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Immersive Control Centre for Space Mission Management and Collaboration

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Abstract

As space missions grow in complexity, managing remote operations and coordinating dispersed teams becomes increasingly challenging. Traditional control systems often struggle to meet the evolving demands of large-scale missions and multi-source data integration. To address these limitations, an immersive control centre is proposed that leverages extended reality (XR) technologies to enhance space mission management and global team collaboration. This next-generation control centre introduces a fully immersive environment by generating high-resolution digital twins of space assets, orbiting vehicles, and space debris. Real-time visualizations allow operators to intuitively interact with dynamic 3D models, monitor mission parameters, and assess spatial relationships in the orbital domain. The system integrates real-time data streams to ensure visualizations remain accurate and context-aware, reflecting live mission updates and environmental conditions. A core innovation lies in the interactive control interfaces equipped with haptic feedback, enabling users to engage tactilely with virtual elements. These features enhance immersion and support complex tasks, such as virtual manipulation of spacecraft or assets, as if interacting with physical systems. The platform also embeds collaborative tools that promote real-time communication and coordination among distributed teams. Operators, engineers, and mission specialists can share data, conduct joint analyses, and make timely decisions within a unified virtual space - streamlining mission workflows and improving operational agility. This study outlines the system's architecture, design process, and early-stage implementation. The immersive control centre aims to bridge the gap between physical operations and digital oversight, offering a scalable solution for future missions. By advancing remote management capabilities and fostering international collaboration, this initiative represents a transformative step in space mission control, enhancing operational performance and supporting the long-term goals of space exploration.

Keywords: Immersive Control Centre, Space Mission Management, Extended Reality (XR), Digital Twin, Real-Time Visualization, Remote Collaboration

1. Introduction

Planning and executing space missions remains a complex challenge, requiring long-term coordination, integration of diverse systems, and adaptability to dynamic conditions. This complexity is especially evident in ongoing lunar and Martian missions, where operations must manage delayed feedback loops, harsh environments, and evolving mission goals. The limitations of conventional mission control technology (MCT) were already apparent during the Mars Exploration Rover (MER) program and persist in current missions. Software developed years in advance often fails to accommodate real-time operational insights, forcing mission teams to rely on workarounds, patches, and "glueware" to meet evolving needs during active deployment [1-3].

Extended Reality (XR) serves as an umbrella term encompassing immersive technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), along with a variety of input mechanisms that facilitate rich interaction experiences. XR spans a continuum of immersive experiences that blur the boundary between the physical and digital worlds [4,5]. This spectrum, conceptualized by Milgram in the reality–virtuality continuum, includes all possible variations and combinations of real and virtual elements [6,7]. In the context of astronautics, XR is increasingly recognized as a transformative tool, enhancing the way missions are conceptualized, executed, and analyzed. These technologies enable mission planners and astronauts to interact with high-fidelity simulations, promoting intuitive spatial understanding, procedural training, and collaborative decision-making.

A significant complement to XR technologies is the integration of haptic feedback systems, which elevate immersion by introducing the sensation of "active touch." Originally introduced by Revesz in 1950 through studies of blind individuals' interaction with their environment, haptics represents a unique sensory modality that differs from conventional tactile or kinesthetic feedback [8]. Modern haptic systems include wearable technologies such as gloves and exoskeletons, which deliver kinesthetic cues directly to the user's body, enabling realistic interaction with virtual objects [9,10]. In space applications, these systems enhance training fidelity and operational preparedness by simulating physical tasks in a zero-gravity environment.

Moreover, the concept of the digital twin - originally introduced during NASA's Apollo program - has become central to modern aerospace strategies. The approach involves creating a dynamic, data-driven replica of a space asset, allowing the Earth-bound model to mirror, simulate, and predict the behavior of its space-based counterpart [11,12]. NASA defines the digital twin as "an integrated multi-physics, multiscale, probabilistic simulation" that leverages physical models, real-time sensor data, and historical trends to track and project the life cycle of a flying system [13]. Since its formal introduction by Hernández and Hernández [14], digital twin technologies have revolutionized aerospace engineering, providing unparalleled visibility and control over mission assets [15].

In astronautics, the convergence of XR, digital twin models, and haptic systems is addressing critical challenges by enhancing real-time collaboration, improving crew training, and supporting design and operational workflows [16–19].

