

# Immersive Computing: Vision, Infrastructure, and Use Cases

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**Abstract**—Immersive computing signifies a paradigm shift in how people interact with digital content and their surrounding 3D environments. In this vision paper, we first outline a comprehensive roadmap for advancing immersive computing, encompassing virtual, augmented, and mixed reality, which are often collectively referred to as extended reality, and immersive content delivery, including 360-degree panoramic video streaming and volumetric video streaming, by identifying key challenges and opportunities. We then describe CoMIC, a research infrastructure that offers a collaborative, visual-first, and hologram-based computing space and a quality-driven, multi-site, and immersive communication framework for collaborative mobile immersive computing. Given the interdisciplinary nature of immersive computing, we present several key use cases that could be enabled by CoMIC. We conclude this paper by envisioning a future where our digital experiences will transcend the boundaries of screens and devices, immersing us in a world where the virtual and physical seamlessly merge.

## I. INTRODUCTION

In the dynamically shifting terrain of technology, few frontiers hold as much promise, intrigue, and fascination as immersive computing [18]. In this emerging era of computing, we find ourselves at the crossroads of the digital and physical realms, where human experience, technology, and imagination converge to reshape the essence of our engagements with the digital world, where the lines separating the digital and physical worlds become increasingly indistinct, and where human experiences go beyond the confines of screens and devices. Represented by spatial computing [45], immersive content delivery [19], [38], and virtual, augmented, and mixed reality (VR/AR/MR), which is often collectively referred to as extended reality (XR), immersive computing is a transformative domain deemed to reshape how we perceive, interact with, and harness the power of digital information. These technologies are more than mere tools that amplify human capabilities, elevate human experiences, and increase understanding of human abilities; they serve as gateways that push the boundaries of human potential.

The metaverse, a concept from science fiction, now looms on the horizon of our digital future, which is empowered by various immersive technologies, 5G and beyond, machine learning, blockchain, and others [32]. It manifests as a vast, interconnected, and enduring virtual cosmos – an evolution of the Internet from which it springs [6]. It introduces us to a world where our senses,

emotions, and creativity are animated with unprecedented fidelity and where information is not restricted to 2D screens but envelops us in 3D magnificence so that we engage with digital content as naturally as we do with our physical surroundings. In the metaverse, we explore expansive digital landscapes, connect with individuals worldwide, and craft our unique narratives [7].

The potential of immersive computing transcends far beyond entertainment, encompassing a wide array of domains that span healthcare, education/training, design, communication, and more. It heralds an era where medical training becomes lifelike and risk-free, students embark on immersive educational odysseys, architects sculpt digital designs in 3D space, remote collaboration feels as organic as sitting across a table, and storytelling embraces an entirely new dimension.

This vision paper is a voyage into the heart of immersive computing, a journey that pledges to unveil the intricacies and opportunities of this transformative paradigm. In this exploration, we will delve into the technical challenges faced by advancing immersive computing, such as high bandwidth and low latency networks, high-fidelity visual content, high computation demands, spatial sharing and synchronization, and security, privacy, and harassment issues, and discuss potential opportunities associated with these challenges (Section II). We next present CoMIC, a research infrastructure that aims to facilitate the community to overcome the technical challenges of immersive computing and foster collaborations, especially for multi-user XR applications (Section III). We then describe several representative use cases of immersive computing that can be enabled by CoMIC, including immersive data visualization and analytics for solar and heliospheric physics, immersive simulated field training for tactical population, and mmWave-5G-enabled and XR-assisted health informatics (Section IV). We offer at the end our vision of the future of immersive computing (Section V).

As we embark on this expedition, we invite the readers to join us in reimagining the future where the physical and digital worlds harmoniously coexist, infusing our interactions with technology with profound depth and richness. Collectively, we will navigate the uncharted waters of this emerging computing paradigm, endeavoring not only to grasp its intricacies but also to envision a world where technology enhances our humanity, strengthens our connections, and enriches our lives in unprecedented ways.

## II. KEY CHALLENGES AND OPPORTUNITIES

**High Bandwidth and Low Latency Networks.** Delivering immersive content such as 360-degree videos and volumetric videos to users requires more network bandwidth than traditional video content [27], [50], [55] and low latency to improve, for example, the accuracy of motion prediction [48], which is essential to enable viewport [38] and visibility [19] adaptation. Millimeter wave (mmWave) 5G networks have emerged as a promising solution to establish high-throughput and low-latency wireless connectivity at the edge, facilitating immersive content delivery. Nonetheless, mmWave presents a directional transmission challenge due to its high attenuation. When delivering immersive content over mmWave, the 6DoF motions of users necessitate continual adjustment of the transmission beams between the access point (AP) and the client (*e.g.*, XR headset). Furthermore, the line-of-sight (LoS) path from the AP to the client can be obstructed by users' movements (such as hand or head gestures) or by other users moving around, leading to an increased need for beam searching to maintain a robust signal-to-noise ratio (SNR). This requires additional mechanisms to select reflected paths, ensuring reliable data delivery. However, the default beamforming in 802.11ad/ay and 5G NR (new radio) networks introduces substantial overhead in handling mobility and obstructions, leading to a degraded quality of experience (QoE) for immersive content delivery. This degradation may manifest as impaired visual quality or extended rebuffering times.

