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A Digital Twin Mixed-reality System for Testing Future Advanced Air Mobility Concepts: A Prototype

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Abstract*—The UK Future Flight Vision and Roadmap defines how aviation in the UK is envisioned to develop by 2030. As part of the Future Flight demonstration segment, project HADO (High-intensity Autonomous Drone Operations) will develop, test, and deploy fully automated Unmanned Aircraft System (UAS) operations at London Heathrow airport. The resource-demanding nature of real-world tests, however, suggests that developing and improving the reliability and efficiency of virtual environment-based testing methods is indispensable for the evolution of such operations. Nonetheless, developing a high-fidelity and real-time virtual environment that enables the safe, scalable, and sustainable development, verification, and validation of UAS operations remains a daunting task. Notably, the need to integrate physical and virtual elements with a high degree of correlation presents a significant challenge. Consequently, as part of the synthetic test environment work package within the HADO project, this paper proposes a Digital Twin (DT) system to enable mixed-reality tests in the context of autonomous UAS operations. This connects a physical world to its digital counterpart made up of five distinct layers and several digital elements to support enhanced mixed-reality functionality. The paper highlights how the static layers of the synthetic test environment are built, and presents a DT prototype that supports mixed-reality test capabilities. In particular, the ability to inject virtual obstacles into physical test environments is demonstrated, highlighting how the sharp boundaries between virtual environments and reality can be blurred for safe, flexible, efficient, and effective testing of UAS operations.

Keywords—Future Flight Vision and Roadmap, HADO, Unmanned Aircraft System, Digital Twin, Mixed-reality

I. INTRODUCTION

A. Context

As a program jointly funded by the UK government and industry, the Future Flight Challenge has established a roadmap for the development of a new aviation system in the UK by 2030. The four-year program is creating the aviation system of the future and will demonstrate the safe integration and operation of unmanned aircraft systems (UASs), advanced air mobility (AAM) operations and regional aircraft by 2024, backed by significant advancements in electrification and autonomy [1]. Fig. 1 illustrates the five main segments of the roadmap timeline, namely development, demonstration, industrialization, scaling and service. The development and demonstration segments aim to align phases two and three of the Future Flight Challenge. As one of the seventeen Future Flight Challenge Phase 3 projects, project HADO (High-intensity Autonomous Drone Operations) will develop, evaluate, standardize, and operationally deploy fully automated UASs at London Heathrow airport, to conduct 24/7 commercial UAS operations. This will involve a 4-month evaluation of beyond visual line of sight (BVLOS) UAS operations in both physical and synthetic test environments. Cranfield University is leading the synthetic test environment development of project HADO.

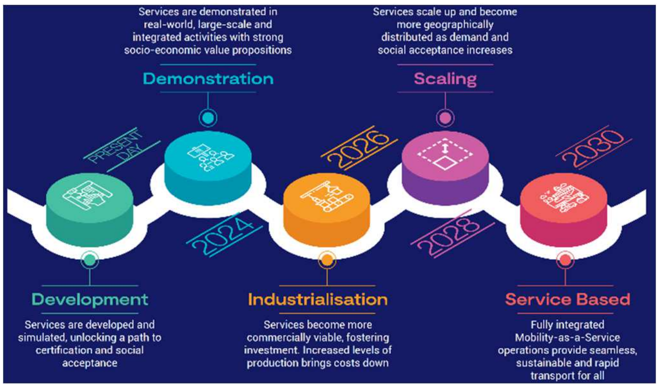

Fig. 1. Future Flight roadmap timeline [1].

To effectively manage UAS operations, a UAS traffic management (UTM) system shall be developed, and all associated services, roles/responsibilities, information architectures, and data exchange protocols shall be clearly identified. Consequently, the progress of ongoing UTM research projects and initiatives is hereby reviewed, primarily considering developments in the EU, Switzerland, the US, and the UK.

The US Federal Aviation Administration (FAA) NextGen Office released an initial Concept of Operations (ConOps) V1.0 for UTM in 2018 which was updated in 2020 to V2.0 [2]. The ConOps describes the essential components and operational concepts required to implement a UTM ecosystem.

