Integrating Fragmented Aerospace Research Data through an MQTT-Driven Serious Game Ecosystem

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Abstract. Introduction*: This paper addresses data fragmentation in aerospace laboratories, where isolated systems hinder tactical decisions.* ***Objective****: To solve this, a Digital Twin ecosystem was developed as a Serious Game, centralizing data via an MQTT backbone to synchronize a 2D strategic touch table and a 3D Mixed Reality headset.* ***Methodology****: A custom Takeover and Handoff protocol over MQTT was implemented to resolve multi-user authority conflicts between the different interfaces.* ***Results****: Results demonstrate this architecture efficiently translates raw telemetry into interactive visualizations, providing a collaborative space that seamlessly connects physical assets to virtual simulations.*
Keywords *Serious Games, Mixed Reality, Digital Twin, MQTT, Aerospace.*

1. Introduction

The rapid advancement of Automatic Dependent Surveillance (ADS) and Unmanned Traffic Management (UTM) has transformed aerospace and defense research. Laboratories dedicated to these fields continuously develop highly specialized algorithms, sensor networks, and autonomous routing protocols. Using a university aerospace research laboratory as the primary case study, this paper addresses a common challenge in these environments, data fragmentation. Different research fronts often produce and analyze data in isolated silos, lacking a unified visual interface. This fragmentation hinders a holistic understanding of complex operational scenarios, making it challenging for operators and researchers to make rapid and informed tactical decisions.

To bridge this gap, Serious Games have emerged as powerful tools. Using high-performance game engines, Serious Games can translate complex raw datasets into interactive real-time tactical visualizations. In this context, this paper presents a unified Serious Game interface designed to centralize heterogeneous data from the laboratory into a single Digital Twin ecosystem. Extending beyond a passive Digital Twin visualization platform, this system incorporates active mechanics inspired by Real-Time Strategy (RTS) games and traditional wargaming. Operators do not merely observe the simulation; they actively interact with the loop by spawning, manipulating, and altering the state of entities in real-time, effectively turning the environment into an interactive tactical sandbox.

The proposed ecosystem acts as a distributed simulation environment. However, visualizing this data effectively requires different perspectives depending on mission needs. Therefore, this project implements and synchronizes two distinct game-based interfaces. The first is a strategic 2D touch interface inspired by Real-Time Strategy (RTS) games for global situational awareness, while the second is a 3D Augmented Reality (AR) interface focused on tactical immersion. Connecting these interfaces to raw research data requires a robust communication backbone capable of ensuring real-time interoperability without overloading the network.

The main objective of this paper is to propose and evaluate an interoperability architecture based on the MQTT protocol to integrate fragmented laboratory data. This work aims to demonstrate the synchronization between strategic and tactical interfaces using a game engine. Furthermore, the work proposes a Takeover and Handoff protocol over MQTT to resolve authority conflicts during multi-user interactions. By fulfilling these objectives, we intend to provide a scalable foundation for tactical decision-making that can transition seamlessly from simulated data to real-world physical assets.

2. Theoretical Foundation

This section establishes the conceptual pillars necessary to understand the integration between immersive simulations and distributed data architectures. The concept of wargaming has deep roots in tactical and strategic training. Historically defined by Perla (1985), a wargame is a model or simulation of a conflict in which the flow of events affects, and is affected by, decisions made by human players representing opposing sides. More recently, Perla (2022) expanded this vision through "The Cycle of Research and Learning," arguing that simulation (wargaming), experimentation, and data analysis must act in harmony to drive innovation and tactical understanding. When these simulations are transposed to a computational environment, they align with the concept of Serious Games. According to Laamarti, Eid, and El Saddik (2014), Serious Games are applications developed using game engine technologies, but whose primary purpose goes beyond mere entertainment, focusing on measurable learning, training, or operational outcomes. In our architecture, the core gameplay loop relies on real-time spatial interaction by creating, moving, and managing entities. Which directly mirrors the mechanics of RTS games. The effectiveness of these applications in simulating complex scenarios has been widely validated in contemporary literature. Damaševičius et al. (2023), for instance, highlight in their meta-review how serious games have matured into robust tools for practical training and data visualization in critical environments. In the specific context of Automatic Dependent Surveillance (ADS) and aerospace operations, the combined application of digital wargaming and serious games allows operators to interact with complex ecosystems, analyze fragmented research data, and test hypotheses in an immersive, safe, and rigorously controlled digital environment.