One possible solution is to create a flexible, cross-layer programmable mmWave edge network capable of seamlessly incorporating user and environmental attributes that are unique to immersive content. This integration will be achieved through real-time MAC/PHY reconfigurability in the lower layers of wireless control. More precisely, one can design interfaces capable of providing user-related information such as 6DoF motion and spatial maps (indicating the presence of ambient reflectors) for precise control of mmWave MAC/PHY parameters. Leveraging user behavior and predicted 6DoF motion during immersive content consumption will enable efficient beam adaptation and switching with minimal search overhead. Likewise, the spatial maps can be utilized to identify ambient reflectors that can maintain mmWave connectivity even in the presence of obstructions

**High-fidelity Visual Content.** A significant challenge in VR is delivering high-quality 3D content consistently at a high frame rate, which demands substantial computational power. Achieving this locally on VR headsets requires high-performance GPUs, a feature often absent in untethered headsets such as Oculus Quest 2, primarily due to their compact design. Integrating heavier components into a headset can lead to negative outcomes, including motion sickness and a suboptimal user experience, especially during prolonged usage. To tackle these issues, modern VR

systems have shifted from rendering all virtual content directly on the headsets to a more efficient method known as remote rendering [46]. In remote rendering, content processing is outsourced to a server. Once the content is rendered, the server transmits the encoded video frames back to the VR headsets for display.

In our initial investigation of multi-user VR applications, which included well-known social VR platforms such as AltspaceVR, Horizon Worlds, Mozilla Hubs, Rec Room, and VRChat, we identified a common practice: these platforms typically handle the rendering of virtual content, such as user avatars, locally [7]. While local rendering is effective for single-user scenarios, it presents scalability challenges when platform servers need to continuously transmit updated avatar data (*e.g.*, user movements) to multiple users. This is because the required bandwidth increases nearly linearly with the number of users. One possible solution to address these challenges is to explore and enhance the remote content rendering process, for example, by investigating collaborative prediction of 6DoF motion of multiple users, which may exhibit correlations. One can also employ techniques such as image-based rendering [40] and neural radiance fields (NeRF) [29] to synthesize the view for a particular user by leveraging similar views from nearby users, rather than initiating the rendering process from scratch.

**High Computation Demands.** Computer vision (CV) algorithms such as object classification and recognition are becoming the key building block of immersive technologies such as AR and MR [52]. These algorithms are computationally demanding and can introduce noticeable latency when executed on mobile devices, particularly as they often involve deep learning (DL). Consequently, a promising solution to address this latency issue in mobile AR/MR is edge offloading. However, the edge, while advantageous for its proximity to end-users, faces resource constraints when compared to centralized cloud infrastructure. These constraints primarily revolve around limitations in computing and network resources, driven by economic considerations. Thus, scalability concerns, such as prolonged end-to-end latency, may emerge, particularly when multiple users simultaneously offload compute-intensive tasks to the edge.

One way to address the scalability of multi-user AR is to leverage the observation that nearby users may have overlapped views to augment (*e.g.*, they may share some common interests when playing together a multi-user AR game [54]). Hence, there is potential to opportunistically share the outcomes of offloaded AR tasks among users and utilize on-device computing resources to alleviate the burden on the edge. This can be achieved by implementing a collaborative local cache to intelligently reuse these results [53]. Moreover, one can develop a GPU scheduler to orchestrate CV/DL tasks of various users, aiming to minimize end-to-end latency and enhance the QoE for XR.