1.1 Rethinking Space Mission Management – The Immersive Control Centre

As the scope and complexity of modern space missions continue to grow, so too do the challenges associated with managing them. These challenges include the coordination of remotely operated systems, real-time integration of vast and heterogeneous data streams, and maintaining situational awareness in unpredictable and dynamic environments. Traditional mission control systems - though foundational - often rely on rigid software architectures and conventional user interfaces that lack the flexibility and intuitiveness required for today's multidimensional mission scenarios. This disconnects hampers both operational efficiency and collaborative decision-making across global teams.

To address these limitations, we propose the development of a fully immersive control centre for space mission management, leveraging the combined power of XR technologies and digital twin frameworks. This next-generation control environment provides high-resolution, real-time 3D visualizations of space assets, orbital debris, and active vehicles. By embedding these digital twins within immersive environments, operators gain a holistic and interactive view of mission parameters, enabling faster and more informed decision-making.

At the core of this immersive control centre lies an emphasis on collaborative decision-making. Integrated real-time communication tools facilitate seamless coordination among globally distributed teams, while shared XR workspaces enable synchronized planning, execution, and review of mission scenarios. These collaborative features are essential for managing the demands of multi-national, multi-phase space programs where real-time consensus and adaptation are critical.

The system further enhances user interaction through advanced haptic feedback technologies, enabling operators to tactically engage with virtual models as if they were physical entities. These interactive interfaces allow for intuitive manipulation of assets, simulation of mission outcomes, and control of critical scenarios with precision and confidence.

The anticipated impact of this immersive control framework is multi-fold. It promises to significantly improve situational awareness, responsiveness, and overall mission reliability. Additionally, it paves the way for accelerated international cooperation and operational integration in deep space exploration. By bridging the gap between digital simulations and physical space environments, the immersive control centre represents a transformative leap forward in how we manage remote space missions-laying the foundation for the next era of space mission control.

2. Immersive Mission Control Centre Architecture

To precisely replicate the dynamics of a space mission within an immersive environment, a MR application was developed using Unreal Engine. Unreal Engine was selected for its powerful real-time rendering capabilities, ease of use, and multi-platform support, enabling compatibility with a wide range of XR devices, including both VR and AR headsets.

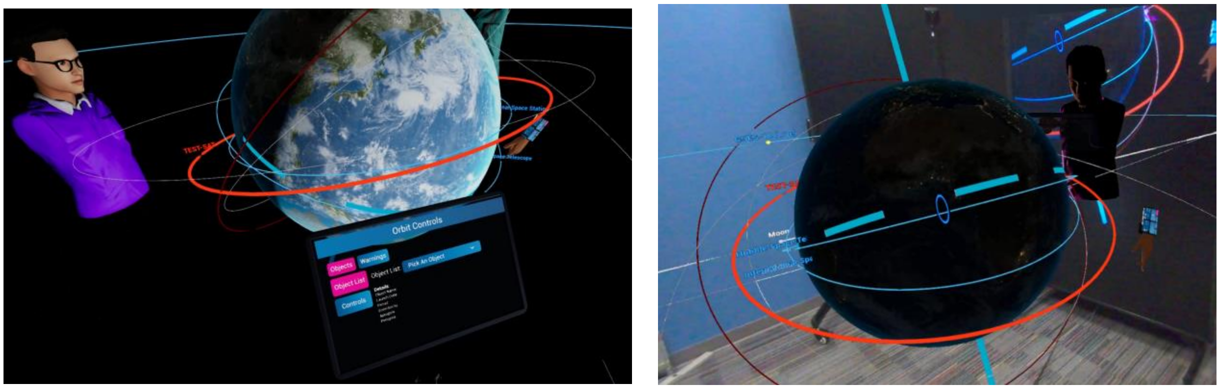
At the heart of the system is a digital twin environment, rendered from the operator's point of view (POV), which offers real-time visualizations of Earth, the solar system, active satellites, orbital debris, and other space assets. As shown in Figure 1, this interactive 3D environment allows users to intuitively explore the spatial relationships and trajectories of orbiting bodies, greatly enhancing situational awareness. The digital twin is dynamically driven by real orbital data, currently utilizing the Two-Line Element (TLE) format as the primary input for tracking objects in space. A sample TLE dataset for April 8, 2025, is presented for the International Space Station (ISS) in Figure 2, demonstrating the integration of live orbital parameters into the system [20].

The simulation accurately depicts the trajectories of well-known spacecraft, including ISS, Hubble Space Telescope, and GOES-18 satellite. These assets are continuously updated based on real-time data feeds, offering a highly accurate operational environment.

