Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management, Orlando, Florida, USA, June 17-19, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250217
Published: June 17, 2025

CONCEPT IO: Open-source Arena for Academic CONOPs Experimentation of Robotics, Models, and Digital Twins

Christopher Shneider Cerqueira
Professor
Department of Aeronautical Engineering
Instituto Tecnológico de Aeronáutica
São José dos Campos, SP, Brazil
chris@ita.br

Jonas Fulindi Bianchini
Professor
Department of Aeronautical Engineering
Instituto Tecnológico de Aeronáutica
São José dos Campos, SP, Brazil
fulindi@ita.br

Lucas Oliveira Barbacovi
Instructor
Department of Aeronautical Engineering
Instituto Tecnológico de Aeronáutica
São José dos Campos, SP, Brazil
barbacovi@ita.br

Daniel Rondon Pleffken
PhD Candidate
University of Central Florida and Instituto Tecnológico de Aeronáutica
Orlando, FL, USA
rondon@ita.br

Abstract

This paper presents the CONCEPT.IO arena - an open-source simulation and demonstration arena architecture designed for academic CONOPs (Concept of Operations) experimentation in system of systems involving robotics, models, and digital twins. The platform integrates mapping, MQTT (Message Qu-based communication, and a multi-modal interaction to replicate both virtual and physical environments. Such integration enables testing and validation of operational concepts, providing an educational resource for student-led projects. Using real-time logging, sensor-driven digital twins, and controlled simulation scenarios, the arena enables to verify that designed CONOPs are both applicable and effective within the intended context. This paper further discusses the challenges and benefits of using open-source elements to bridge theoretical instruction and practical application, ultimately advancing academic research in systems engineering and system of systems.

Keywords
CONOPs, Demonstration Arena, Digital Twins, Robotics, System of Systems

1. Introduction

Modern systems operate within environments characterized by increasing complexity. Multiple systems, diverse technologies, and heterogeneous domains now coexist, creating intricate, and often uncertain, operational landscapes of system of systems (INCOSE 2023) (DeLaurentis et al. 2022) This complexity poses significant challenges in developing robust Concepts of Operations (CONOPs) (INCOSE 2023) (ANSI/AIAA 2018) (IEEE 1998) that are both realistic and comprehensive.

In such multifaceted environments, the need to capture and validate stakeholder intentions becomes paramount. The CONOPs phase in systems engineering is designed to demonstrate that the needs and intentions of all stakeholders have been accurately identified and integrated. A structured approach is essential to ensure that every aspect of a system's operational plan is feasible and aligned with real-world demands. The challenges are not confined to industrial or governmental projects; they extend to academic and project-based environments as well. Student-led projects benefit from a dedicated simulation and demonstration arena (Andersson et al. 2021). Such a facility provides both students and professors with a controlled yet realistic platform to test and validate their projects, thereby bridging the gap between theoretical design and practical application, closing the CDIO (Conceive-Design-Implement-Operate) loop (Crawley 2007).

A simulation arena serves as a microcosm of a more complex projects where similar validations are employed at the end of the development lifecycle. NASA (National Aeronautics and Space Administration) (NASA 2019) states that one of the methods that can be used to validate is the demonstration and defines as: "showing that the use of a product achieves the individual specified requirement. It is generally a basic confirmation of performance capability, differentiated from testing by the lack of detailed data gathering. Demonstrations can involve the use of physical models or mock-ups; for example, a requirement that all controls shall be reachable by the pilot could be verified by having a pilot perform flight-related tasks in a cockpit mock-up or simulator. A demonstration could also be the actual operation of the product by highly qualified personnel, such as test pilots, who perform a one-time event that demonstrates a capability to operate at extreme limits of system performance, an operation not normally expected from a representative operational pilot."

By replicating the conditions under which projects are validated, particularly close to their operational objectives and setting up complex exercises' setup (Brazilian Air Force 2024) shows as a complex system by itself, especially academic, in educational settings, to test and refine their design in complex operational scenarios. To try to accomplish that, the hypothesis is a construction of a simulation/demonstration environment that can replicate real-world conditions and facilitate the systemic evaluation of system performance. So, our objective, shown in this paper was to describe the creation of a simulation-demonstration arena, called CONCEPT.IO, designed to provide an environment for CONOPs experimentation, where was necessary to consider:

- an easy to interconnect protocol to monitor and distribute data through the analyzing systems and the simulated entities;
- a multi-modality of entities and their appearance-interaction;
- a common place where operational entities would interact; and
- a background history to provide provoking situations to the entities deal with it.

This paper is organized as follows:

- Section 2 describes the arena infrastructure, covering the communication framework, agent interactions, and the high-fidelity mapping that collectively support integration between virtual and real-world elements.
- Section 3 presents the CONOPs-based simulation framework, outlining the design of operational scenarios, the implementation of hackathon-style challenges, and the application of Measures of Effectiveness to assess system performance.
- Section 4 discusses the experimental results, providing insights into the practical validation of the CONOPs and lessons learned from the integration these technologies.
- Section 5 offers a discussion on the challenges encountered, the implications for future research, and the potential for application of this arena.

- Finally, Section 6 concludes the paper by summarizing the contributions.