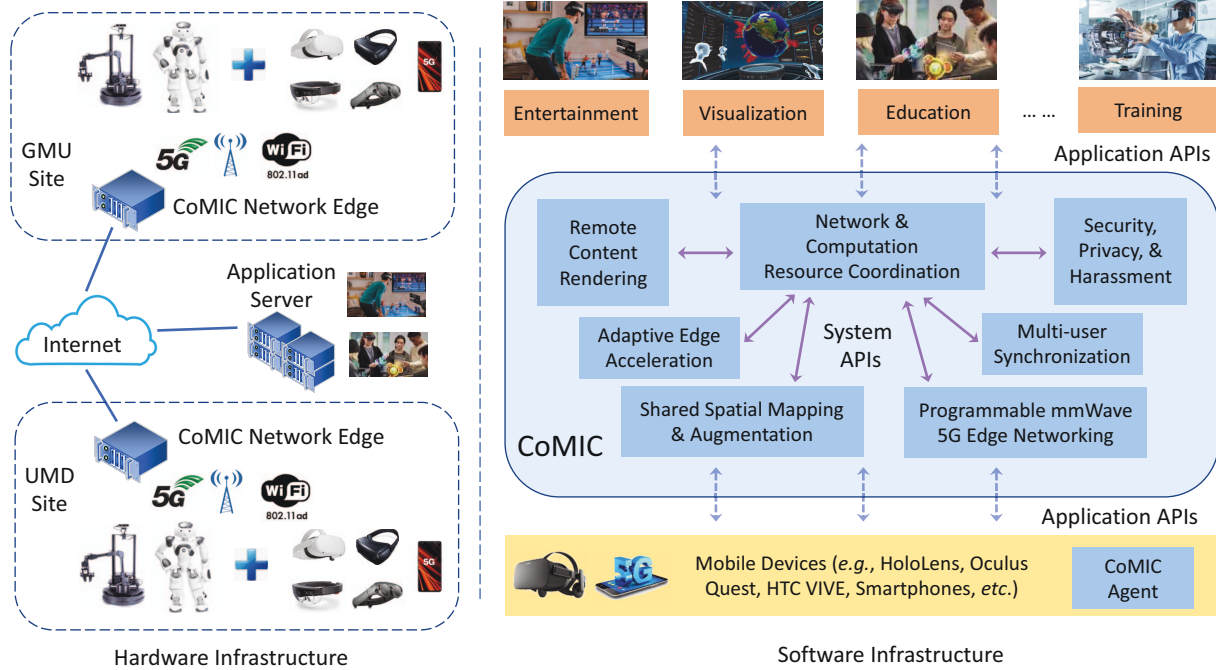


Figure 1: The system architecture of CoMIC [20].

**Spatial Sharing and Synchronization.** When multiple users collaborate simultaneously within a shared AR/MR environment, they can view and interact with shared virtual objects. However, the actual physical environments at different user sites may differ in terms of room and furniture arrangements. Consequently, a simplistic, direct approach of placing virtual objects in front of users could lead to issues such as occlusion by real-world furniture or walls. To address these challenges, one can take into account both the geometric aspects and the semantic characteristics of users' real-world surroundings when enhancing the shared environment with virtual objects. For example, one can calculate a collaborative space devoid of obstacles for multiple users by assessing the unoccupied areas in each user's vicinity. Within this shared space, virtual objects such as a virtual car can be displayed and manipulated without causing occlusion or collisions with obstacles for any user. Moreover, if we can access the geometrical and semantic data of objects within a user's environment using computer vision methods (such as plane detection and object recognition) on RGB-D data collected by XR headsets (*e.g.*, Microsoft HoloLens), we can utilize this information to intelligently position virtual objects in a contextually appropriate manner. This enhancement would ultimately elevate the quality of the user's immersive experience.

In order to facilitate user collaboration, precise synchronization of 6DoF device poses is imperative in multi-user XR. Without this synchronization, users may en-

counter situations where they perceive the same shared virtual object at different locations and orientations, significantly diminishing their experience. In single-user scenarios, widely-used AR frameworks such as Google ARCore<sup>1</sup> and Apple ARKit<sup>2</sup> offer standardized interfaces for accessing the 6DoF pose of mobile devices. However, the acquired 6DoF pose cannot be directly employed in multi-user XR, as it is inherently tied to the device's pose at the initiation of the AR experience. To tackle this issue, one can develop an edge-assisted approach aimed at achieving rapid and resource-efficient multi-user synchronization, which may enhance accuracy while minimizing computational and communication overhead by, for example, capitalizing on multi-user SLAM (simultaneous localization and mapping) and offloading the computationally intensive global map construction to the edge [47].

**Security, Privacy, & Harassment.** Similar to any other computing paradigm, immersive computing faces a range of security and privacy threats as well as safety concerns. For instance, there is a risk of identity theft through compromised VR glasses. The metaverse introduces novel challenges, including the need to defend against immersive attacks [4], such as disorientation attacks that could lead to collisions with physical objects and motion sickness. Health-related applications should protect patient privacy,

<sup>1</sup><https://developers.google.com/ar> (accessed on 20-September-2023)

<sup>2</sup><https://developer.apple.com/augmented-reality> (accessed on 20-September-2023)

safeguard data integrity, and follow legal and ethical norms, as indicated by HIPAA (Health Insurance Portability and Accountability Act) compliance. Even more concerning, recent reports have highlighted incidents of harassment, including cases of sexual assault, taking place on social VR platforms.

These incidents and responses underscore the need for multi-user XR to provide not only the security and privacy protections expected in traditional digital environments but also more thoughtful defense and safety features akin to those found in the physical world. Along with the challenges, there are plenty of opportunities to make the metaverse secure and safe. For example, one can develop a privacy-preserving, adaptive, and continuous authentication system, which will utilize a zero-trust framework based on federated learning to authenticate users via their multimodal biometric data [5]. One can also investigate security and privacy-related policies and construct an all-encompassing framework for detecting and preventing harassment, which will include features such as early alert systems, automated activation of personal spaces, and automatic reporting of misconduct, among others.

**Other Challenges.** Due to the space limit, we will not delve into other challenges of immersive computing in this paper, including hardware advancements (immersive computing requires powerful, affordable, and energy-efficient devices, such as headsets, haptic feedback systems, and sensors), content creation (*e.g.*, exploring automated content generation, 3D modeling techniques, and AI-driven tools for content creators), and accessibility (*i.e.*, ensuring accessibility for all individuals, including those with disabilities by leveraging inclusive design, personalized design, assistive technologies, and usability studies), *etc.*

We emphasize that a common obstacle in the above challenges is to build efficient AI-driven models, for example, for multi-user 6DoF motion prediction, neural-based content rendering, accurate object recognition and tracking, and harassment detection and prevention.