In addition to immersive visualization, the system includes an interactive tablet interface designed to complement the headset experience. This handheld device enables operators to monitor, control, and manipulate the position of designated satellites, facilitating intuitive interaction and reducing the cognitive load often associated with extended

XR headset use. Operators can track satellite movements, issue control commands, and quickly adapt to changes without needing to fully remove the headset.

For enhanced mission safety, a collision detection algorithm is embedded within the system. The projected positions of all tracked objects are continuously monitored at predefined time intervals. Any two objects approaching within a specified distance threshold - calculated using bounding-box dimensions tailored to each object - are flagged as potential collision risks. These alerts provide timely decision support, helping operators anticipate and mitigate critical events during mission execution.



(a) (b)

Fig. 1. Digital twin environment showing real-time orbital data in an immersive XR interface for a. VR user, b. AR user

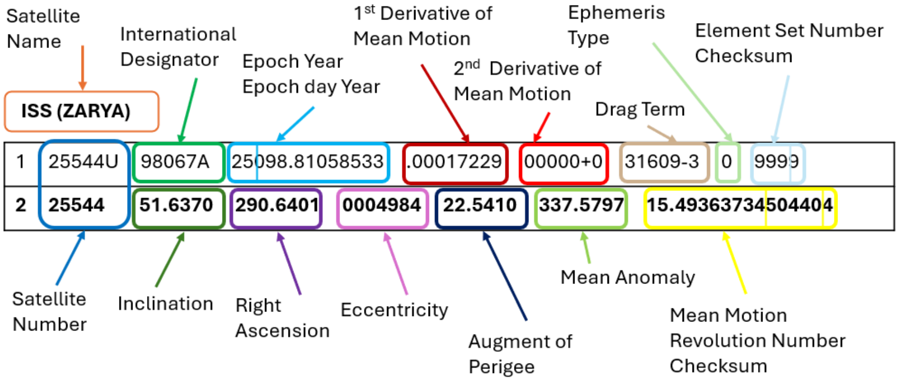


Fig. 2. Two Line Elements (TLE) data format used for the purpose of this study (data shown for the International Space Station sample are valid for April 8, 2025) [20]

Figure 3 illustrates the simplified architecture and data flow of the immersive control centre, designed to provide real-time visualization and interaction with orbiting space assets. The architecture integrates orbital information, user commands, and graphical rendering through a synchronized pipeline to ensure operator immersion and situational awareness. The System begins with the initialization of the Veyond Connect Server which provides an invitation to select participants to join a collaborative session. Once the participants have joined the session, the Server application ensures the data between all participants is synchronized. Each participant then begins retrieving orbital data inputs in the form of Two-Line Element (TLE) sets, which provide the position and velocity information for tracked objects such as satellites, debris, and ISS. This data, along with controller inputs and point-of-view (POV) graphics, is shared over the server to every participant. The Unreal Engine acts as the core simulation environment, where digital twin representations of orbiting objects are updated in real-time based on TLE data.

Users interact with the system through either haptic force-feedback gloves or conventional XR controllers. These input devices enable intuitive control over space assets and allow real-time command inputs, which are processed by the embedded code within the MR application. Orientation data from the head-mounted display (HMD) and controllers are also captured and synchronized to enhance spatial coherence in the immersive environment.

To enhance user immersion, a virtual display is embedded within the MR scene, showing a live POV feed using a webRTC plugin. This plugin leverages a well-established video communication system to not only share video data from the satellite, but also audio and video between each participant for more effective collaboration.

