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Exploring Gaming Technologies, Digital Twins, and VR to Visualise Wireless Propagation Simulations

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***Abstract*—Over the years, the wireless communication industry and the research community investigated methods of creating accurate and efficient models for signal propagation. The recent advancements in wireless communications and its exponential usage through high mobility of numerous connected devices introduced challenges in simulating dynamic radio propagation. To address these challenges, specialized software have been developed, offering high-fidelity simulations. However, these solutions have expensive cost requirements and are largely dependent on offline computations, lacking flexibility and scalability. As a result, their wider use in scientific and industrial sectors is limited. In response to these limitations, this paper proposes an alternative solution leveraging the latest developments in Gaming technologies, GPU technology, and Virtual Reality through the concept of Digital Twins to develop a prototype for a deterministic channel simulator. The prototype utilise a game development engine, high-performance GPU, and commercial VR headsets to achieve a low cost, accessible and scalable method for visualizing wireless signal propagation in real time. This paper presents the work in progress, describing the system architecture, current state of development and intended functionalities.**

***Index Terms*—Digital Twins, Raytracing, Virtual Reality, Wireless Propagation Simulations**

I. INTRODUCTION

The recent advancements in Artificial Intelligence (AI), eXtended Reality (XR), high performance computing accelerated by Graphics Processing Units (GPUs), networking hardware and sensors, have drawn significant academic and industrial interest, with important impact in a wide range of computing and engineering domains. The field of networks and wireless propagation, particularly with the 5G/6G wireless networks, is one of these highly evolving areas. For many years, the research community is actively pursuing work towards developing accurate and efficient radio channel prediction models to combine speed, accuracy and resolution [1]. Especially with the latest developments in wireless communications, where the high mobility of the many connected devices creates very dynamic radio propagation environments, which are extremely difficult to be simulated. A range of specialized software solutions are available for signal propagation visualisation, such as Remcom's Wireless InSite®, and Ranplan Professional®, capable of providing high fidelity and accurate signal propagation simulations. However, these software solutions are expensive, rely heavily on offline calculations, and lack openness and expandability, restricting their adaptability and broader application by the wider scientific and industrial community. Considering these rigid requirements, there is a pressing need for alternative solutions providing accessible, expandable and cost-effective solution for signal propagation visualization [2]. Leveraging the recent advancements in software and hardware computer graphics and XR, promising potentials now exist in addressing some of the complex needs and provide opportunities to develop new tools for signal propagation visualizations that could overcome current limitations and provide more accessible, sustainable, and cost effective solutions.

The project presented in this paper is a work in progress prototype, focusing on developing a deterministic channel simulator to visualise signal propagation in 3D and in Virtual Reality (VR). The objective of the prototype will be achieved through utilising the powerful rendering capabilities of a sophisticated game development engine facilitating the implementation of complex mathematical calculations, high-performance GPU, and complemented by the use of commercial VR headsets for an efficient and immersive simulation experience.

II. BACKGROUND AND CONTEXT

A. Wireless Propagation Simulations

The need for accurate radio propagation modelling raised substantial research attention over the past few decades. Numerous modelling techniques have been proposed, and classified in 3 categories based on their approach of calculating path loss: empirical, semi-empirical, and deterministic [3]. Empirical models are described by a set of equations fitted to the results obtained from extensive number of path loss measurements. They are efficient (fast) and simple to use, however, they lack accuracy and have limited applicability to environments similar to the ones the measurements were originally conducted [4]. Deterministic models utilise electromagnetic theory and geometrical methods (such as Ray Tracing) applied to a site-specific environmental description (e.g. a 3D CAD drawing) [5] and can be generic and relatively accurate for arbitrary environments, but they carry large computational overhead leading to heavy computational load and delay. For this reason, the research community and the telecom industry focused their efforts in developing and using semi-empirical models applicable to particular scenarios, environments or technologies [1], [4]. However, the recent trends and developments in wireless communication together with the significant increase of modern computers' processing power which is typically facilitated by their GPU, is diverting the focus back to deterministic channel modelling using Ray Tracing (RT) approaches [6]–[8].