In 2017, U-space was established as the European system to manage UAS traffic in Europe. This is defined as a set of services and procedures relying on a high level of

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digitalization and automation to support the safe, efficient, and secure integration of a large number of UAS operations [3]. The Single European Sky Air Traffic Management Research (SESAR) project has thereby initiated a series of projects to explore and demonstrate future implementations of U-space concepts. In particular, the ConOps for European UTM systems (CORUS) project [4] encompasses two years of exploratory research funded by the SESAR Joint Undertaking aimed at achieving a harmonized approach to integrating UASs into very low-level (VLL) airspace. Notably, it elaborates on how U-space services can be combined to improve the safety, public acceptance, and efficiency of UAS operations [5]. In 2020, the Swiss U-Space ConOps was proposed, in alignment with the EU U-space concept. This document described the high-level requirements for developing and deploying crewed and uncrewed operations within the Swiss U-Space system [6].

In the UK, Connected Places Catapult (CPC), in collaboration with the Department for Transport (DfT), Civil Aviation Authority (CAA) and several industrial stakeholders, developed a national UTM framework termed Open-Access UTM between 2018 and 2021 [7]. This program developed an Open-Access UTM (OUTM) concept that demonstrated how UTM could effectively deliver air traffic management (ATM) services [8].

In light of the notional UTM architecture proposed by NASA (UAS UTM ConOps V2.0), the UTM services proposed within U-space, the UTM actors proposed in Swiss U-space, and the OUTM architecture in the UK, the HADO project is developing a UTM system for BVLOS UAS operations at Heathrow airport. This paper focuses on the development of a digital twin (DT) mixed-reality test system to facilitate virtual and mixed-reality testing of the UTM systems developed within the HADO project.

B. *Related Work*

In general, a DT can be defined as a virtual representation of a physical object or process, that is capable of collecting information from the real environment to represent, validate and simulate the physical twin's present and future behavior [9]. A general framework for DT architectures is composed of three main elements: the physical world, the virtual world and the connectivity between the two. Each element involves several sub-components, dependent on the needs and requirements of the environments and operations under consideration.

The level of integration between the physical and virtual worlds can range from a simple two-dimension (2D) or 3D digital model to a one-way digital shadow, and a fully integrated DT [10]. At the lowest level, a digital model is a saved data copy of the physical state, with one-way data flow from the physical object to the digital one [11]. This means that the virtual and physical worlds are not automatically connected, so any changes in the physical environment must be manually modified in their digital counterpart. A digital shadow moves a step further to integrate unidirectional automatic information flow from the physical world to the virtual world. A DT, however, involves full bi-directional connectivity between the physical and virtual environments. This means that information can automatically flow to and from each world.

A DT maturity spectrum is proposed in [10] to define several maturity levels for DT building, as shown in Table 1. Element 0 represents the lowest maturity level of a DT (based only on existing physical assets). Element 1 is the typical entry point for new assets. These are often the outcome of the design process, such that the DT is updated through reality capture. Element 2 can add, tag, and pull data from existing systems, instead of embedding or storing them in the 2D/3D model directly. Element 3 obtains and displays dynamic data in real (or near-real) time through a one-directional flow from the physical to the digital asset. In Element 4, the state and condition of the physical asset can be changed via the twin, with the output and results fed back into the DT and used to update it. In Element 5, the DT is fully autonomous, able to react to anomalies and take the necessary corrective actions with little or no human interaction. These elements are not necessarily linear or sequential, such that a DT might possess features of higher-order elements before lower-order ones.

TABLE 1. DIGITAL TWIN MATURITY SPECTRUM [10]

Maturity Element	Defining principle
0	Reality capture (e.g., point cloud, drones, photogrammetry or drawings/sketches)
1	2D map/system or 3D model (e.g., object-based, with no metadata or building information models)
2	Connect model to persistent (static) data, metadata and building information model (BIM) Stage 2 (e.g., documents, drawings, asset management systems)
3	Enrich with real-time data (IoT, sensors)
4	Two-way data integration and interaction
5	Autonomous operations and maintenance

DTs have been employed in numerous industrial applications, including lifecycle management platforms, predictive maintenance systems, and elements within the automotive industry [9]. A literature review was conducted on the DT applications relevant to this paper and a summary of these applications is presented in Table 2. To date, most DT implementations do not exceed a maturity level of three, and few have started integrating the system with real-time data streams.

While virtual simulations within DTs support cost-effective and safe evaluation of UAS operations, they often fall short in accurately modelling all the elements of a complex real-world environment. Evidence obtained from physical tests is typically a crucial requirement for certification processes. Directly transitioning from a simulated environment to a fully deployed in-field test, however, significantly increases the associated risk of failure. Five critical stages for the deployment process of a multi-UAS system are therefore proposed in [12], as illustrated in Fig. 2. Mixed-reality tests are a crucial stage of this process, that can help bridge the gap between fully virtual and fully physical testing. These offer a cost-effective, safe and collaborative solution to enhance physical tests with virtual obstacles and agents, by enabling a real UAS to detect and react to virtually simulated entities. Such capabilities, however, have not yet been widely exploited within DTs for multi-UAS operations. The proposed DT architecture thereby aims to include mixed-reality capabilities, to ensure full support across the development life cycle of a multi-UAS system.