2. Arena Infrastructure

This section details the core components that form the arena infrastructure. There are just a few open research-related examples crossing the words "demonstration arena" and ("multidomain" or "system of systems"), to be able to go into a deep survey of the Arenas to understand the main requirements points needed to prepare a setup to do virtual/real multi-domain testing. As example, was found the WARA-PS Arena (Andersson et al. 2021) (Yu 2024) which is an arena designed to robot experimentation in the subject of public safety (and already a partner of this project); it allows virtual and real entities to collaborate towards a mission-based approach to be solved by water-air-ground multi-domain systems. The same approach was designed to the Project SHERPA (Marconi et al. 2012) in the context of the Swiss Air Rescue into alpine environments. However, it is important to note that there are several domain-specific demonstration arenas as the UAS (Unmanned Aerial System) Traffic Management (UTM) Field Test Arena conducted to validate stands and capabilities to drone operations in virtual-real world (FAA 2023). From such examples, three main elements can be addressed: Communication, Agents, and Map.

2.1 Communication

An interconnection between entities is crucial for easy integration and real-time data exchange. Digital twins, simulation agents, and user interfaces must interact continuously to support dynamic scenario modeling and decision-making. This connectivity ensures that updates, commands, and data flows remain synchronized across the simulation ecosystem.

There are several standards to do distributed simulation and complex exercises as HLA (High Level Architecture) (Dahmann 1997) (Dahmann and Morse 1998) and DIS (Distributed Interactive Simulation) (Fullford 1996) (IEEE 2015). Both require an expensive setup and hard definitions of the artefacts and interfaces. To not undermine the barrier of the interconnection, we adopted the MQTT (Message Queuing Telemetry Transport) (ISO 2016) communication protocol as the backbone of our arena, based on the EMQx[1] implementation. MQTT is a lightweight, publish-subscribe messaging protocol designed for IoT applications, which makes it particularly well-suited for environments where low bandwidth and minimal overhead are essential. Its simplicity and reliability have made it a popular choice for connecting disparate systems in real-world IoT deployments.Leveraging MQTT, our simulation arena communication framework facilitates message exchange between digital twins, agents, and users. Its versatile implementations span multiple languages such as MATLAB, C++, Java, and Python, and even extend to embedded systems like Arduino, Raspberry Pis, ESPs and others. This broad compatibility allows developers to integrate MQTT into various platforms, easing the effort for using the arena, and performing their experiments.

MQTT is utilized for multiple purposes, illustrade in Figure 1, where (a) simple message sending to the broker allows various systems to publish into topics. For example, digital twins and simulation agents can send sensor readings, event alerts, or status changes as lightweight messages that the broker distributes efficiently. This ensures that the entire simulation is kept up to date with minimal overhead; (b) a user interface (UI) subscribes to specific topics on the MQTT broker to consume real-time information. In this setup, the UI acts as a listener, automatically receiving data from entities as soon as messages are published. This capability enables the UI to provide visualizing, which is critical for monitoring and situational awareness; and (c) MQTT facilitates control commands from the UI to the entities in the simulation, operating similarly to a ROS action approach (Macenski et al. 2022). In this case, the UI sends control messages that trigger specific actions in the system entities. The entities then acknowledge and execute these commands, ensuring that user inputs lead to the desired operational changes in the simulation environment. This interactive control mechanism mimics the feedback loop found in ROS actions, where a goal is sent, progress is monitored, and a result is returned, ensuring acknowledgment mechanisms over the simulation arena.

[1] Available at: https://www.emqx.com/en

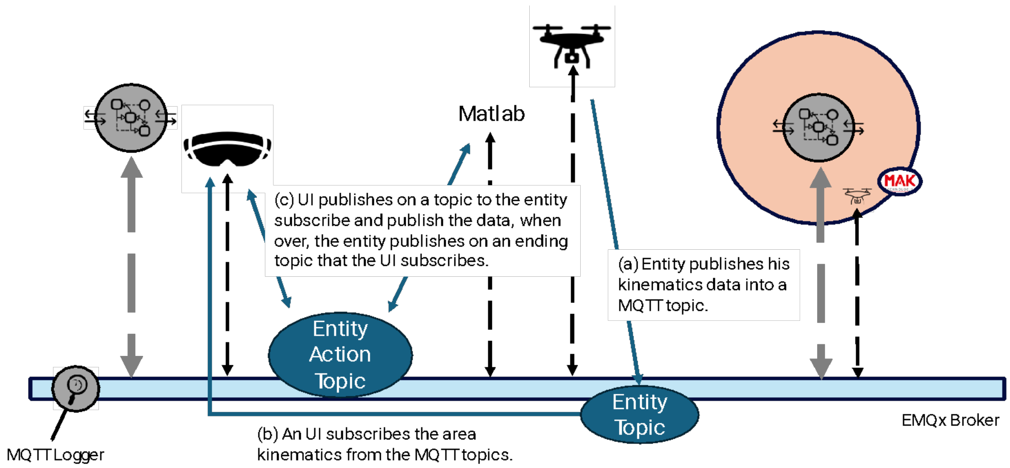

Figure 1. Example of the structure implemented with the MQTT.