B. Ray Tracing in Wireless Propagation

RT is a well-known term in computer science and engineering, often linked to the field of computer graphics as a technology for rendering, used to simulate the way light interacts with objects in a virtual world to create 2D images out of 3D virtual scene [9]. It is based on the principles of Geometrical Optics, studying the ways of light propagation in terms of rays. In the radio signal propagation domain, RT is used to identify all possible ray paths and their respective intersections with objects between the transmitter and receiver locations, using high-frequency electromagnetic theory to calculate the amplitude, phase, delay and polarisation of each ray. RT channel modelling accurately estimates the signal spatio-temporal parameters i.e. power delay profile (PDP), channel impulse response (CIR), angles of arrival (AoA) and departure (AoD) [5], [10]. This ability is quite important given the recent developments in wireless communications, including notable increase in frequency extending into the millimeter-wave (mmWave) spectrum, sophisticated antenna systems such as phased-arrays, development of massive-MIMO systems leveraging multipath propagation, and with growing use of Reconfigurable Intelligent Surfaces (RIS) [11]–[13].

Historically, the main challenge of RT modeling was its expensive processing demand. This issue has been effectively addressed through the use of parallel/distributed computing and by shifting a significant portion of the computation from the Central Processing Unit (CPU) to the GPU, significantly increasing computation performance, and several works have started being proposed recently in this topic. For example, in [6], the authors present a GPU-based kD-tree-accelerated beam-tracing method (GKBT) which appeared to run 66 times faster than conventional RT models in the specific environments they have run their trials in. [7] use the combination of different techniques, i.e., environment discretization, visibility preprocessing, and GPU parallelization, achieving a computational efficiency up to 4 orders of magnitude compared to a reference RT algorithm. The recent advancements in GPU technology, and most importantly the built-in RT functionality support provided in specific GPU series capable of performing RT calculations at hardware level, creates many opportunities for exploring their applicability and efficacy to ultra-fast deterministic channel modelling. For instance, the authors of [8] analyse the complexity of a large-area electromagnetic simulation environment and propose a method to accelerate the calculation process using the NVIDIA® OptiX™ tracing engine demonstrating notable acceleration in the channel prediction. One of the most important recent developments is a true-to-reality 5G simulation platform developed by Ericsson and NVIDIA [2]. This platform leverages the accelerated computing capabilities offered by the Omniverse®, NVIDIA's high-performance cloud platform that facilitates the development, deployment, and management of advanced 3D applications [14]. The partnership focused on integrating their technologies and expertise to create a platform capable of accurately modeling radio propagation and network performance in dynamic environments. The platform capitalizes on the Omniverse's high processing speed, enabling real-time calculations of spatiotemporal signal characteristics in complex wireless environments, serving as a robust and efficient example of the 'Digital Twin' concept [15].

C. Digital Twins

The concept of Digital Twins is one the recent emerging technologies fostering the ongoing digital transformation, with widespread attention and adoption in both industry and academia. The increasing interest is being reflected in the growing number of academic publications, implementation examples, and in commercial marketing [16], [17]. Due to its growing usage, many definitions describing the concept and its applicability have been devised. Their meaning is heavily context specific, but mostly have shared characteristics [18]. In its simplest form *"a Digital Twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making"* [19]. Put simply, real-world sensors provide real-time data analyzed through sophisticated algorithms, visualized through a virtual model that mirrors a physical system. The sensor data is directly linked to its digital counterpart, mirroring its functioning, and allowing observers to access near-real-time insights about the physical system's operation [18]. Digital Twins synchronously merge data and knowledge with analytics and visualization tools, to maintain alignment between the real and virtual worlds [20], and there is growing need to capitalise on Digital Twins as a result of the recent technological advancements and increasing industrial/market demands. Requirements such as the need for real-time monitoring, operational flexibility, improved inventory management, personalized services among others, are key drivers in engineering. At the same time, advancements in the field of AI, XR visualisations, computational hardware, sensors, wireless and communications technology are also pivotal in driving innovation [18], [21].

The telecom industry shows great interest in implementation of Digital Twins of physical wireless networks for real-time analysis and visualization of signal propagation. In the context of mobile networks, a Digital Twin is defined as a virtual model that mirrors real-world network entities and processes, including the environment and users, regularly updated at set intervals and fidelity [22]. Previous research explored the implementation of Digital Twins to simulate real world network scenarios through edge computing and service management [23], and in non-real-time applications (e.g. site engineering) [20]. Recent studies focused on using Digital Twins for real-time simulations, particularly in physical modeling of environments and signal propagation, by integrating

3D mapping, sensing, RT, and AI to create, update, and use real-time Digital Twins effectively [24]. [22] presents several use cases with diverse scopes, where networked Digital Twins have the potential to create significant value, with Network Performance Evaluation and Radio Resource Management in factories being identified as very promising in the field. The literature on Digital Twins mainly focus on methodologies, analytical approaches, and challenges related to data gathering and integration [17]. However, there is a need for practical implementation examples within the radio propagation domain, demonstrating outcomes and benefits.