TABLE 2. OVERVIEW OF PREVIOUS DT APPLICATIONS (SOME APPLICATIONS ARE ADAPTED FROM [9])

Domain	**Ref.**	**Physical Twin**	**Simulation**	**Communication**	**Data Analysis**	**Sensors**	**Eval.**	**Matur. Level**
Smart Cities	[13]	Urban space	ANSYS	Bluetooth, NFC, MQTT, HTTP, Ethernet	Machine Learning (ML)	Camera, pressure, vehicle GPS, travel cards, temp., etc.	-	-
Smart Cities	[14]	Educational building	OPAL-RT	IoT, Ethernet, LoRa	Artificial Intelligence (AI)	Temp., humidity, light, CO2, VOC, sound, etc.	Sustainable building rating systems	3
Smart Cities	[15]	Water distribution system	GIS	IoT	Big data	Level, pressure, flow, quality, etc.	-	3
Smart Cities	[16]	Electricity distribution network	Python	-	Reinforcement learning (Markov decision process)	IoT electricity meters	77-node test scheme	3
Smart Cities	[17]	Urban space	ArcGIS	-	ML (ICP, C2C, M3C2), Big data	LIDAR, UASs, satellites, ranging sensors	-	2
Smart Cities	[18]	Urban space	Unity3D, SUMO	IoT	ML, AI	IoT sensors	-	2
Automotive	[19]	Automated car systems	Unreal, Matlab Simulink, Python, SUMO	5G	ML, AI	LIDAR, RADAR, GPS, CAN	Accuracy testing, ISO standards	3

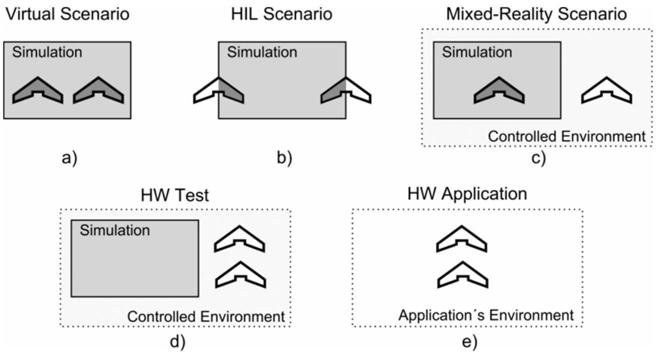

Fig. 2. Stages of the typical development process for a UAS system [12].

C. Contributions

In summary, developing a high-fidelity, real-time, and constructive DT environment remains a challenging task. This must enable the safe, scalable and sustainable development, verification and validation of autonomous UAS operations, such that the associated difficulties increase when a high degree of correlation between the physical and virtual worlds is required. There is also a recognized need to develop a DT with mixed-reality features, whereby agents in the physical world can detect and react to virtually simulated entities.

This study thereby proposes and demonstrates a DT prototype for autonomous UAS operations. It highlights how the layers of a digital world are built, and discusses a DT prototype architecture that supports mixed-reality test capabilities. The work aims to contribute to the growing research field of DTs for future AAM, and the main contributions are as follows:

a) A generic DT mixed-reality framework for testing autonomous UAS operations is proposed, and a prototype based on the Unreal Engine, AirSim and Cesium is developed, tested and evaluated.

b) Mixed-reality functionality is introduced within the DT architecture through sensor and communication spoofing. In particular, the ability to inject virtual obstacles into physical test environments is demonstrated, highlighting how the sharp boundaries between virtual environments and reality can be blurred for safe, flexible, efficient and effective testing of UAS operations.

D. Paper Structure

The remaining part of the paper is organized as follows: Section II presents the proposed methodology to develop the DT architecture; Section III presents and discusses the experiments and results used to evaluate the proposed methodology for creating a digital world; and Section IV presents and disucsses the experiments and results used to evaluate the proposed mixed-reality features. Finally, in Section V, the main conclusions of this work are summarized and the future direction of this research is proposed.