2.2 Agents: User, Digital Twins, Robots, Systems

The arena supports a diverse set of users. Each user group is provided with tailored interfaces and can interact with the simulation environment. The design encourages intuitive interaction, minimizing the learning curve for new users while offering advanced functionalities for experienced operators. Within the CONCEPT.IO arena, interactions can occur along a broad spectrum, ranging from purely physical (real-to-real) to entirely digital (virtual-to-virtual), as well as hybrid scenarios (real-to-virtual and virtual-to-real). These various modes of interaction are illustrated in Figure 2, which presents a taxonomy of possible configurations involving real users, digital twins, robots, autonomous systems, and AI-driven components. Whether the interaction takes place in a traditional Graphical User Interface (GUI), through Virtual Reality (VR), Augmented Reality (AR), Cross-Reality (XR), Mixer Reality (MR) or Hyper Reality (HR), the underlying requirement remains the same: all exchanges must be sensed, tracked, and logged. (Cerqueira 2018) (Kiner et al. 2012)

To achieve this, the arena's infrastructure monitors and records each interaction (through a logging service), regardless of whether it involves a physical robot responding to a virtual command or a digital twin operating in parallel with a real-world counterpart. For instance, a human operator in VR can issue navigation commands to an autonomous robot in a physical environment, while the same scenario is mirrored by a digital twin for further analysis. This comprehensive tracking ensures that the entire system—users, digital twins, autonomous platforms, and any supporting AI—can be visualized in real time. By unifying these interaction streams under a single monitoring framework, students gain a holistic view of ongoing operations. The ability to see through different reality paradigms (GUI, AR, VR, XR, HR) or combine them in novel ways makes the arena. Ultimately, the goal is to maintain situational awareness across all facets of the simulation, enabling more informed decision-making and a clearer understanding of how different CONOPs may perform under both physical and virtual conditions.

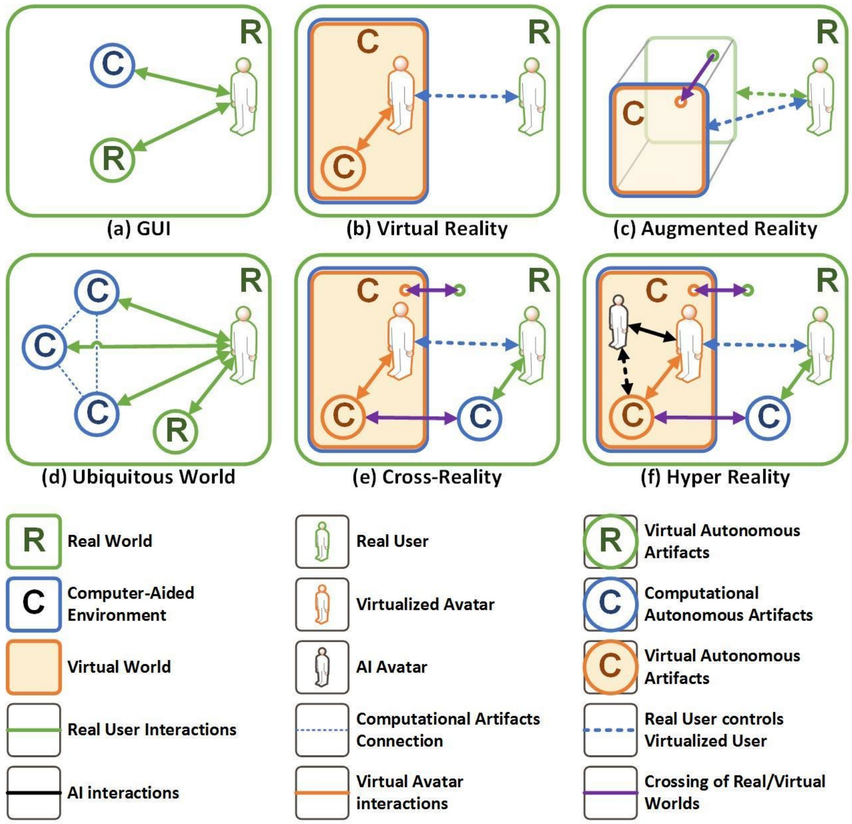

Figure 2. A taxonomy of potential interactions in the arena, spanning real and virtual domains. (Cerqueira 2018)

Uttermost the desired environment is the hyper reality, where human intelligence cooperates with artificial intelligence, to be able to do the human-AI teaming, a digital representation of the human needs to be available inside of the virtual world to interact with the AI, and within this interaction, feedbacking back to the real human.

2.3 Map

The map serves as an overlay that superposes virtual elements onto the real world. To achieve this level of detail, rather than relying solely on traditional building blueprints, we employed photogrammetry captured by drones using Reality Capture[2] software. This approach ensures that the overlay reflects an accurate representation of the current environment, up until it a revitalization or a new building appears.

The map itself is a digital twin. It can be continuously updated by sensors placed around the campus to capture variables such as vehicle and pedestrian movement, temperature, wind, pollution, illumination, and more. These sensor network create a digital representation of the environment, where each characteristic influences both the behavior of simulated agents and real-world operations. For example, wind conditions that physically affect drone trajectories are mirrored within the simulation to ensure consistency between virtual predictions and physical outcomes. In our current implementation we use the software VR-Forces from MAK[3] as a situation simulator to create virtual conditions (weather) as well as virtual entities, and within an internally designed plugin we publish all the simulated entities on the MQTT as well as reading all the user entities being published on the subscribed node.

Figure 3 illustrates this superimposed structure of the real location (in gray on the bottom) augmented with the virual layer (in blue on the top). These together are twins, the simulated situation is created and exported to the MQTT broker, as well as real entities assets that could be on demonstration at the arena.