### III. THE CoMIC RESEARCH INFRASTRUCTURE

CoMIC tackles the aforementioned critical issues and establishes the essential framework necessary to bring the ambitious vision of the Metaverse into reality. It is dedicated to enabling a *collaborative, visual-first, and hologram-based* computing environment while also designing *QoE-driven, multi-site, and immersive* communication system. CoMIC incorporates numerous vital functionalities for conducting research in multi-user XR.

#### A. Software

As illustrated in Figure 1, CoMIC operates on edge servers, which can be deployed for individual sites or shared among neighboring sites. The CoMIC software comprises six essential building blocks designed for multi-user XR.

(1) *Programmable mmWave CoMIC 5G Edge Networking.* CoMIC creates a flexible mmWave 5G edge networking

framework that facilitates adaptable, cross-layer, and robust interfaces to deliver high-speed, low-latency, and immersive content to multiple users through real-time PHY/MAC reconfiguration.

(2) *Adaptive Edge Acceleration.* CoMIC intelligently delegates compute-intensive XR tasks, such as semantic segmentation, to GPU-accelerated edge servers to reduce end-to-end latency and enhance QoE [52].

(3) *Multi-user Synchronization.* Due to its multi-user, multi-site nature, CoMIC harmonizes the interactions of users spread across different locations, ensuring synchronization with the presented holographic content and establishing a shared perspective during collaborations [53].

(4) *Remote Content Rendering.* To reduce the computational burden associated with rendering high-quality holographic content on mobile devices [1], CoMIC strives to pre-render content efficiently for multiple users on the edge server, guided by predicted 6DoF user motion.

(5) *Shared Spatial Mapping & Augmentation.* Through the exchange of spatial maps, CoMIC facilitates seamless collaborations among users, allowing virtual objects to be augmented at each user's location in a manner that respects collision avoidance by leveraging local scene geometry and semantics.

(6) *Security, Privacy, & Harassment.* CoMIC is committed to safeguarding users against security risks and upholding their privacy within the shared environment. It implements effective privacy-preserving authentication measures to secure users' digital assets and shield them from potential harassment.

In addition to the six components located on the edge server, the on-device CoMIC agent primarily handles the collection of real-time data, such as monitoring the 6DoF motion of users and configuring the wireless network interface when necessary.

#### B. Testbed

The CoMIC testbed will be equipped with a variety of XR devices, including smartphones and headsets such as Microsoft HoloLens 2, Magic Leap 2, Apple Vision Pro, Oculus Quest 3, and HTC VIVE. To enable remote access and replicate human actions for automated experiments, we will employ two types of robots mounted with XR devices. The NAO Power V6 Robot<sup>3</sup>, an autonomous humanoid robot, is programmable and widely used to simulate human movements such as walking, sitting, and standing. NAO can be wirelessly connected for program updates and offers a full SDK in Java, C++, Matlab, and Python. The LoCoBot<sup>4</sup>, on the other hand, is an affordable, open-source mobile manipulator that operates on Facebook AI's PyRobot, a user-friendly interface built on top of the robot operating system (ROS). It features the

<sup>3</sup><https://www.robotlab.com/store/nao-power-v6-educator-pack> (accessed on 20-September-2023)

<sup>4</sup><http://www.locobot.org> (accessed on 20-September-2023)

capable WidowX 200 Mobile Arm, boasting 5DoF, high torque, and enhanced durability.

We will outfit the testbed with two types of mmWave networks: 60 GHz 802.11ad/ay WiFi and 28 GHz 5G NR cellular networks. Our existing Mason-Milli testbed<sup>5</sup> already boasts an extensive array of 60 GHz software radios and 802.11ad commercial off-the-shelf (COTS) devices. To enhance the XR headsets' connectivity, we will integrate 802.11ad/ay chipsets equipped with multi-phased antenna arrays to facilitate mmWave communication with APs. We have developed the capability to reconfigure MAC/PHY on COTS 802.11ad devices, allowing us to modify beam configurations and extract PHY information, enabling comprehensive experiments and MAC/PHY reconfiguration on the mmWave WiFi testbed.

Regarding the 28 GHz spectrum, CoMIC will use the SiversIMA 28 GHz RF frontend<sup>6</sup> along with USRP X310s<sup>7</sup> and N310s<sup>8</sup> software radios, and full-stack 5G NR equipment<sup>9</sup>, which are compatible with commercial 5G networks but offer reconfigurability through relays. Commercial mmWave 5G NR-enabled smartphones will serve as XR devices in this context. We will create cross-layer APIs for software radios using GNURadio blocks and for 5G NR commodity devices using vendor-supplied interfaces integrated with Linux drivers.

### C. Tools and Datasets

CoMIC aims to substantially reduce the obstacles associated with developing multi-site, multi-user XR applications by providing an extensive set of tools and datasets.