II. METHODOLOGY

To support the exploration and development of fundamental aspects of UAS operations, a generic DT framework is proposed in this paper. Notably, this includes components of a typical UTM ecosystem, to further enable the testing of autonomous UAS Operations and UTM services. The generic architecture is illustrated in Fig. 3 and is composed of three main elements: the physical world, the virtual world, and the connectivity between the two.

The physical world can be decomposed into UTM/UAS operations and the environment in which they operate. Fig. 3 shows the generic architecture for UTM and UAS operations and highlights various actors and components, their contextual relationships, and the associated high-level functions and information flows.

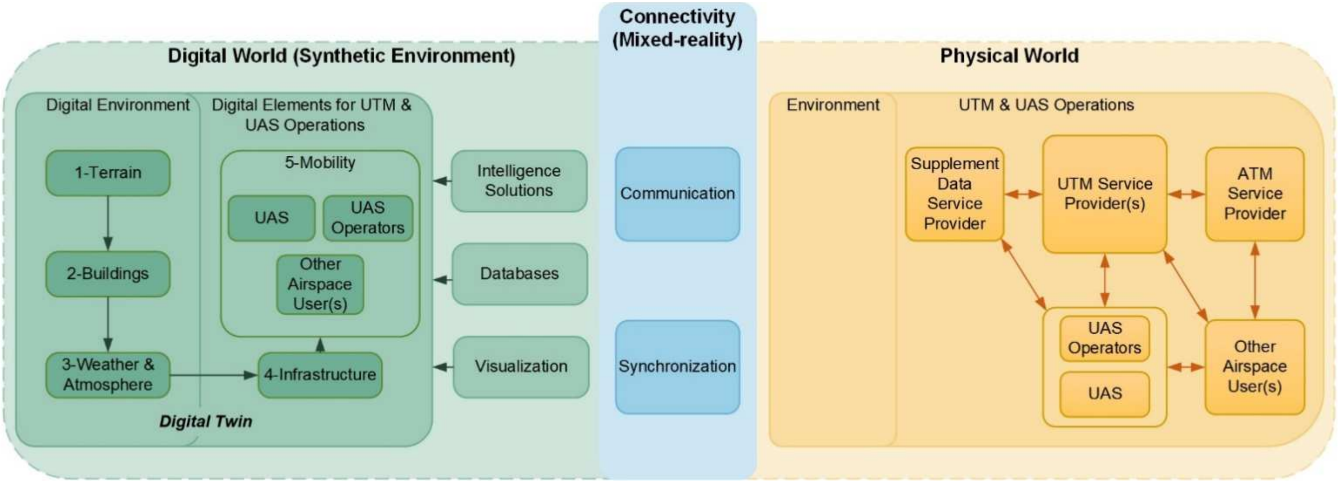

Fig. 3. Generic DT architecture, consisting of the digital world, the virtual world, and the connectivity between the two.

Conversely, the digital world can be decomposed into the DT itself and its enabling capabilities, including intelligent solutions, databases, and visualization tools. The former encompasses both the digital environment and the digital elements needed to support UTM and UAS operations. Five layers are defined for the DT, with the first three layers (terrain, buildings and weather/atmosphere) building up the digital environment, and the last two layers (infrastructure and mobility) relating to the digital elements required for UTM and UAS operations. In this prototype, the DT simulates the UASs, their operators, and other airspace users within the UTM ecosystem. For testing purposes, interactions with other actors defined in the physical world will be enabled through a series of interfaces.

The connectivity server is the core of the DT architecture and is pivotal to the realization of mixed-reality capabilities within the DT. It is responsible for communication between the physical and digital worlds, and the synchronization of all elements within the test environment.

A. Digital World

a) Digital Environment: The methodology employed to build the five layers of the digital environment is described in this section. A cross-platform 3D graphical engine (such as Unity or Unreal) is necessary to visualize the digital environment. All five layers of the environment are therefore built up in such a 3D graphical engine. The workflow for building these five layers is illustrated in Fig. 4.