[2] Available at: https://www.capturingreality.com

[3] Available at: https://www.mak.com/mak-one/apps/vr-forces

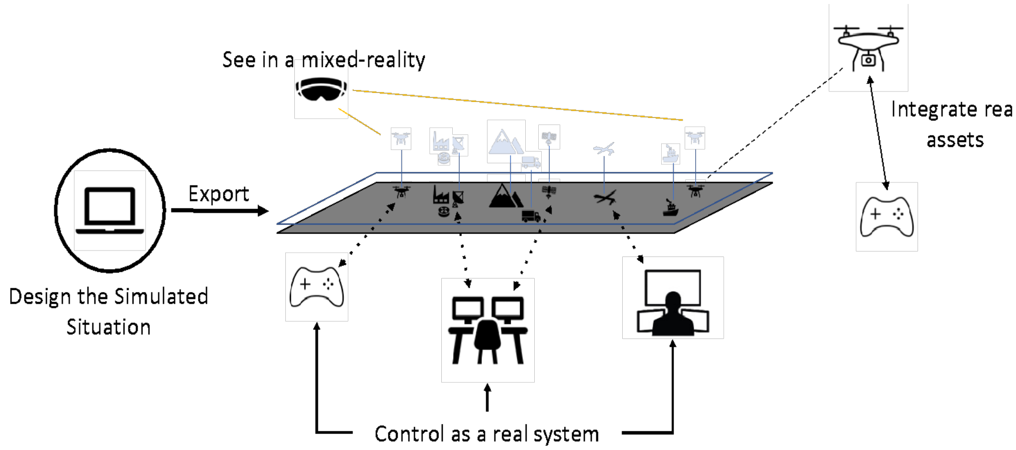

Figure 3. World combination structure.

Real and Virtual layers (aka Digital Twins) can represent part real and part virtual to explore real entities assets on the design space integrated with simulated systems, with autonomous algorithms or being virtually controlled through real interfaces. A desired situation can start the demonstration with virtual elements, being seen by different user interfaces (table / MR / specific interfaces).

Simulated entities can participate and being seen on different user modalities (Figure 4). As all the data is on the MQTT bus, each interface can show it on a different approach, with MR, was explored to see it with the Meta Quest 3 glasses, with embedded software exported from the Unity Game Engine; with tabletop, was mounted a 85" TV with a touchscreen layer to be able to interact with the system of system creation as a wargame strategic map; and the usual TV output of generated map from the VR-Forces simulator. This combination of MR, tabletop, and standing TV views highlights the flexibility in accommodating different user preferences and collaboration styles through this simple MQTT data distribution.

Figure 4. Multimodalities of visualization.

Left is a MR View using the Meta Quest 3 glasses where we can see the map of the simulated area - where the user is capable of seen the entities being simulated like a "hologram"; on the top right a tabletop view of the map – where the users is capable of seen the entities on a 2D map around the table and discuss looking to each other; and on the bottom right a standing TV view with the visualization of the VR-Forces generated Map – where the user see the entities on a flat screen that can show in 2D/3D but they are all facing the TV and to discuss they have to change the attention from the map to the other person.

Furthermore, the other systems can be part of the map to supports the simulation, as the integration of virtual management systems. By incorporating these virtual management entities, the arena can include UTM (Unmanned Traffic Management) behaviors, management of airspace and (to be implemented in the future) ground or water traffic. This enables the verification and validation of complex CONOPs of such systems being used by the other systems. Figure 5 exemplifies the integration of UTM data into a simpler map and the same area on the process of being fully captured by drone photogrammetry.

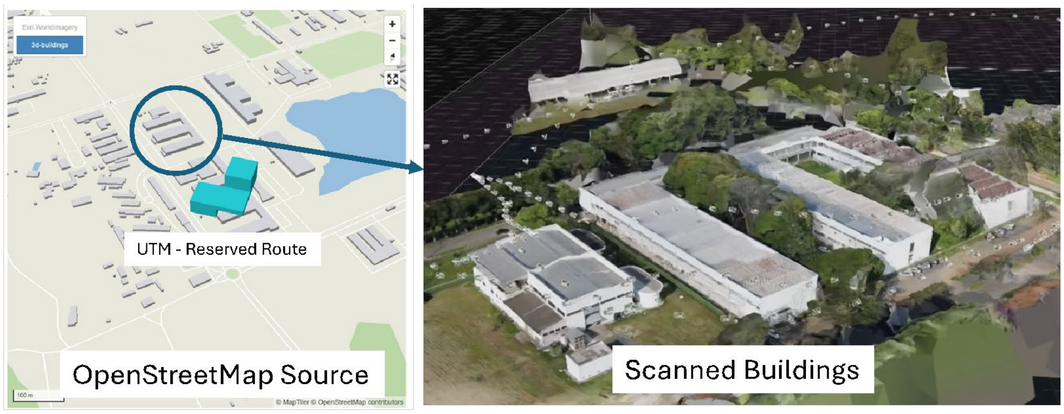

Figure 5. Map digital twin creation.

On the left an student implementation of an Unmanned Traffic Management System, showing a reserved route between some building. It is circled a complex of three buildings that are shown on the right that was reconstructed from the captured pictures during student flights around the school campus.