Extended Reality (XR) serves as a contemporary umbrella term encompassing a spectrum of immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). According to the recent terminological mapping by Laato et al. (2024), these technologies differ primarily in their level of immersion and relationship with the physical world: while VR completely replaces the user's environment with a digital model, AR overlays interactive elements onto the real world. In the domain of defense and traffic control systems, these technologies have transitioned from experimental to fundamental. Hurter, Causse, and Cordeil (2024) highlight in their analysis of XR trends in aviation that these immersive interfaces (such as 3D headsets) offer undeniable advantages for trajectory visualization, spatial depth perception, and individual tactical awareness in complex aerial scenarios.

Complementing the tactical immersion of XR, touch interfaces in a digital tabletop format fulfill the role of strategic visualization. As pointed out by Lei and Wong (2009) in their analysis of multi-touch interfaces, this technology revolutionized collaborative interaction. By providing a global view based on 2D maps (akin to Real-Time Strategy - RTS game dynamics), touch tables facilitate multi-user collaboration, allowing different operators to simultaneously discuss, plan, and interact with airspace data.

A distributed simulation occurs when different components of a system operate in distinct processes but maintain a synchronized virtual state. To enable this architecture without bottlenecks, the use of a highly efficient communication bus is critical. In this context, the MQTT (Message Queuing Telemetry Transport) protocol stands out. According to the official OASIS standard (2019), MQTT is a lightweight, client-server publish-subscribe messaging transport protocol. In MQTT, the central server is referred to as the broker. The broker is in charge of transmitting data from publishers to subscribers. The effectiveness of MQTT for real-time telemetry and resource-constrained environments is widely recognized. Aleesha and Laseena emphasize in their review that MQTT is a publish-subscribe messaging system that is both simple and effective. It is highly suitable for IoT architectures because it has a slim header structure that lowers packet parsing, making it ideal for energy-constrained devices. For an aerospace Digital Twin dealing with Automatic Dependent Surveillance (ADS) data, this means that a coordinate update published by a simulated algorithm or a real aircraft is instantly propagated to all connected strategic (2D) and tactical (3D) interfaces, ensuring absolute state consistency without overloading the local network infrastructure.

3. Materials and Methods

This section details the technologies employed and the architecture developed to design the proposed ecosystem. To solve the challenge of unifying the laboratory's various research fronts into a single immersive space, the project utilized a set of software tools, hardware, and communication protocols. To integrate physical and virtual systems developed in different programming languages, the MQTT protocol was utilized as the central data bus (backbone). Its main advantage is its lightweight nature and interoperability: an isolated laboratory algorithm acts as a publisher (sending variables), while the visual interfaces act as subscribers (consuming these variables) using standard JSON (JavaScript Object Notation) format. For the graphical environment and simulation logic (Serious Game), the Unity game engine was used, justified by its native capacity for high-performance 3D rendering and support for IoT integration packages. To ensure reproducibility and transparency, the core JSON protocol scripts and the lightweight interactive test scenes (excluding the heavy photogrammetry assets discussed below) are available in two separate open-source repositories, divided into the 3D and 2D modules (Silva and Cerqueira, 2026a; Silva and Cerqueira, 2026b).

From a hardware perspective, the strategic planning interface was executed on a large-format display adapted with an Infrared Touch Frame, while Meta Quest 3 Mixed Reality headsets were employed for tactical immersion.

The ecosystem was designed to simulate aircraft traffic based on Automatic Dependent Surveillance (ADS) technology, standardizing data with classical aerial surveillance parameters: Entity Identification (ID), Latitude, Longitude, and Altitude. To provide a high degree of tactical fidelity, the virtualized physical scenario reproduces the airspace of a university research campus. This process began with drone flights to capture videos of the studied airspace. The footage was processed in the RealityScan software (Epic Games) to generate a highly detailed 3D terrain model (Figure 1).