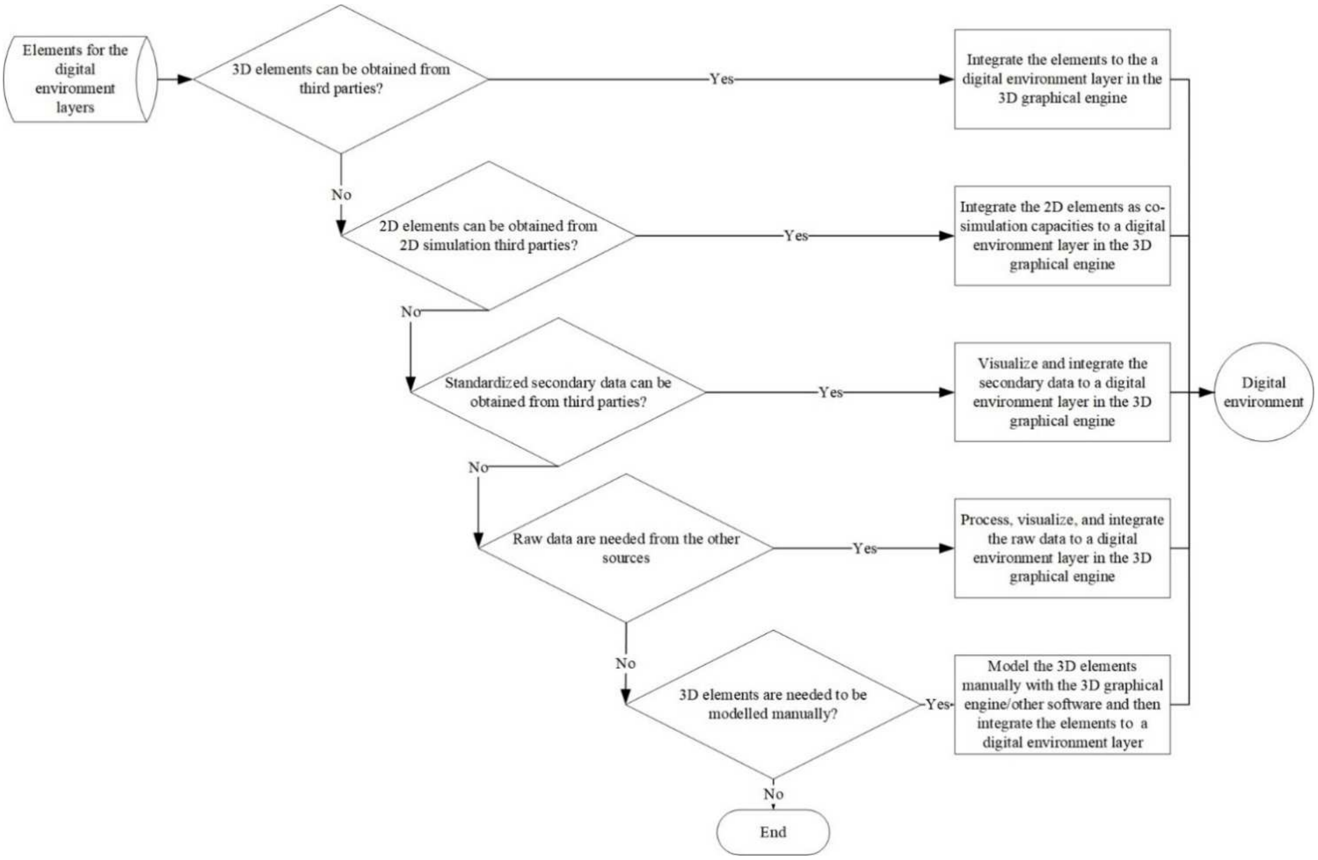

Fig. 4. Flowchart for building the digital environment.

As shown in Fig. 4, if 3D elements for a layer can be obtained from third parties, they can be directly integrated into a digital environment layer in the 3D graphical engine. Alternatively, if 2D elements can be obtained from 2D simulation third parties, the 2D elements are included as co-simulation capacities. If, instead, standardized secondary data can be obtained from other sources, the secondary data is integrated and visualized in the 3D graphical engine. If not, the fourth step is executed, whereby raw data is gathered from other sources. This raw data shall be subsequently processed, integrated, and visualized in the 3D graphical engine. If raw data is not available, the fifth step is executed, in which 3D elements are manually modelled in the 3D graphical engine. The digital environment can thereby be built up using such a five-step method.

The first (terrain) and second (building) layers form the static layers of the digital environment. As is shown in Fig. 5, the static layers can be built up using several sub-layers, including a 2D maps and imagery sub-layer, a terrain sub-layer, a buildings sub-layer, a lidar point cloud sub-layer, a photogrammetry sub-layer, and a sub-layer for other static elements. For demonstration purposes, it is sufficient to only consider the 2D maps and imagery, terrain, buildings, and other static elements sub-layers. For real-time mixed-reality DT tests, lidar point cloud and/or photogrammetry sub-layers are also needed to build ultra-precise vectorized digital maps, such as high-definition (HD) or ultra-HD (UHD) maps.

b) Digital Elements for UAS Operations and UTM Services: As shown in Fig. 2, digital elements for UTM and UAS operations predominantly comprise infrastructure and mobility layers. Fig. 5 further shows the digitalized components for UAS operations modelled in the 3D graphical engine. The UTM services are not simulated in the prototype. For test purposes, UTM services can therefore be interfaced with the DT mixed-reality system.