It is important to point that, to address privacy concerns and data protection, the arena is designed to replace real sensor data with virtual avatars on the map when representing people and vehicles. This anonymization ensures that while environmental and operational data is captured for analysis, the privacy of individuals is maintained throughout the simulation – and there was no continuity between captured movements through the sensors implemented.

3. CONOPs Based Simulation

The creation of a simple but effective CONOPs is critical to the success of the arena as a verification tool. In this context, the CONOPs must be developed with an understanding of the existing map, incorporating pre-prepared problems and opportunities designed for student engagement. Crafting an overall CONOPs is a challenge, as the responsible team needs to analyze the mapped environment and envision scenarios that could occur within it (virtually and physically).

Once the CONOP scenarios are established, students are presented with situational challenges in a *hackathon-style format*. They must design and implement solutions tailored to address the specific scenarios, thereby proving the practical applicability of their projects. This dynamic approach not only simulates real-world pressure but also fosters innovation and collaborative problem-solving. Figure 6 illustrates possible placeholders of the mission that could be given to the students – where the students and their professors were asked to use aerial on different flight formations (left), in this, the students had to study how to control formation flight; and such swarm should be able to detect entities on the scenario and perform collision avoidance maneuvers in time to do not hit other aircrafts or obstacles while coordinating w/ a virtual Unmanned Traffic Management (depicted on the left of the Figure 5) – where the students and their professors were asked to do this complex strategic deconflict and virtual detect and avoid maneuvers.

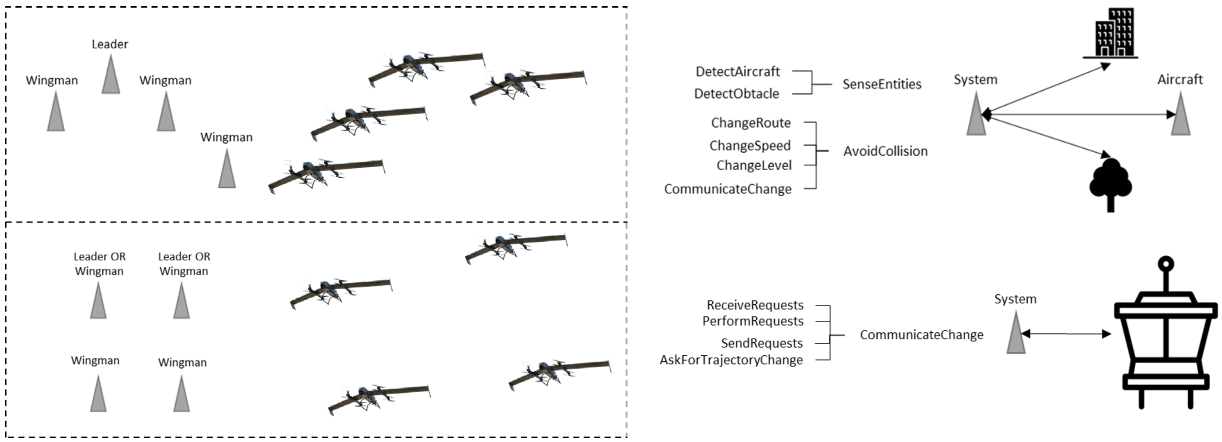

Figure 6. Example of possible situations to be placed as challenges.

On the left a fleet of eVTOL drones that can be settle as the available elements, as well as decide patterns of searching. On the right a detection set of attributes that can be decided regarding the system interaction with other entities of the arena (problem domain, map entities or other user entities).

As it is a Systems Engineering exercise, the use of Measures of Effectiveness (MoEs) plays a pivotal role in this process. MoEs are quantifiable metrics that evaluate the mission success of the system of systems involved (Frenz et al, 2010). For instance, in a search and rescue scenario, one MoE could be the average response time to victim detection, which assesses how quickly the system can locate individuals in distress. Another example might be the accuracy percentage in correctly mapping hazard versus safe zones, ensuring that the deployed resources are optimally utilized. These metrics, among others, encompass various operational parameters such as resource utilization and overall mission completion rates, providing a standardized way to assess whether the objectives of the CONOPs have been met.

To collect the necessary data for these evaluations, students must analyze logs generated by the MQTT communication broker. This log analysis is also a mission in itself - students are asked to prove that they completed their tasks effectively by meeting the MoEs. The logged data provides a detailed record of system interactions at the MQTT, allowing for an objective assessment of each project's success.For example, consider a search and rescue mission scenario simulated on a university campus. In this scenario, the CONOPs team designs a situation where a simulated event has occurred on campus. Students must coordinate digital twins of emergency response units, deploy autonomous drones (real ground w/ simulated aerial) to survey the area, and analyze sensor data to locate possible victims. The mission's MoEs could include response time to locate survivors, accuracy in mapping hazard zones, and efficient allocation of rescue resources.

By analyzing MQTT logs, the students can validate whether their system met the required metrics, thereby demonstrating the efficacy of their operational design. So, it also reminds that ir order to be able to evaluate, all the participating agents must share data, and that is critical to the success of the Arena.

4. Discussion

The development of this work was not different from the development of a local, virtual-physical, MMORPG (Massive Multiplayer Online Role-Playing Game). The arena brings challenges in syncronization of the messages, which relies on the edge within the agent entities tracking time, and on the engaging of the user to expose more data as possible to aid the validation of CONOPs for the complex systems. By integrating diverse components - from MQTT-based communication and digital twin overlays to sensor-driven mapping and autonomous agent interactions - the demonstration arena proposed is a quite simple testbed where both virtual and real-world elements can coexist and be evaluated together - infrastructure wise is just a server with a MQTT broker.