D. Gaming Technology and eXtended Reality

3D gaming and GPU hardware technology provides opportunities for developing models of radio networks [15]. Gaming technology is known for handling intricate and expensive scene geometry, high fidelity graphics, and dynamic AI actor behaviour, which when repurposed appropriately can offer opportunities for representing a network and providing promising capacities to accurately simulate a radio network within a Digital Twin framework [20]. One of the most recent technological developments that drew research and industrial attention (gaming industry inclusive) is eXtended Reality (XR). XR is an umbrella term encapsulating Augmented, Virtual and Mixed Reality technologies, referring to all real and virtual settings, software, hardware, and human–computer interactions generated through them [18]. XR offer access to immersive experiences, providing increased sense of presence and involvement to users, with the potentials to disrupt the way we perceive real and digital worlds and develop highly immersive future applications [18]. In Digital Twins, XR is used frequently used for visualization and interaction with the rich data provided by the digital representation, and its effectiveness have been explored and evaluated in a wide range of domains recently with very positive results [25], [26]. Within this context, exploring the possibility of a low cost flexible tool to visualise deterministic modelling in real time, through gaming technologies, Digital Twins and VR creates unique opportunities. It is now more than ever worth-exploring the idea of creating a portable and low cost ultra-fast deterministic channel model that will make a powerful tool in the hands of telecom engineers and researchers, offering the desired accuracy and resolution in real-time when simulating very dynamic radio environments.

Previous work includes a number of prototypes aiming to run such simulations using game engines. ‘DeepWiSim’ is a RT based wireless signal simulator focusing on automating deep learning process from data generation to model training for wireless signal research built on Unreal Engine to predict the change of signal characteristics [27]. ‘See the Radio Waves’ demo utilises VR to enable users ‘to see’ the radio waves, and provide a method of using the radio waves for designing and optimizing wireless communication systems [28]. A simulation tool for visualising Computational Electromagnetic Simulations with a focus on indoor environment using Unreal Engine and the MATLAB based CEM simulator was developed by [29] to interpret spatial simulation-domains, RT/path propagation data, and scalar fields. [30] proposed an architecture of a large-scale wireless emulator and created a system that applies radio wave propagation models in a 3D space to enable evaluation using physical radio devices. It implements software based virtual radio nodes to enable large-scale emulation by interconnection between physical radio node and virtual node. However, computing real time radio propagation simulations with the user ability to visualise and interact with the environment is extremely difficult due to the intensive computational demands of RT, and can significantly affect the user experience. While RT can provide accurate and detailed visualization of signal paths and interactions with objects, it requires substantial processing power, leading to reduced framerates in real-time applications affecting the overall experience and performance. Especially in VR, low framerates can make the experience disorientating and unusable. Reducing the resolution and graphics fidelity can increase performance but would decrease the visual quality and quality of the experience. Therefore, research is imperative to investigate methods and techniques for addressing the challenges posed by the intensive computational demands of real-time wireless propagation simulations. Optimization techniques for real-time rendering, utilisation of hardware acceleration, resolution techniques, and methods for supporting optimal user experience need to be investigated. Furthermore, the development and implementation of wireless propagation mechanisms is a complex software development task. Considering previous work, the inherent challenges of real time wireless propagation simulations, and the latest software and hardware advancements, the prototype work presented in this paper seeks to integrate the concepts of Digital Twins, wireless propagation, and VR, developed using gaming technologies to support the overall simulation process while providing access to immersive user experience.

