed decisions and take appropriate actions.

In the Decision stage, MEML leverages the insights obtained from the Observation and Orientation stages to drive data-informed decision-making. These decisions encompass various aspects, such as optimizing model performance, adjusting parameters, or deploying new models to cater to specific requirements within the metaverse. MEML places great emphasis on making timely decisions to uphold the efficiency and effectiveness of the metaverse ecosystem. To facilitate accurate predictions and determine the most appropriate course of action, the decision stage often incorporates the utilization of forecasting models, recommendation models, and reinforcement models. Forecasting and recommendation models rely on historical data and statistical techniques to forecast future trends and patterns within the metaverse ecosystem. By leveraging these models, MEML can anticipate changes and proactively make decisions to optimize performance and address potential challenges. On the other hand, reinforcement models employ reinforcement learning algorithms to learn from past experiences and interactions within the metaverse. These models enable MEML to dynamically adjust parameters and policies based on feedback and rewards, ensuring continuous improvement and adaptation to evolving user needs.

Finally, in the Action stage, MEML carries out the decisions formulated in the preceding stages. This involves the implementation of updates to models, retraining algorithms, and deploying new features to enhance the overall metaverse experience. By swiftly and effectively taking action, MEML ensures that the metaverse ecosystem remains dynamic and responsive to the evolving needs of its users. The implementation process in the action stage incorporates human-in-the-loop techniques, which involve further updating existing models based on the insights gained from the Decision stage. This iterative approach allows MEML to incorporate user feedback and refine model performance accordingly. By actively involving users in the improvement process, MEML can better align its offerings with their preferences and requirements.

Overall, MEML’s OODA-based model management approach enables efficient and effective utilization of metaverse models. By continuously observing, orienting, deciding, and taking action, MEML optimizes the performance and functionality of models within the metaverse ecosystem. This approach ensures that the metaverse experience remains immersive, interactive, and adaptable to evolving user demands.

4 Application Scenario of UbiMeta

The UbiMeta model, consisting of the URML, AIML, and MEML layers, offers the potential to construct a wide range of application scenarios across different fields. Each layer plays a unique role in enhancing user experiences and driving innovation.

4.1 UbiMeta for medical health

UbiMeta holds immense potential for transforming the field of medical health within the metaverse. One application scenario is the virtual doctor-patient consultation. With UbiMeta, patients can interact with healthcare professionals in a virtual environment, eliminating the need for physical visits. Through speech interaction and visual interaction technologies, patients can communicate their symptoms and medical history to doctors, who can then provide diagnoses and treatment recommendations. This virtual consultation not only saves time and resources, but also enables patients to receive timely medical advice from the comfort of their homes.

Furthermore, UbiMeta can facilitate remote patient monitoring and telemedicine. By integrating environmental perception and IoT-based medical devices, UbiMeta can collect real-time data on patients’ vital signs, such as heart rate, blood pressure, and oxygen levels. These data can be analyzed using advanced algorithms within the AIML layer to detect anomalies and provide early warnings for potential health issues. Healthcare professionals can remotely monitor patients’ conditions and provide timely interventions, reducing the need for hospital visits and improving overall patient care.

4.2 UbiMeta for industrial practice

By leveraging the capabilities of UbiMeta, industries can create virtual simulations and models for training purposes, allowing employees to gain practical experience in a safe and controlled environment. This is particularly valuable in high-risk industries, such as manufacturing or construction, where hands-on training is essential.

While collaborative model training across corporations can yield the best model performance, one of the major concerns is the security of raw data. The use of federated learning in AIML restrictions and differential privacy techniques ensures that only the collaborated model needs to be shared, rather than the raw data itself. This ensures the protection of sensitive and confidential data while still benefiting from the collective knowledge and insights gained within the metaverse.

4.3 UbiMeta for education

UbiMeta has immense potential in the field of education, revolutionizing traditional teaching methods and creating immersive learning experiences. With UbiMeta, educators can create virtual classrooms and interactive learning environments, enabling students to engage with educational content more dynamically and interactively.

MEML, in conjunction with the MaaS approach, can provide various teaching models. Moreover, feedback from students is crucial in selecting or adapting the most suitable model. The OODA loop in MEML enhances the teaching process by allowing continuous observation, orientation, decision-making, and action-taking to optimize the learning experience.

4.4 UbiMeta for agriculture

UbiMeta holds great promise for transforming the agricultural industry by improving productivity, sustainability, and resource management. One application scenario is precision farming. UbiMeta can integrate environmental perception and IoT devices to collect data on soil moisture, temperature, and nutrient levels. By analyzing these data using advanced algorithms within the AIML layer, UbiMeta can provide farmers with real-time insights and recommendations for optimizing irrigation, fertilization, and crop management. This precision approach minimizes resource wastage, reduces environmental impact, and maximizes crop yields.

Furthermore, considering the high-level abstraction of URML, UbiMeta can facilitate farm automation and robotics. By integrating gesture interaction and visual interaction technologies, UbiMeta enables farmers to remotely control and monitor agricultural machinery and robots. This enhances operational efficiency, reduces labor requirements, and improves overall farm productivity.

5 Conclusion

This paper delves into the convergence of virtual and real worlds and presents the UbiMeta model, a specialized ubiquitous operating system designed specifically for the metaverse. UbiMeta extends the capabilities of the UOS and focuses on adapting business models and operational capacity to effectively function within the metaverse. It comprises four layers: the URML, the AIML, the GIML, and the MEML.

The paper provides a detailed design for each layer and explores the application scenarios of UbiMeta in specific metaverse domains such as entertainment, industrial, and education. It demonstrates that UbiMeta has the potential to enhance human engagement within the metaverse environment. This paper aims to generate greater interest in metaverse operating systems, particularly in the advancements offered by UbiMeta.

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