One key discussion point is the effectiveness of using MQTT as the communication backbone. Its flexibility to support messaging across a variety of platforms and programming languages has enabled seamless integration among digital twins, physical agents, and user interfaces, however lacks on the capability of distributed simulation standards as HLA or DIS. A more robust communication framework would ensure that the real-time data exchanges are reliably tracked and recorded, providing the preciseness to evaluate system performance based on the established Measures of Effectiveness (MoEs).

Another focal area is the integration of the maps generated via photogrammetry with real-time sensor data. This dual-layer approach not only enhances situational awareness but also replicates the physical details of the environment within a digital twin. The ability to mirror real-world influences, such as wind affecting drone trajectories, in the simulated domain has proven essential for testing realistic operational scenarios. Moreover, the map's capacity to incorporate virtual management systems for UTM/UAM demonstrates the potential for advanced traffic and airspace control simulations. However, with annually events, changes on the real place must be replicated on the virtual world, this will add a layer of activity that will require a cyclic photogrammetry work previously to each event.

The CONOPs-based simulation framework offers significant pedagogical and operational benefits, particularly for academic settings. Students are challenged to quickly adapt and respond to dynamic, hackathon-style scenarios, leveraging real-time data from the MQTT logs to prove their projects' effectiveness against predefined MoEs. This hands-on approach not only validates their technical solutions but also bridges the gap between theoretical design and practical application—a critical step in systems engineering. It is important to have a professor, or senior students, with enough awareness of Systems Engineering to engage the responsibility to preapare a well designed CONOPs. With the students, we learned that the ones with previews knowledge on table RPG experience are the one with better changes to think in the whole mission and find gaps on the simulation history line. AI also helps on creating those situations and can be explored by the student and use the hallucinations as a non-sense exploration of things that could go wrong. Despite academic, industry and government can benefit from a demonstration arena infrastructure, where like the WARA-PS setup, the arena becomes a place to show engineering solutions towards a mission-based / CONOPs based scenarios, helping into the integration of settings as the triple-helix approach.

Despite some successes in classes use, challenges remain. Synchronizing interactions across multiple reality paradigms - virtual-to-virtual, real-to-virtual, virtual-to-real, and real-to-real - requires continuous refinement of both software and hardware interfaces. Issues such as evolving mixed-reality hardware, frequent updates in gaming engines that affect preview definitions, reliance on non-local Python libraries, and inconsistent campus-wide internet connectivity all contribute to these challenges. Furthermore, non-collaborative behavior in real-world settings can disrupt simulation continuity.

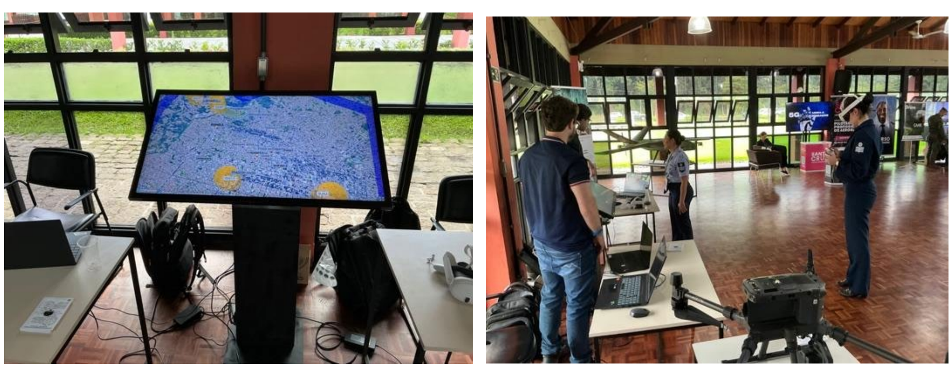

Figure 7. Example of a mobile setup of the arena at an event related to Air Traffic Management of Drones. On the left the touch screen interaction and on the right the first person view with the glass.

As the arena was designed to run with low specifications, several demonstrations are being done on events related to the multi-domain. Figure 7 exemplifies two of such use alternatives, where the picture on the left illustrates the touch screen interaction, synchronized with a MR Glass (on the right) that exhibits the same map. With a change of the map place (zoom, pan, rotation) on the touch screen, the map on the MR followed to show the same map on the glass – explicating the interconnection of two user showing the same area with different perception awarenesses.

The arena described in this paper leverages digital twins and cross-reality (Kirner et al. 2012) techniques to create a representative environment that the students can experiment their robots, model-only entities, digital twins and autonomous systems. This dual approach - encompassing both virtual simulations and physical testbeds - provides a versatile tool for CONOPs experimentation. By integrating digital representations with real-world elements, the platform tries to offer a systemic view of system behavior under various operational scenarios.

6. Conclusion

This paper introduced the CONCEPT.IO arena - a simulation/demonstration platform designed for CONOPs experimentation in complex systems involving robotics, digital twins, and autonomous systems. By integrating mapping, MQTT-based communication, and a multi-modal interaction framework, the arena replicates both virtual and physical environments, enabling rigorous testing and validation of operational concepts.