(1) *Remote controller of XR devices and robots.* CoMIC enables users to remotely configure and manage a wide range of XR headsets, depending on the specific capabilities of each device. Certain XR headsets, such as the Oculus Quest 2, offer features that facilitate the testing of XR applications by automating predefined input playback<sup>10</sup>. We will enhance these features to support remote access to XR devices. Additionally, we will create tools for remote XR teleoperation of robots, allowing users to remotely control robots for tasks like object manipulation.

(2) *Remote controller of mmWave 5G networks.* CoMIC empowers users to remotely adjust PHY/MAC settings (e.g., mmWave transmit and receive beams), access link measurements (e.g., channel state information and signal-to-noise ratio), and manage userspace interfaces.

<sup>5</sup><http://www.phpathak.com/mason-milli.html> (accessed on 20-September-2023)

<sup>6</sup><https://www.sivers-semiconductors.com/sivers-wireless/evaluation-kits/evaluation-kit-evk02001> (accessed on 20-September-2023)

<sup>7</sup><https://www.ettus.com/all-products/x310-kit> (accessed on 20-September-2023)

<sup>8</sup><https://www.ettus.com/all-products/usrp-n310> (accessed on 20-September-2023)

<sup>9</sup><https://airfidenet.com/technology.php> (accessed on 20-September-2023)

<sup>10</sup><https://developer.oculus.com/documentation/unity/ts-autodriver> (accessed on 20-September-2023)

(3) *Testbed customizer.* We will develop tools that allow remote users to personalize the CoMIC infrastructure, such as substituting a component in our reference implementation with their own solutions.

(4) *Collectors of KPIs (key performance indicators).* CoMIC creates tools for gathering essential metrics from multi-user XR applications, including metrics related to communication overhead for synchronization and other QoE metrics relevant to multi-user AR.

(5) *Web portal for user requests and service provisioning.* This web portal will provide community users with the capability to submit requests for utilizing CoMIC sites, whether for remote access or in-person experiments.

Utilizing CoMIC as the foundation, we will support diverse applications, including XR-based training, healthcare, and data analytics, that offer multi-user XR experiences. Through these applications, we will generate innovative datasets that capture how multiple users interact while performing specific tasks. For instance, we can monitor the collaborative behaviors of users in a virtual workspace or their engagement with volumetric content presented in XR within a shared physical environment. The data collected will encompass details such as 6DoF body pose, 6DoF head pose, eye gaze, and more. This dataset will empower us to conduct more comprehensive analyses to gain insights into human collaboration, potentially enabling the training of generative models capable of emulating human collaborations, for applications such as synthesizing motions for human-robot cooperation.

Moreover, as CoMIC operates on edge servers with its agent integrated into XR devices, we will gather network traffic traces and resource utilization data from both the server side and client side. This data will encompass metrics such as CPU, GPU, and memory usage, providing valuable insights into multi-user XR environments.

## IV. POTENTIAL USE CASES

### A. Immersive Data Visualization & Analytics for Solar and Heliospheric Physics

**Background & Overview.** Immersive technologies offer exciting opportunities for scientific data visualization (e.g., visualizing astronomical data, high-dimensional statistical results, and geometrical structures), and enable collaborative analytics that investigate novel interactions and visualization methods for decision-making and analytical reasoning. Collaborative immersive analytics allows scientists, engineers, designers, and other professionals to simultaneously work with real-time data modeling, sharing, and visualization, raising possibilities for collaboration between various disciplines [11], [12], [25]. CoMIC facilitates the exploration of distributed, synchronous immersive analytics, offering an experience similar to face-to-face collaboration by addressing crucial technical challenges such as scalability (i.e., the number of collaborative sites) and network-friendly sharing of visualized data.

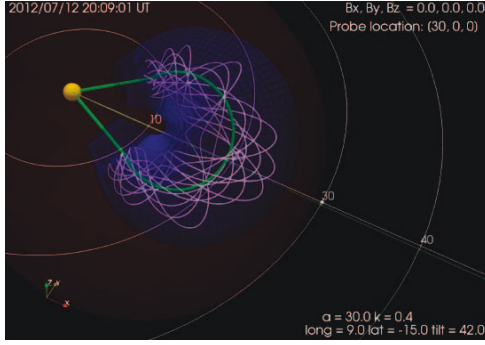


Figure 2: 3D model of a realistic CME observed by STEREO A/B and SOHO spacecraft. The yellow ball indicates the Sun. The CME is shown in a point cloud (blue color). Immersive computing helps us understand CMEs in a truly revealing way.

CoMIC can be utilized to enhance scientific research in the area of solar and heliospheric physics, which concerns the condition and activity of our Sun and its extended solar wind. A particular line of research to be focused on is how solar eruptions (*i.e.*, powerful solar flares, coronal mass ejections, and energetic particle storms) disturb our space environment and produce severe space weather that may wreak havoc on various high-stake technological systems, such as satellite operation, communication, navigation, and electric grids [51].