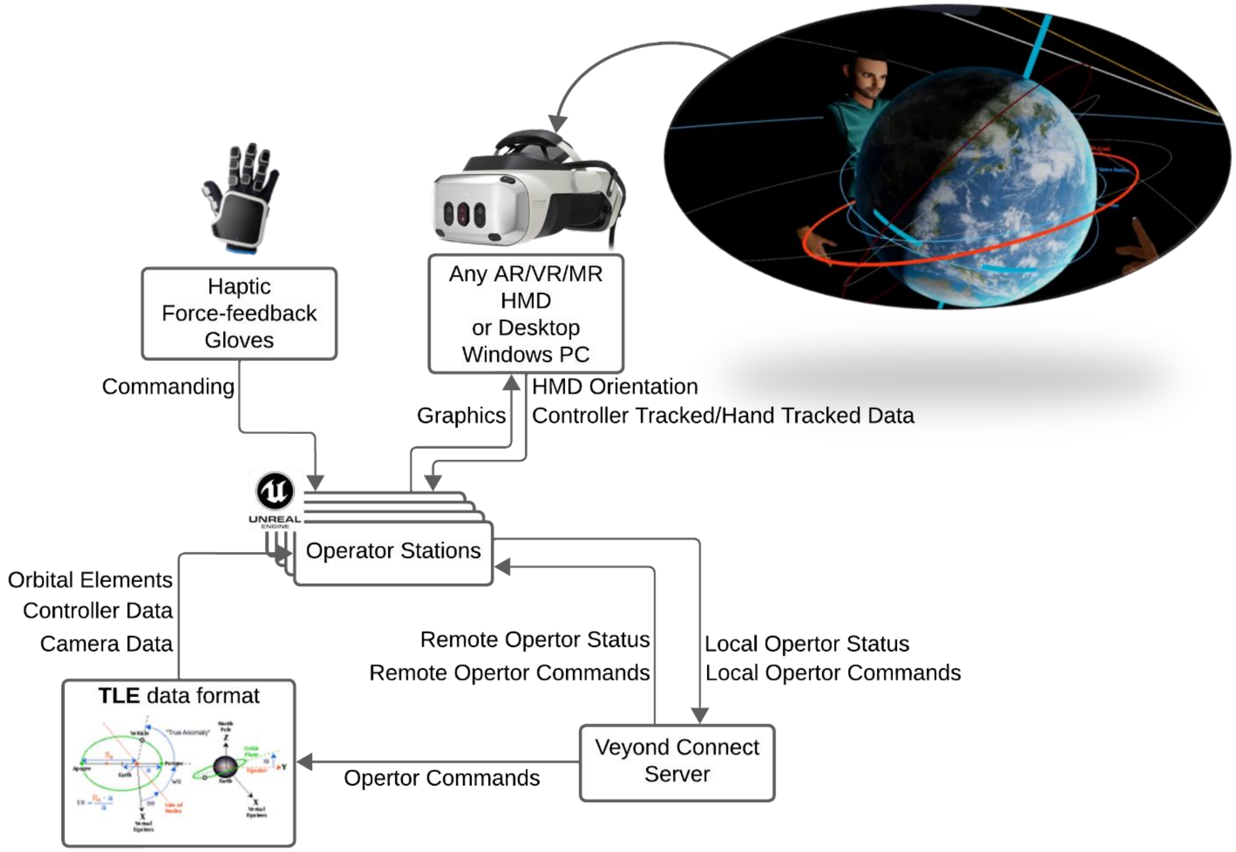


Fig. 3. Simplified flowchart describing the process of displaying mission control centre information in the immersive environment

4. Results and Scenario Verification

To verify the current capabilities of the immersive control centre, a simulation scenario was defined in which a satellite was predicted to enter a collision course with a piece of orbital debris. The aim of this scenario was to demonstrate the system's functionality in supporting real-time decision-making, collaborative mission planning, and orbit modification through a shared immersive digital twin environment.

The following two figures showcase the key stages of this verification scenario: (1) identifying the collision threat and initiating collaborative analysis, and (2) designing, testing, and implementing a new orbital path to prevent the collision.

Figure 4 illustrates the first stage of the scenario, where operators become aware of a potential collision and initiate a collaborative mission session within the immersive control centre. In this figure, the digital twin environment shows the satellite's current orbital path intersecting with a projected trajectory of an orbital debris object. The system uses bounding-box proximity thresholds and predicted time intervals to identify potential collisions based on TLE updates. This visual warning, rendered in the immersive interface, alerts the operators in real-time to an imminent threat. Operators from different geographical locations join the session via their XR headsets. The immersive control centre enables real-time shared views of the 3D orbital scenario, with synchronized visualizations and communication tools. Users can point, annotate, and discuss using virtual pointers and in-scene avatars. Here, the mission team discusses the severity of the threat and evaluates response timelines. The use of immersive audio and gesture interaction enhances communication efficiency. The team evaluates multiple parameters such as satellite manoeuvrability, time-to-collision, and available propulsion capacity. Using control inputs mapped to haptic devices or handheld controllers, users access panels that simulate the effects of potential orbital changes. This immersive approach enables intuitive understanding of complex orbital dynamics, offering better situational awareness than traditional 2D screens.