It is valid to note that there are plenty of simulators that perform multi-domain, or System of System, simulations – like the one that was used in the arena (the MAK's VR-Forces). Such software type could potentially allow live simulations, very close in concept of what this arena is proposed to do – where users perform their demonstrations / operations in real world, at real time rate. This arena setup tried to provide a more easier entry level to create such setups to both the arena host and to the arena quests. The platform's modular design not only facilitates interconnections among digital twins, sensors, and autonomous agents, but also provides an educational resource. Through real-time monitoring and detailed logging, students and invited researchers can analyze systems against their Measures of Effectiveness, ensuring that simulated scenarios reflect desired operational dynamics. The inclusion of diverse interaction styles - ranging from virtual-to-virtual to real-to-real - adds flexibility of the possible approaches to understand the scenarios.

Overall, the arena attempts to be a replicatable simulation environment, based on open-source elements, that enables verifying CONOPs in complex settings. By bridging the gap between theoretical classes and practical hands-on application, this platform offers significant potential for advancing academic research. Future work will also focus on enhancing the integration of sensors, expanding the range of simulated scenarios, and further refining the protocols to ensure logging capabilities and responsiveness in the environment.

Note

Artificial Intelligence was used to translate the text from Portuguese to English and improve the cohesion of the sentences.

Acknowledgements

We would like to demonstrate our gratitude to the SAAB Combitech, who introduced us on the Core Sytem that is used on the WARA-PS Arena, for its support in providing the knowledge that enabled this project. We would also like to thank the FINEP (Brazilian Financier of Studies and Projects), CAPES (Brazilian Coordination for higher Education Staff Development), and DECEA (Brazilian Airspace Control Department) for the project funding that allowed this infrastructure to be created and allowed the scholarships of the students that researched and implemented all the features.

References

American Institute of Aeronautics and Astronautics. *ANSI/AIAA Guide for the Preparation of Operational Concept Document*, G-043B-2018. ANSI/AIAA G-043B-2018. 2018.

Andersson, O., Doherty, P., Lager, M., et al. WARA-PS: A Research Arena For Public Safety Demonstrations And Autonomous Collaborative Rescue Robotics Experimentation, Auton. Intell. Syst. 1: 9. https://doi.org/10.1007/s43684-021-00009-9. 2021.

Brazilian Air Force. CRUZEX Exercise – Multinational Operational War Exercise in Latin America. Available: https://cruzex.fab.mil.br, Accessed on Jun 15, 2025, 2024

Cerqueira, C. S. *Tangible Collaboration Applied Into Space Systems Concurrent Engineering Concept Studies*, 219 p., São José dos Campos. Available: http://urlib.net/ibi/8JMKD3MGP3W34P/3QJP7M2. 2018.

Crawley, E. F. *Rethinking Engineering Education: The CDIO Approach*, New York: Springer. 2007.

Dahmann, J. S., *High Level Architecture for simulation. roceedings First International Workshop on Distributed Interactive Simulation and Real Time Applications*, Eilat, Israel, 1997, pp. 9-14, doi: 10.1109/IDSRTA.1997.568652. 1997.

Dahmann, J.S., Morse, K. L. High Level Architecture for simulation: an update. Proceedings. *2nd International Workshop on Distributed Interactive Simulation and Real-Time Applications (Cat. No.98EX191)*, Montreal, QC, Canada, 1998, pp. 32-40, doi: 10.1109/DISRTA.1998.694563. 1998.

DeLaurentis, D. A., Moolchandani, K., and Guariniello, C. *System of Systems Modeling and Analysis* (1st ed.), CRC Press. https://doi.org/10.1201/9781003231011. 2022

FAA. *UAS Traffic Management (UTM) Field Test*. Available at: https://www.faa.gov/uas/research_development/traffic_management/field_test, accessed on Jun 15, 2025, 2023.

Frenz, P., Roedler, G., Gantzer, D. J., and Baxter, P. *Systems Engineering Measurement Primer: A Basic Introduction to Measurement Concepts and Use for Systems Engineering*, version 2.0, San Diego, CA, USA: INCOSE-TP-2010-005-02. Accessed April 13, 2015. Available at: http://www.incose.org/ProductsPublications/techpublications/PrimerMeasurement, accessed on Jun 15, 2025, 2010.

Fullford, D. A. Distributed interactive simulation: its past, present, and future. In *Proceedings of the 28th conference on Winter simulation (WSC '96)*. IEEE Computer Society, USA, 179–185. https://doi.org/10.1145/256562.256601. 1996.

IEEE. *Guide for Information Technology – System Definition – Concept of Operations (ConOps) Document*, in IEEE Std 1362-1998, pp. 1–24, December 22, 1998. doi: 10.1109/IEEESTD.1998.89424. 1998.

IEEE. *IEEE Standard for Distributed Interactive Simulation (DIS) -- Communication Services and Profiles*. in IEEE Std 1278.2-2015 (Revision of IEEE Std 1278.2-1995) , vol., no., pp.1-42, 6 Nov. 2015, doi: 10.1109/IEEESTD.2015.7459689. 2015.

INCOSE. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 5.0, Hoboken, NJ, USA: John Wiley and Sons, Inc. ISBN: 978-1-119-81429-0. 2023.

International Organization for Standardization. ISO 20922:2016 – Information Technology – Message Queuing Telemetry Transport (MQTT) v3.1.1, Geneva, Switzerland: International Organization for Standardization. Available: https://www.iso.org/standard/69466.html, accessed on Jun 15, 2025, 2016.