The merging of edge-assisted collaborative immersive analytics and solar/heliophysics research is timely and instructive, leading to potential new scientific discoveries. Among all space-related scientific programs (*e.g.*, planets, stars, nebulae, galaxies, and universe), the solar/heliophysics program is probably best positioned to be integrated with immersive data visualization and analytics for the following reason. In the last decade, the observations of our Sun have entered into a 3D/stereoscopic era (*i.e.*, multi-view observations of the Sun from the front, side, and even backside), enabled by spacecraft moving far into deep space (*e.g.*, STEREO-ahead and STEREO-behind [23], SDO [35], and SOHO [10]). Interpreting remote-sensing imaging data and in-situ sampling data from multiple viewpoints from a vast space is generally challenging. Immersive data visualization and analytics are invaluable in addressing this challenging issue through the unique nature of being truly 3D and interactive. We highlight the following two research directions that shall have an immediate impact on the research community in solar and heliospheric physics.

**Direction #1: Immersive Data Visualization & Analytics of Coronal Mass Ejections from Sun to Earth.** Coronal mass ejections (CMEs) are the most energetic eruptive phenomenon in our solar system and the main driver of severe space weather. Understanding its origin, evolution, and possibility of Earth-impact is one of the main goals in solar and heliospheric physics. A CME is intrinsically 3D in nature, containing a coherent

magnetic field in a twisted flux rope shape and a complex density structure made of electrons and protons [33]. The research objective is to determine the exact propagation direction and speed of a CME, its angular size, aspect ratio, tilt angle, and internal magnetic field, and how these parameters change with time (Figure 2) [21]. (1) Immersive data visualization and analytics allow one to analyze CME models in an XR setting, including simulating the viewpoints from actual spacecraft or envisioned spacecraft. This will provide a comprehensive and complete perception of the model in 3D, making the essential task of model validation straightforward. (2) Immersive data visualization and analytics enable the development of more realistic models. Given the sparsity of observational data, prevalent CME models, which consist of only a limited number of free parameters, are highly simplified or ideal. With the help of edge-assisted immersive computing, one could easily identify the differences between multiview observations and simplified models. Thus, the perception of differences will allow us to develop more sophisticated CME models. (3) The CME model analysis and development can significantly benefit from CoMIC by utilizing its computing power on the edge and the enabled real-time collaborations among scientists that are traditionally not accessible. Immersing multiple scientists at different geolocations in the same 3D scene allows efficient data sharing and full data exploration, stimulating scientific discussion.

**Direction #2: Immersive Data Visualization & Analytics of Local and Global Magnetic Field of the Sun.** While the methodology in the previous task is based on interpreting observational data from space-distributed spacecraft, another fundamental methodology of studying solar and heliospheric physics is to use advanced 3D numerical simulations, which are based on fundamental equations (*e.g.*, magnetohydrodynamic equations) combined with prescribed boundary and initial conditions [43]. Advanced 3D simulations generate the desired set of scientific parameters (*e.g.*, temperature, density, pressure, vector velocity field, and vector magnetic field) in every voxel on a 3D grid in the simulated volume with a high time cadence showing the evolution. Edge-assisted immersive computing is an ideal platform to analyze and visualize the simulation data in an interactive way. Since the data volume is huge, and data at each time and voxel contains multiple parameters, such interactions demand high throughput of mmWave 5G networks for data transmission from collaborative parties and the computing power at the edge to quickly render and update the 3D model in a real-time fashion. Thus, CoMIC is essential and ideal for studying the data generated by advanced numerical simulations of scientific systems.

*B. Immersive Simulated Field Training for Tactical Population*

**Background & Overview.** The COVID-19 pandemic has led to unprecedented reliance on online learning for not

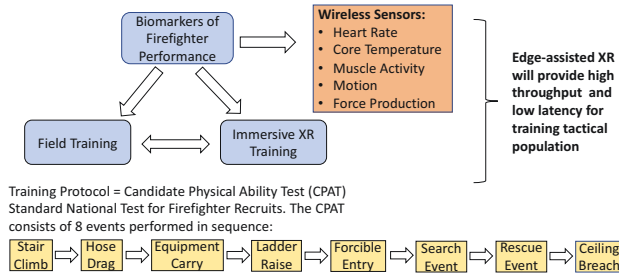


Figure 3: Comparing physiological demands of XR-based training to field training.

only students but also professionals. Hence, it is critical to transform the teaching/training and learning experience through immersive technologies and innovative educating, training, and mentoring practices in both formal settings including physical and virtual classrooms, as well as informal settings such as museums and libraries [22], [39]. The 5G edge computing paradigm connects students and professionals from anywhere to see, share, and collaborate on persistent, immersive 3D content in real time. CoMIC will enable the research of holographic instructional content sharing and the investigation of technical issues related to the duplication of the serendipity of in-person learning for students, educators, and co-workers in a virtual environment, without the time and cost of travel.

Tactical populations (*e.g.*, firefighters, police officers, and military personnel) need to perform numerous occupational tasks in the field that require high levels of physical preparedness (*i.e.*, operational readiness) and cognitive functioning. While performing occupational tasks, a variety of stressors (*e.g.*, physical fatigue, sleep deprivation, nutritional, load carriage, and environmental conditions) may attenuate performance [3]. The inherent dangers of actual field conditions are a current barrier to advance knowledge regarding the interactions of these factors on performance. For example, firefighting requires intense physical efforts (*e.g.*, moving equipment, stair climbing, and forced entry) while simultaneously performing a variety of cognitive tasks [17] (*e.g.*, visually scanning, object recognition, and short-term memory recall). Thus, XR-based simulations are a viable alternative to conduct research and training of occupational tasks performed by emergency responders [26].