III. PROTOTYPE DEVELOPMENT AND METHODOLOGY

To investigate the feasibility of implementing an accurate low cost version of a real time immersive radio propagation simulator, a prototype is currently under development to ascertain: i) the feasibility and effectiveness of Unreal Engine in simulating wireless signal propagation and its capacity to accurately represent key propagation mechanisms; ii) the level of simulations detail and accuracy that can be achieved; iii) explore the Digital Twin concept into the visualization process for immersive, interactive radio propagation environment in VR; and iv) understand the technical requirements and user experience challenges associated with rendering these simulations. The proposed prototype is currently exploring the deployment of two main operational components: i) a radio propagation simulator operating in a 3D environment that enables dynamic ray generation, designed to implement key propagation mechanisms: reflection and refraction; ii) immersive visualisation of a heat-map mode, enabling users to navigate and explore the signal behaviour through VR.

IV. SIGNAL PROPAGATION SIMULATION PROTOTYPE

A. *Simulator Architecture*

The prototype is designed around a *Transmitter - Obstacle - Receiver* architecture. One of the key requirements and main contributions of this project in its current state, is the implementation of the complex propagation mechanisms to ensure accurate results. The model in the simulation is constructed based on the paths traced by virtual rays as they travel from the *Transmitter* to the *Receiver* either through open space or as they interact with any *Obstacle* they encounter along the way. The simulation mechanics are developed using an object-oriented approach through a group of objects utilizing a shared cache system encompassing: i) a component representing the signal, containing information about its frequency, polarization and other information; ii) a shared cache object that captures the scope of each unique *Transmitter*; iii) a shared cache that captures the scope of each primary ray; iv) tree node that contains information about each individual ray casting; v) a receiver that captures and calculates the signal at the *Receiver*'s end. For every traced ray, the complex electric field is calculated at every point of interaction with the physical environment and at any receiver cell that the ray is captured before it gets discarded after reaching some predefined termination conditions. A vertical ($\perp$) and a horizontal ($\|$) component of the electric field are calculated to enable polarization consideration. Additionally, the obstacles' physical and electrical properties can be defined by the user via a convenient interface within the game engine.

1) Transmitter: The *Transmitter* acts as a digital counterpart to a real-world transmitting source (eg. a Wi-Fi access point), serving as the starting point for the propagation modelling. High-Frequency radio propagation can be approximated (in the Geometric Optics concept) by launching rays around a sphere. Depending on the antenna radiation pattern and polarization, the *Transmitter*, emits discrete rays (referred to as *primary*) in a user-defined spherical (or conical) area. Each of these rays is assigned an initial electric field vector $\vec{E^i}_{xyz} = \begin{bmatrix} E^i_x & E^i_y & E^i_z \end{bmatrix}$, which is composed of the electric field's x, y, z components and depends on the electric field E_0 emitted from the antenna, the antenna's gain $P(\theta, \phi)$ and the polarization of the antenna $\hat{p}$ ($\hat{\theta}$), which vary according to the azimuth (θ) and elevation (ϕ) angle of each emitted ray i^{th}. As the ray travels through the environment it's value diminishes exponentially depending on the travelled distance r_i and this is implemented through the following equation:

$$\vec{E^i}_{xyz}^{\perp,\|}(r_i) = E_0 \frac{e^{-jkr_i}}{\sqrt{4\pi} * r_i} P(\theta, \phi)\hat{p} \tag{1}$$

2) Obstacle: The *Obstacle* is a digital representation of any real-world object that may interact with a radio signal, thus greatly altering its electric field. In the radio propagation domain, any obstacle material is characterised by its electrical properties: permittivity ε, permeability μ and conductivity σ. Since most building materials are non-magnetic, the focus is primarily on permittivity, which is used in a complex form to indicate that the obstacle affects the signal amplitude and phase. When a ray from the transmitter hits an obstacle, two new rays are generated; one reflected, and one refracted following Snell's law. The reflected ray bounces off the obstacle at an angle equal to its incident angle, while the refracted ray passes through the obstacle, changing direction slightly. However, this change in direction is typically insignificant and is ignored for simplicity. In order to estimate the proportion of the signal that gets reflected or transmitted through the material, the respective reflection and transmission coefficients are calculated. A dyadic version of these coefficients is used that takes into account the polarization, angle of incidence, complex permittivity and thickness of the obstacle [31]. Another special propagation mechanism exists when the incident ray hits the knife edge of the obstacle, called diffraction. This work focus on indoor radio propagation in which losses are dominated by reflections and refractions, therefore the effects of diffraction are ignored.