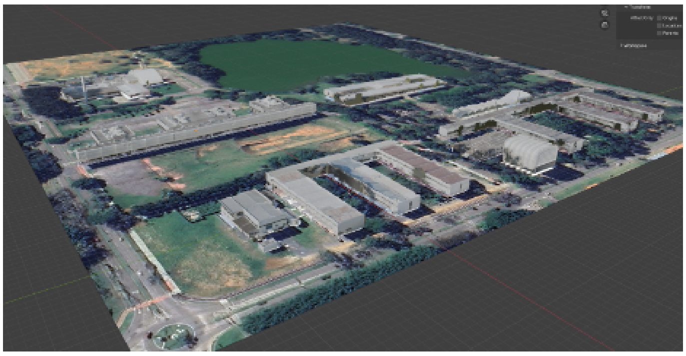

Figure 1. 3D terrain mesh generated via photogrammetry for the simulation scenario.

Because this initial mesh was too heavy for Mixed Reality headsets, it was imported into Blender for a drastic polygon reduction, optimizing it to run smoothly without losing visual fidelity. Inside Unity, a script named GPSMoving was implemented using five fixed calibration points to align the real geographic coordinates with the virtual world, automatically converting real Latitude and Longitude into Unity's local (X, Y, Z) position system.

The connection between Unity and the MQTT data bus was established using the M2MqttUnity library (Viganò, 2018). With it, the system receives messages and renders the aircraft on the screen. From this point, the project diverges into two distinct experiences. The first is a strategic 2D touch interface focused on a global view using monitors. The interaction works similarly to Real-Time Strategy (RTS) games: the user touches the screen, and the system calculates exactly where that touch intersects the 3D map to create, move, or delete entities (Figure 2).

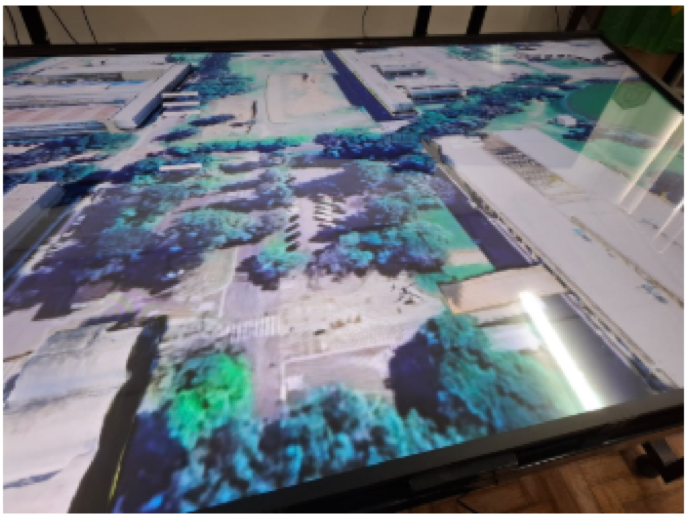

Figure 2. Strategic 2D touch interface.

The second experience is a tactical 3D Augmented Reality (AR) interface. The Meta XR All-in-One SDK package (Meta, 2024) was used to facilitate hand interactions. An important detail of this version is that the map is not static. To ensure the drones tracked the scenario, if the user decided to move or rotate the holographic map with their hands, all virtual entities were configured as "child" objects of the terrain mesh. Thus, visual synchronization is maintained regardless of the table's position (Figure 3).

Figure 3. Tactical 3D AR interface in Mixed Reality.

The biggest challenge of the distributed simulation occurred when both simulators attempted to interact with the same entity simultaneously. Since MQTT is fundamentally a publish-subscribe message broker without native state management mechanisms, it merely forwards conflicting coordinate updates, causing a visual "rubber-banding" effect. Traditional distributed simulation standards, such as High-Level Architecture (HLA) or Distributed Interactive Simulation (DIS), manage state ownership robustly. However, literature highlights that HLA is notoriously "heavy", complex to learn, and demands high-level software engineering skills to implement (Aizstrauts and Ginters, 2024). Furthermore, HLA's reliance on callback functions can introduce communication delays, making it cumbersome for agile XR environments. To solve this authority problem while maintaining the lightweight nature of MQTT, a custom Takeover and Handoff protocol was developed. By utilizing custom JSON payloads, the system manages authority and resolves the rubber-banding effect directly within the real-time rendering loop (Figure 4).