**Direction #1: Immersive XR-based Training to Compare Physiological Responses to Real Training.** We can collect physiological data during actual firefighting shiftwork and real firefighting training of occupational tasks. The data would serve as an important baseline for guiding the development and adaptation of XR firefighting training experiences (Figure 3). To ensure that physiological responses during XR training adequately mimic actual occupational tasks, a validation study is needed, for which participants would complete scenarios designed to simulate tactical events in the lab. During

the simulations, biomarkers of human performance would be recorded using wearable devices, 3D motion capture, force plates, electroencephalogram, and electromyography. These data would provide valid and reliable measures of physiological performance and fatigue. However, one practical challenge is the huge amount of data generated by these devices/sensors, which needs to be sent between the field training and XR training sites for providing real-time validation and feedback, posing a stringent latency requirement. CoMIC will boost the processing of high-volume data and provide low-latency feedback to participants regarding the current state of readiness.

**Direction #2: XR-based Training Intervention and Study Effects of Individual Differences on Performance Outcomes.** While tactical agencies are beginning to incorporate forms of VR training, it is unknown how individual differences may influence training outcomes. Prior to VR training, standardized testing would be conducted to obtain participants' fitness [31], diet [30], sleep [37], and personality [36], which has been found to be associated with human performance [31]. Cognitive performance would be assessed as reaction time to stimuli presented, short-term memory recall, and decision-making abilities during the scenarios. For example, participants may be given an XR training scenario in which they have to traverse over and around objects in the lab and react to simulations as quickly as possible while carrying loads. Based on the participants' performance tracked, the XR training scenario will dynamically adapt its simulations, virtual content, and tasks to guide the participants to improve progressively. CoMIC can provide low-latency responses of the XR environment that are necessary for the training to be perceived as authentic and adaptive. Analyses would focus on the effects of simulated training on cognitive performance. Thus, CoMIC would also facilitate an immersive XR training intervention. Specifically for this task, it would provide real-time physiological feedback and adaptive, personalized training content to participants during training, which has been demonstrated to be valuable to optimize performance [2].

#### *C. mmWave-5G-enabled and XR-assisted Precise Health Informatics*

**Background & Overview.** While telehealth is becoming increasingly popular during the COVID-19 pandemic, the current practice still leverages traditional telepresence technologies for communication between patients and doctors. This makes accurate and timely diagnosis and precision health difficult, or sometimes even not feasible, mainly due to the limited interactions and visualizations that can be supported by existing systems. Initial research work on teleradiology [8], teleradiology [16], telenutrition [13], and teleradiology [15] focuses on the analysis of system requirements and lacks a deep understanding of the technical challenges for providing immersive medical-related services. CoMIC allows systematic studies of telehealth

through the design, implementation, and evaluation of various key building blocks such as real-time nutrition assessment and just-in-time nutrition intervention.

CoMIC will substantially promote multidisciplinary research and practice on nutrition informatics, specifically on telenutrition, just-in-time adaptive intervention (JITAI) delivery, and nutrition education based on edge-assisted immersive computing, advancing obesity and non-communicable chronic diseases prevention and control. As the nation's healthcare system is challenged by the pandemic with mandated social distancing, telenutrition offers unique opportunities for remote nutrition assessment and interventions within the realm of telehealth. According to the Academy of Nutrition and Dietetics, telenutrition involves the interactive use of electronic information and telecommunication technologies to implement the nutrition care process with patients at a remote location [34].

**Direction #1: XR-assisted Real-time Nutrition and Dietary Intake Assessment.** Real-time nutrition status and diet assessments, nutritional diagnosis, and periodic nutrition and diet monitoring and evaluation are the essential components of telenutrition. As a novel approach, telenutrition has been used in various areas and shown promises for improved nutrition care and counseling (*e.g.*, weight management and cancer patient care) [14], [24], [28], [44]. However, despite the increasing acceptance and popularity, telenutrition is still in its infancy. One unique challenge is that traditional diet assessments largely rely on dietary recalls through food frequency questionnaires and food records. Recall bias is almost inevitable when using these traditional nutrition data collection methods. In addition, patients are required to estimate the quantities of the food they consume based on their subjective visual judgment. Immersive computing enabled by mmWave 5G edge networks makes real-time nutrition assessment possible in which patients can use XR headsets to report the food types they consume in a real-time fashion and estimate the volume/quantity of the food using XR-assisted estimation tools on various eating occasions with high accuracy.