Right after the interaction with the obstacle, the reflected and refracted electric field is calculated for each polarization by multiplying equation 1 with the respective reflection $R^{\perp,\|}$ transmission $T^{\perp,\|}$ coefficient for each polarization. Before being received at any receiving location, each ray path will undergo a multiple combinations of interactions with the environment obstacles, unless it gets discarded because its electric field drops below a predefined threshold or it has encountered more than the allowed number of interactions. Therefore the electric field vector at any receiving point at a distance R_i for the i_{th} ray can be calculated using:

$$\vec{E}^{\perp,\|}(R_i) = E_0 \frac{e^{-jkR_i}}{\sqrt{4\pi} * R_i} P(\theta, \phi)\hat{p} \prod_{m=1}^{n_R} R_m^{\perp,\|} \prod_{m=1}^{n_T} T_m^{\perp,\|} \tag{2}$$

,where n_R and n_T are the total number of reflections and refractions encountered by the ray.

3) Receiver: A *Receiver* is implemented as a logical object in the environment. It can be described as a 3D grid cell that can register any rays that overlap with it and calculate their electric fields using equation 2. The total Electric field at the receiver is the norm of the vectorial sum of all the captured rays which is calculated using:

$$E_{total}^{\perp,\|} = \sqrt{\sum_{i=1}^{N} E_x^2 + \sum_{i=1}^{N} E_y^2 + \sum_{i=1}^{N} E_z^2} \tag{3}$$

,where N is the total number of ray paths captured at the receiver. The simulation's primary interest lies in the received signal power rather than the electric field, therefore the following conversion is implemented:

$$P_{dBm} = 10 \log_{10} \left| \frac{E_{total}^2 \lambda^2 G_R}{8 Z_0 \pi} \right| \tag{4}$$

,where Z_0 is the impedance of free space (377Ω) and G_R the gain of the receiver.

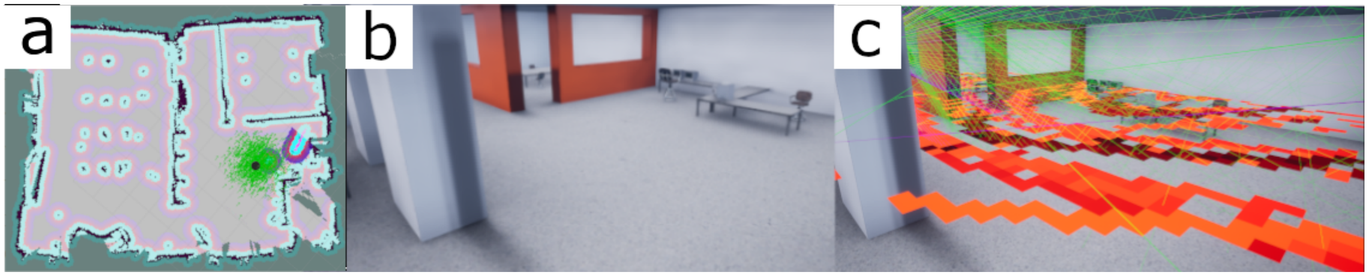

Fig. 1. Preliminary version of the the Digital Twin development process and simulation examples: (a) 2D layout generated through Turtlebot2; (b) 3D Digital Twin; (c) Example ray tracing simulation and heatmap visualisation

B. *Digital Twin Prototyping*

Creating a Digital Twin is a complex process that includes the creation of a model, data input, and regular data updates. Literature suggests two main approaches for designing a Digital Twin: i) constructing a system model that represents a physical object, and ii) establishing a data structure that connects sensor data and other relevant information [32]. Data connection is required to enable interaction and real time updates of between the physical and virtual elements encompassing the Digital Twin. Therefore, to create an accurate representation of a physical entity using a Digital Twin, all available context specific information must be integrated and continuously updated, for example geometrical data, simulation models, sensor data, even environmental conditions [32]. To develop the Digital Twin for this prototype, Unreal Engine 5 is used leveraging its flexible development tools, sophisticated geometry, lightning, and rendering system. Currently, an initial Digital Twin prototype of a real setting is developed, to provide accurate spatial information at this point. We have replicated a 100 m^2 computer lab environment located at the University of Central Lancashire, Cyprus (UCLan Cyprus). To accurately model this physical space and be in line with the project's emphasis on cost-effectiveness, we have used the Turtlebot2 to capture and generate the environment. Turtlebot2 is a mobile research robot equipped with various sensors, including a Microsoft Kinect 2D/3D distance sensor offering capabilities for mapping a physical environment into 2D grid map. We manually tele-operated the robot to navigate and map the physical space. For the mapping process, we employed the gmapping method, a laser-based Simultaneous Localization and Mapping algorithm designed to create a 2D map of the environment ("Fig. 1a"). We then used Unreal Engine's built-in environment design tools, using static mesh actors to reconstruct the physical setting in 3D ("Fig. 1b"). Subsequently, these actors were converted into *Obstacles*, as detailed in Section IV-A2. The system provides provisions to add material information to each *Obstacle* such as thickness, relative permittivity and conductivity, later to be used for calculations accuracy. Sensors will be placed at a later stage for real time updates on movement within the physical setting.