In the Initial Domain phase, when Simulator A creates a drone, it declares itself as both owner and controller, while Simulator B receives the entity and marks it as isRemote = true (acting merely as a visual mirror). During the Authority Transfer (Takeover), if the user of Simulator B interacts with this drone (e.g., grabbing it), its system forces the publication of a packet changing the controller to "Node B". Simulator A detects it is no longer the controller, pauses its movement logic, and activates isRemote = true. Finally, in the Return (Handoff) phase, as soon as the user of Simulator B releases the object, the system publishes a new JSON returning the controller to "Node A", which resumes its original control (isRemote = false), ensuring the multi-user ecosystem functions smoothly, effectively eliminating the rubber-banding effect.

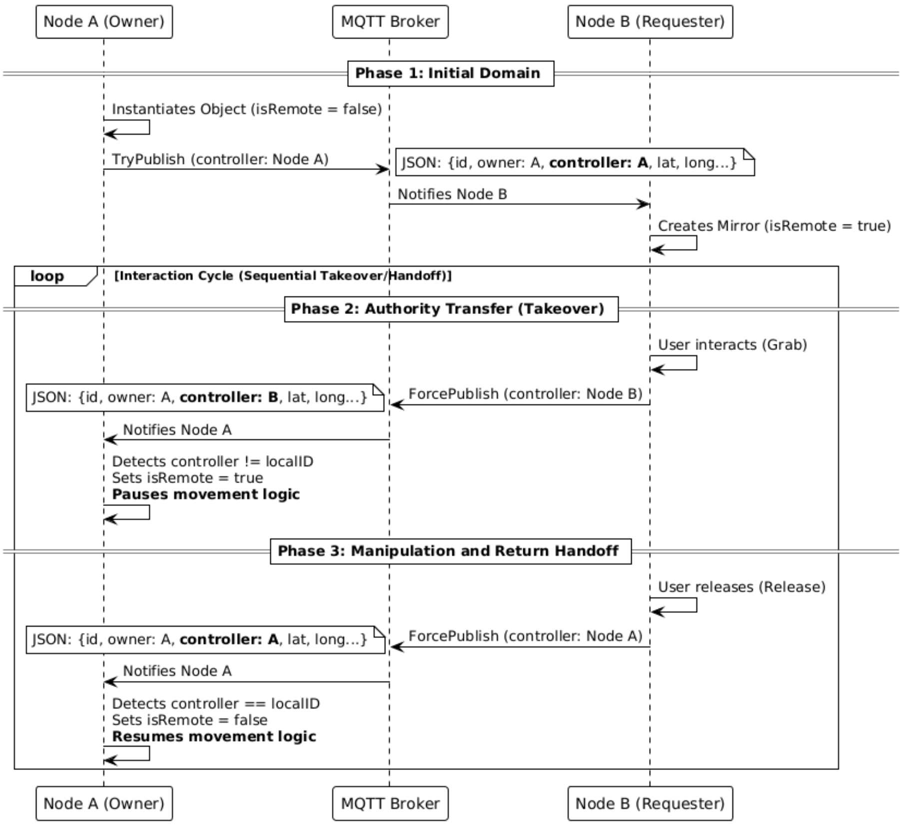

Figure 4. Sequence Diagram: Handoff and Synchronization Protocol.

4. Results and Discussion

This section analyzes the results obtained from implementing the proposed architecture, evaluating the fulfillment of the initial objectives, the system's limitations, and its scalability potential. The central hypothesis of this work presumed that data fragmentation in airspace management research could be mitigated through a centralized MQTT architecture. Practical results confirmed this premise. The data bus demonstrated total flexibility regarding the information source. In practice, the visual interface does not distinguish whether the coordinates (lat, long, alt) come from a simulated Python routing algorithm or from an antenna capturing real drone telemetry. This characteristic successfully fulfills the objective of transcending the purely virtual environment, connecting physical assets directly to the Digital Twin's data mesh.

Furthermore, providing complementary perspectives for decision-making was another achieved objective. While a single viewpoint can limit the planning of complex missions, real-time synchronization proved that the ecosystem meets different operational needs simultaneously. The strategic interface (2D touch screen) allows commanders to manage global traffic similarly to RTS games, while field operators can use the immersive interface (3D AR) to understand spatial depth and telemetry around them. This duality transforms raw data into intuitive tactical experimentation.