**Direction #2: XR-assisted Just-in-time Nutrition Intervention.** CoMIC facilitates high-speed and real-time data transmission of the dietary intake data to food composition data server and instantaneous dietary data analyses via linkages with food databases (*e.g.*, standard release food commodity database and food patterns equivalents database) to estimate the intakes of food, vegetables, beverages, and nutrients. mmWave 5G edge networks with the above databases will allow us to generate estimates of nutrient intake from food and beverages and assess diet quality according to the above guidelines in real time. Individual-level food and nutrient information will then be used as input and processed by background personalized nutrition algorithms at the mmWave 5G edge to generate food intake recommendations for patients based on their

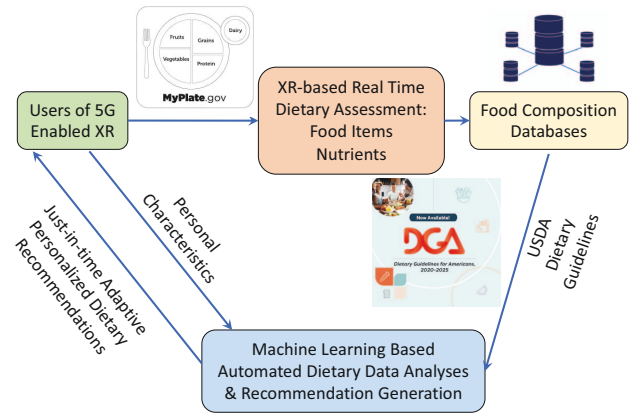


Figure 4: 5G-enabled and XR-assisted just-in-time adaptive dietary intervention.

profiles. These personalized nutrition suggestions will be delivered to patients instantly with XR simulations of the health consequences to promote healthy eating behaviors through JITAI (Figure 4).

**Direction #3: XR-assisted Health and Nutrition Education.** We can also take advantage of immersive technologies enabled by CoMIC to improve nutrition education. Nutrition education plays a central role in non-communicable disease prevention and control through influencing people's energy balance related behaviors including food choices, dietary practices, and physical activity. Existing studies have shown the possibilities of using AR to simulate food making process [49], aid calories estimation of the foods [42], educate users about food size estimation [41], and carbohydrate content estimation [9]. However, the applications of immersive technologies in nutrition education remain largely underdeveloped. We will explore the possibilities of integrating immersive technologies assisted by mmWave 5G edge in nutrition education for patients with chronic diseases. Specifically, we will build a platform for patients to learn the macro/micronutrients of the food and beverages they usually consume and educate them about the biology of health and potential consequences through immersive data visualization. At the same time, this platform can be used by students (*e.g.*, nutrition and health informatics students) to practice nutrition counseling and integrate the platform with health informatics tools to promote digital healthcare.

## V. ENVISIONED FUTURE

In the near future, our digital encounters will break free from the confines of screens and gadgets, enveloping us in a realm where the virtual and the tangible effortlessly blend together. This thrilling transformation represents the potential of immersive computing, an innovative domain that is reshaping how we engage with technology and connect with one another. Immersive computing will seamlessly

integrate into our everyday existence, elevating human-machine interaction, boosting productivity, and nurturing creativity. Collaborative, cross-disciplinary research will propel technological progress, tackling challenges while upholding ethical, accessible, and secure digital experiences. As we gaze upon this visionary horizon, we can imagine a world filled with astonishing possibilities and transformative changes, as listed below.

**Immersive Learning: The Future of Education.** The horizon of education is destined to become immersive. Students will embark on journeys through virtual history lessons, delving into ancient civilizations, conducting science experiments in virtual labs, and mastering languages by immersing themselves in virtual cultures with telepresence. Teachers will wield formidable tools to captivate and educate students, surpassing the limits of our current imagination. Education will transform into a boundless adventure, transcending conventional boundaries.

**Augmented Healthcare: Transforming Lives.** Immersive computing stands poised to transform the landscape of healthcare. Surgeons will harness the power of AR to execute intricate procedures with unparalleled precision, mitigating risks. Patients will benefit from personalized treatment regimens and immersive therapy experiences tailored to their needs. VR will emerge as a potent tool for pain management, anxiety reduction, and phobia treatment. Telemedicine will advance to the point where doctors can diagnose and treat patients with a sense of physical proximity, regardless of geographic distances.

**Workplace of the Future: Breaking Down Barriers.** The conventional workplace is on the cusp of a profound transformation. Immersive computing will empower remote teams to collaborate seamlessly, replicating the experience of being in a shared room. Virtual offices will adapt to cater to individual preferences, enhancing comfort and productivity. Meetings will evolve into dynamic and engaging sessions, blurring the lines between work and home as we reimagine the concept of work-life balance.

**Entertainment Redefined: From Spectators to Participants.** Entertainment stands ready to shift towards immersive participation with personalized experience. With VR/AR/MR and AI, we will journey to fantastical realms where we assume the roles of heroes in our personal narratives. Live events will undergo a transformation, as enthusiasts join concerts and sports events from prime vantage points, irrespective of their global location. Interactive storytelling will empower us to mold narratives in real time, redefining how we engage with our loved stories.

## VI. CONCLUSION

This vision paper outlines a roadmap for the advancement of immersive computing, highlighting its technical challenges and opportunities, research infrastructure for enabling multi-user interactions, and promising use cases in various domains. The future of immersive computing

offers the potential for a world where our digital experiences are more vibrant, engaging, and deeply meaningful, becoming a natural extension of ourselves and enriching our life beyond our current imagination. As we venture into this emerging era, we should embrace the opportunities it offers and collaborate to ensure that the evolution of immersive computing aligns with a vision where technology genuinely serves the betterment of humanity.

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