A key feature under development is the dynamic generation of an intuitive heatmap to visually represent the signal strength across the entire digital space ("Fig. 1c"). This allows visualising signal strength variations to understand signal propagation in various transmitter and base signal configurations. The digital space is partitioned into a finite set of discrete *Receiver Cells* through an influence map method, designed to register incoming rays. The distribution and intensity of signal power each *Receiver Cell* receives are converted into RGB pixel colors, with the color depth indicating signal intensity levels. The heatmap coordinates and resolution are defined by the user before running the simulation, for detailed visual analysis.

The system is currently used through the 3D Desktop mode, and will support VR using the Meta Quest 2 in PC-tethered connection. Users are currently able to visualise the real-time ray generation, tracing, reflections, and important data captured for each ray as reflected at each *Obstacle* in 3D desktop mode and the Heatmap will be able to be visualised in VR ("Fig. 1c").

V. DISCUSSION AND FUTURE WORK

This paper presents a work-in-progress prototype exploring the use of gaming technologies, Digital Twins and VR to create an accurate, cost-effective, and immersive wireless propagation simulator. The current stage of development focus on implementing the complex propagation mechanisms, and features an initial Digital Twin to conduct basic experimentation with. Next steps in development focus at: i) implementing sensors in the physical setting to provide real-time information to the Digital Twin, and further refine the 3D model by providing additional details such as the thickness of walls and other properties of build materials to enhance the accuracy of the simulation; ii) exploring the feasibility of implementing the simulation and immersive visualisation functionalities into two separate system components. The first component will be responsible for running the signal propagation simulations in real time, responsive to dynamic changes on the environment, and experienced in desktop 3D mode. This task poses several challenges to overcome related to performance requirements, offering opportunities for research and innovation through advanced software development and optimisation techniques. Future work aims to validate and evaluate the accuracy and performance of the proposed prototype through simulations in a conventional commercial simulator and small-scale in-situ measurements. The second component focus at enhancing and validating the heatmap module for VR exploration and visualization of signal strength and path-loss of the generated signal propagations. The system would be able to provide accurate color-coded representation of the signal strength variations as generated by the simulation component across different areas within the environment to identify zones of signal coverage. The team will explore the feasibility of incorporating 3D plots to depict Power Delay Profiles (PDP) and Channel Impulse Responses (CIR), offering detailed and spatially-oriented view of how signal power varies over time and space, to allow analysis of the signal characteristics and propagation.

This research project aims at demonstrating how the fusion of gaming technologies, VR, and Digital Twins can contribute to the field of wireless propagation, exploring opportunities more flexible, cost effective, and portable solution for researchers and professionals. Telecom engineers for example can investigate and explore the radio-channel dynamics, immerse and visualise the physical radio-channel simulations, offering them the ability to configure the parameters of the network and the antenna by 'seeing' the effects. The intended tool can offer opportunities to support optimization of wireless network design by enabling the engineer to use VR simulations to optimize the placement of antennas and other network components for improved signal coverage and strength. System performance and user evaluation studies exploring technical and user experience characteristics (such as VR sickness) will be conducted, to ascertain the extend to which the prototype can be effectively used to support real time simulations and visualisations. The future research plans will guide us in determining the practicality, benefits, and limitations of this approach, building the premises for further research and innovation in the domain. Furthermore, by integrating advanced technologies like VR and Digital Twins, the intended system will represent a step closer to realizing concepts related to the Metaverse, where virtual and physical worlds converge, creating new possibilities for simulation, analysis, and interaction in a plethora of domains.

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