Kirner, C., Shneider, C., and Goncalves, T. Using augmented reality cognitive artifacts in education and virtual rehabilitation, in *Virtual Reality in Psychological, Medical and Pedagogical Applications*, InTech. doi: 10.5772/46416. 2012.

Macenski, T., Foote, B., Gerkey, C., Lalancette, W., and Woodall, N. Robot Operating System 2: Design, architecture, and uses in the wild, Science Robotics 7, May 2022.

Marconi, L, Melchiorri, C., Beetz, M., Pangercic, D., Siegwart, R., Leutenegger, S. The SHERPA project: Smart Collaboration between Humans and Ground-Aerial Robots for improving Rescuing Activities in Alpine Environments. *2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR),* College Station, TX, USA, 2012, pp. 1-4, doi: 10.1109/SSRR.2012.6523905. 2012

National Aeronautics and Space Administration. *Systems Engineering Handbook*. Available: https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook, accessed on Jun 15, 2025, 2019.

Yu, Y., Lakemond, N., Holmberg, G. AI in the Context of Complex Intelligent Systems: Engineering Management Consequences. *IEEE Transactions on Engineering Management*, vol. 71, pp. 6512-6525, doi: 10.1109/TEM.2023.3268340. 2024.

Biographies

Dr. Christopher Shneider Cerqueira received a B.Sc. in Computer Engineering from the Federal University of Itajubá (UNIFEI) in 2010, and an M.Sc. in Space Engineering and Technology from the National Institute for Space Research (INPE) in 2014. In 2018, he completed his Ph.D. at INPE, concentrating on integrating Tangible User Interfaces with Model-Based Systems Engineering (MBSE) for complex space missions. He has more than 10 years of experience in digital engineering, systems-of-systems analysis, and aerospace systems design. Dr. Cerqueira has collaborated with major international institutions, including NASA, through the SPORT mission, and has led multiple funded research projects sponsored by Brazilian space and defense agencies. He is currently a Tenured Assistant Professor in the Aeronautics Engineering Department at the Instituto Tecnológico de Aeronáutica (ITA), where he coordinates a national research network on MBSE. His research interests include AI-assisted systems engineering, formal methods for safety-critical systems, and integrated digital frameworks for certification and operational readiness.

Dr. Jonas Fulindi Bianchini earned a bachelor's degree in computer engineering, an M.Sc. in Space Engineering and Technology from the National Institute for Space Research (INPE), and a Ph.D. in Space Sciences and Technologies from the Aeronautics Institute of Technology (ITA). As part of his doctoral work, he spent one year at the Massachusetts Institute of Technology (MIT) under the Brazilian Science Without Borders initiative, researching Systems Engineering and Launch Operations. He has contributed to multiple high-profile space programs in Brazil, including the development of microsatellite launch vehicles (VLM-1) and CubeSat missions, and has held key roles in configuration management, hazard analysis (STPA), and verification and validation of aerospace platforms. He has more than 15 years of experience in model-based development, safety analysis, and concurrent engineering, and has served as a thesis advisor and conference speaker. His academic contributions include peer-reviewed publications in systems engineering, satellite design, and launch vehicle architecture. Dr. Bianchini's current work focuses on systemic safety analysis, systems modeling, and innovation in space mission architectures.

Cap Av. MSc Lucas Oliveira Barbacovi received bachelor's degrees in Aeronautical Sciences and Public Administration from the Brazilian Air Force Academy in 2011, and an MBA in Software Engineering. He has over a decade of operational experience in military aviation, performing air transport, tactical operations, and flight instruction. He is certified as a military flight instructor and has completed advanced training in air navigation, tactical employment, and accident prevention. Currently, he is a Captain Aviator in the Brazilian Air Force and a graduated Aerospace Engineering at the Aeronautics Institute of Technology (ITA). His background includes coordinating flight operations in high-tempo environments and supporting institutional initiatives on flight safety and airspace management. He combines operational expertise with academic training to advance defense-related aviation systems and aeronautical capabilities within the Brazilian Air Force.

Maj Av. MSc Daniel Rondon Pleffken received dual bachelor's degrees in Aeronautical Sciences and Public Administration from the Brazilian Air Force Academy, followed by an M.Sc. in Systems Engineering from the National Institute for Space Research (INPE) and an MBA in Leadership and Management from the Brazilian Air Force Command (COMAER). He is currently pursuing a Ph.D. in Systems Engineering at the Aeronautics Institute of Technology (ITA) and serving as a visiting researcher at the University of Central Florida (UCF). Mr. Pleffken has over 20 years of experience in the aerospace sector, including seven years as a military pilot and flight instructor, accumulating more than 1,500 flight hours on transport and training aircraft. He served as an aircraft accident investigator, trained by the Brazilian Center for Investigation and Prevention of Aeronautical Accidents (CENIPA). and later held senior positions at the Brazilian Military Certification Authority (IFI/DCTA), coordinating certification campaigns for advanced defense platforms such as the KC-390. He has managed major avionics integration programs, led regulatory compliance initiatives, and published peer-reviewed articles in airworthiness, systems engineering, and aerospace safety. Since 2022, he has been on the faculty at ITA, teaching airworthiness, verification, validation, and regulatory systems. His current research explores the application of Model-Based Systems Engineering (MBSE) and Large Language Models (LLMs) to streamline compliance processes in aerospace certification.