Regarding technical performance, practical evaluations confirmed that the primary efficiency of the proposed architecture lies in its data integration capabilities. Because the MQTT broker forwards interoperable, lightweight text-based JSON payloads, it efficiently unifies fragmented laboratory systems regardless of their native programming languages. In our implementation, we actively limited the publish/subscribe rate to one tick every 0.1 seconds (10 Hz) to test this integration pipeline. At this frequency, both the Meta Quest 3 headset and the strategic touch table processed the incoming telemetry smoothly without frame drops. Therefore, the efficiency of the system is demonstrated by its computational interoperability, successfully translating raw, multi-source telemetry into a synchronized 3D environment without overwhelming the local network infrastructure.

Despite the robust architecture, the implementation has practical limitations related to network infrastructure and Mixed Reality hardware. Technically, the primary limitation lies in the requirement for continuous connectivity, rather than bandwidth. Although the choice of the MQTT protocol successfully minimizes data payload and functions well in constrained networks, the Digital Twin still relies entirely on the continuous arrival of these messages to update its state. Therefore, severe network instability or complete physical disconnections directly impact the visual fidelity of the simulation. While latency, packet loss, or temporary network outages do not crash the application, they cause the simulated entities to stall, exhibit a rubber-banding effect (teleporting upon reconnection), or disappear entirely if no telemetry updates are received after a predefined timeout period. Regarding user experience, Human-Computer Interaction (HCI) literature points out well-known challenges for the tactical interface in Augmented Reality. Using Mixed Reality headsets for extended periods is known to cause physical discomfort, visual fatigue, and cybersickness (motion sickness induced by VR). Therefore, there is an inherent ergonomic limitation to the chosen hardware: while holographic 3D vision offers an incredible tactical immersion, it demands operational breaks and does not completely replace the comfort of a traditional 2D screen for uninterrupted work sessions.

5. Future Work

Beyond immediate tactical advantages, the implemented architecture serves as a highly scalable foundational base. Since the MQTT protocol allows adding infinite variables to the JSON payload without altering Unity's core structure, the system is ready for complex evolutions. Upcoming work will integrate No-Fly Zone detection logic, where aircraft dynamically calculate detour routes when approaching these geometries. Furthermore, the platform is intended to serve as a robust logistics planning tool. The 3D mesh will be fed with real-time meteorological variables (changes in wind, humidity, and temperature) to evaluate fleet behavior, aerodynamic performance, and battery drain prior to real-world flights.

As the primary scope of this work was to validate the MQTT network's technical viability as a Proof of Concept (PoC), a notable limitation is that formal empirical studies regarding Human-Computer Interaction (HCI) were not conducted in this initial stage. Since prolonged use of Mixed Reality interfaces can introduce ergonomic challenges, upcoming laboratory evaluations will include formal usability testing and user studies. These tests are essential to assess operator comfort, measure potential visual fatigue, and validate the decision-support effectiveness of the AR environment during extended simulation sessions.

6. Conclusion

Beyond immediate tactical advantages, the implemented architecture serves as a highly scalable foundational base. Since the MQTT protocol allows adding infinite variables to the JSON payload without altering Unity's core structure, the system is ready for complex evolutions. Regarding the intended decision-support outcomes, the platform will function as a collaborative mission planning tool capable of fusing data from different and isolated research laboratories. By breaking down these data silos, multidisciplinary teams can evaluate complex operational scenarios together. For instance, future work will integrate real-time meteorological variables to assess aerodynamic behavior, dynamic No-Fly Zone detour logic, and fleet battery drain prior to authorizing real-world physical flights.

The main contribution of this paper to the scientific community lies in demonstrating the feasibility and efficiency of using the MQTT protocol as a unification tool for complex research environments. By combining the lightweight nature of IoT protocols with the rendering power of game engines (Unity), the project successfully converts raw telemetry data into intuitive visual representations. It is concluded, therefore, that this architecture can transform isolated information silos into a collaborative and scalable space, allowing researchers and operators to have a unified, immersive, and accessible perception of everything studied and produced in the laboratory.

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