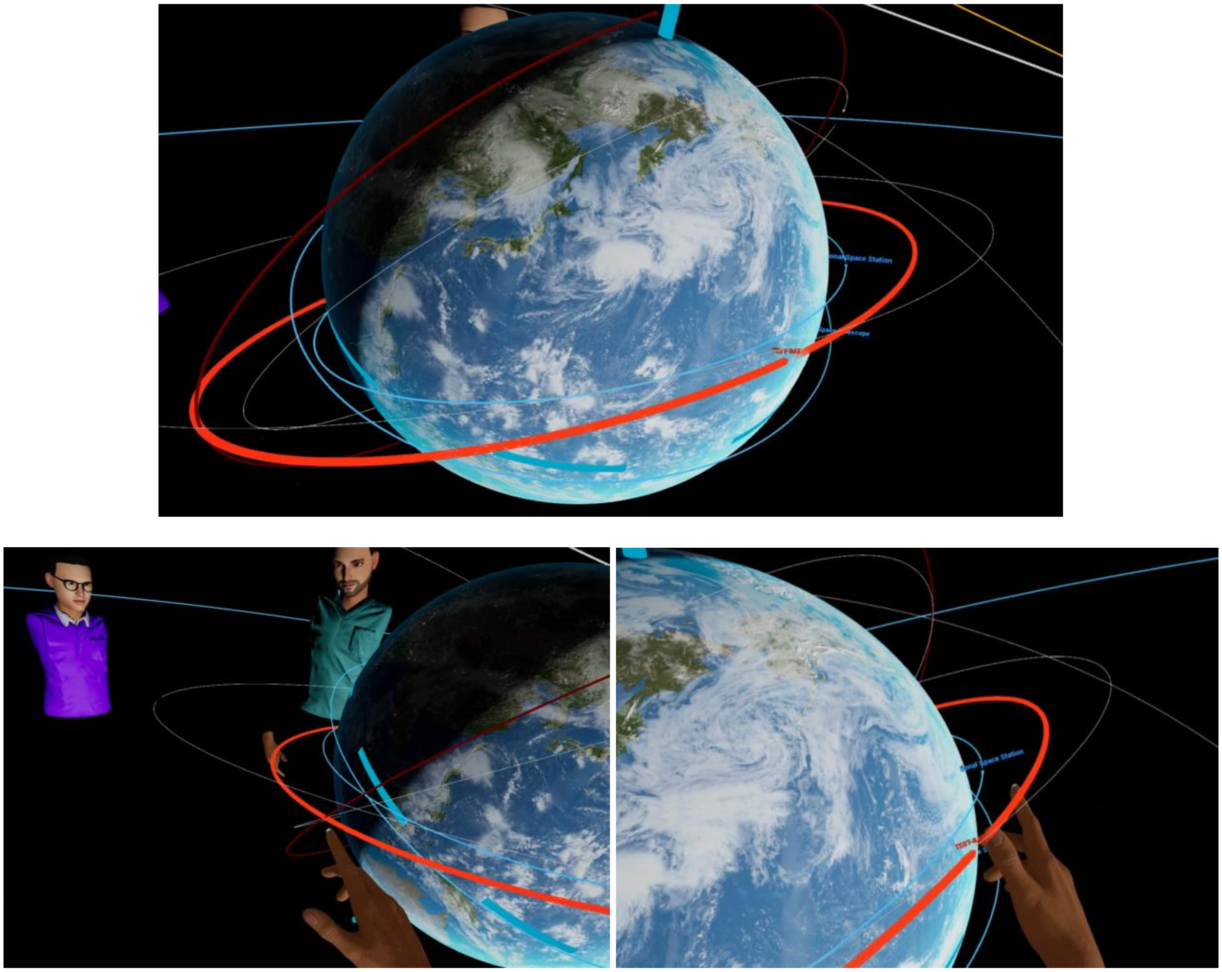


Fig. 4. Collision risk identification and collaborative response

Once the collision threat is confirmed, the mission team proceeds to design and test an orbital adjustment strategy in the digital twin environment before applying changes to the real satellite. With respect to figure 5, the team collaboratively defines a new orbital trajectory that alters the satellite's velocity vector to achieve a safe distance from the incoming debris. The 3D model shows the adjusted trajectory, rendered with predictive analytics and motion simulation. The immersive interface allows the users to intuitively visualize the orbital transfer and ensure that the satellite remains within mission parameters post-manoeuvre. Before implementing the manoeuvre on the actual satellite, the newly defined orbit is tested within the digital twin simulation. The MR system simulates satellite behaviour post-adjustment, including orbital period, path stability, and clearance from both the debris and other known objects. By visualizing these dynamics in real-time, the operators can verify that the manoeuvre achieves the desired outcome without introducing new risks. Once verified, the manoeuvre commands are confirmed and transmitted to the satellite. The immersive control centre displays the transition of the satellite into its new orbit, which is tracked live via updated TLE data. Post-execution, the team continues to monitor satellite status and confirms that no secondary threats are present. Feedback is also provided to the digital twin for future model calibration.

This scenario showcases the practical utility of the immersive control centre in real-world applications. From threat identification and collaborative planning to safe implementation, the system facilitates a seamless transition between simulation and execution. It demonstrates how XR, haptics, and digital twin technologies can significantly enhance astronautics operations by promoting situational awareness, reducing decision latency, and minimizing mission risks.

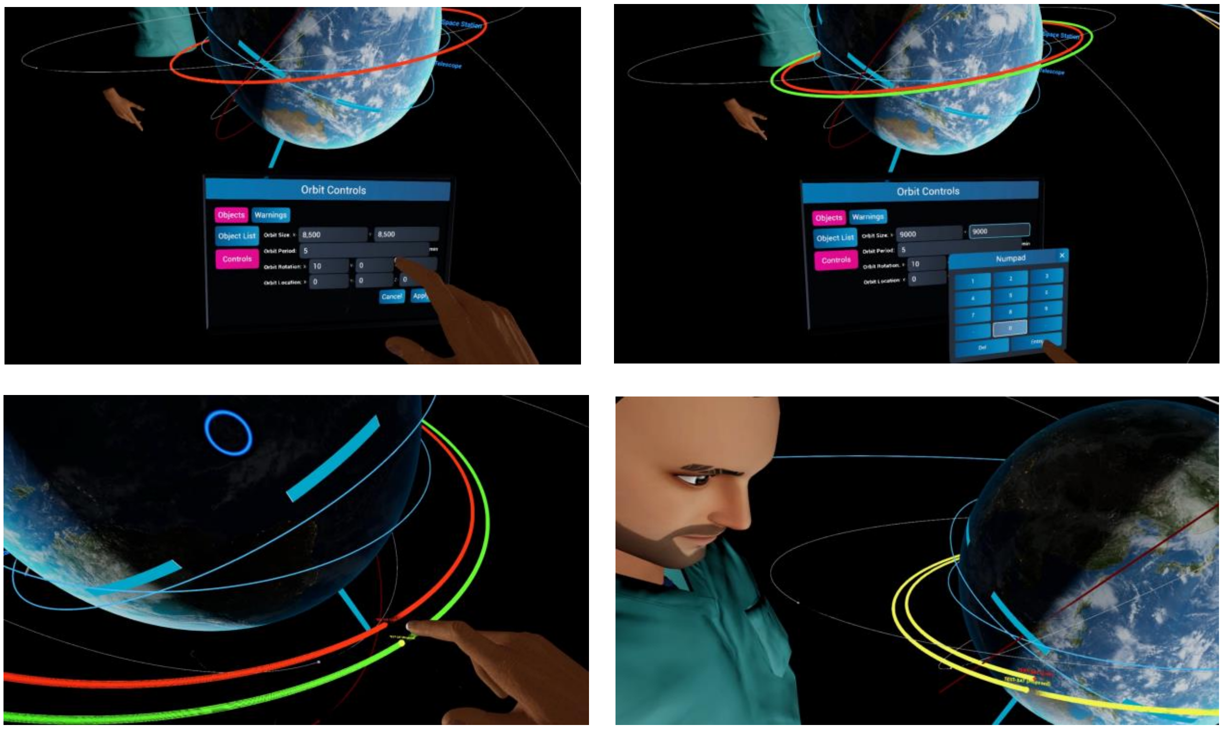


Fig. 5. Orbital adjustment simulation and execution

6. Conclusions

This work presented the development and verification of an immersive control centre designed to transform the management of complex space missions. By integrating XR, real-time data processing, and digital twin environments, the system enhances operator situational awareness, collaborative decision-making, and mission responsiveness. The architecture, developed in Unreal Engine, allows seamless cross-platform deployment, haptic interaction, and wireless streaming to XR headsets. Through a representative collision avoidance scenario, we demonstrated the centre's ability to detect orbital threats, facilitate global team collaboration, simulate alternative trajectories, and verify outcomes before applying them to real systems. This approach bridges the physical and digital domains, offering a practical solution for next-generation space mission control. The immersive control centre sets a foundation for future advancements in deep space operations, where intuitive, real-time interaction and collaboration are essential. Ongoing work focuses on expanding system scalability, AI integration, and enhanced autonomy for broader mission applications.

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