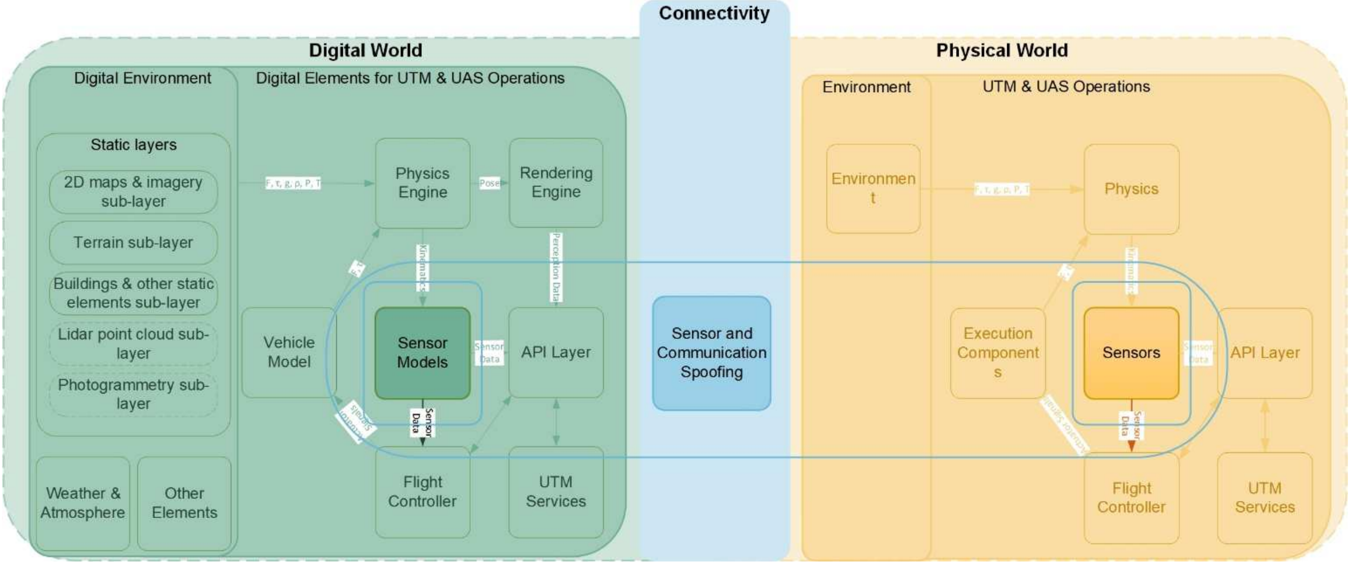

Fig. 5. Proposed DT architecture.

In general, the core components of the digital elements include the flight controller, sensor models, vehicle model, physics engine, rendering engine, and public application programming interface (API) layer. Specifically, the role of the flight controller is to take the desired state as input, estimate the actual state using sensor data, and drive the actuators such that the UAS state approaches the desired state. For a quadrotor UAS, the desired state can be specified as a specific roll, pitch, and yaw, for instance. The flight controller could thereby use sensor data from an accelerometer and gyroscope to estimate its current pose and compute the motor signals required to achieve the desired pose.

Sensor models can simulate the role of sensors that sense data from the environment and physics engine and transmit the sensed data to the flight controller and API layer. Typical sensors include an inertial measurement unit (IMU), magnetometer, global positioning system (GPS) sensor, barometer, camera, and light detection and ranging (LIDAR) sensor. Moreover, the vehicle model includes parameters such as mass, inertia, coefficients for linear and angular drag, and coefficients of friction and restitution, which are used by the physics engine to compute the behavior of the rigid body. The kinematic state of the body is expressed using six quantities, namely: position, orientation, linear velocity, linear acceleration, angular velocity, and angular acceleration. The goal of the physics engine is to compute the next kinematic state for each body given the forces and torques acting on it. Conversely, the rendering engine is the 3D graphical engine that enables the visual rendering of the UAS. Finally, the API layer allows programmatic interactions with simulated vehicles. These typically support retrieving sensor data, getting state definitions, controlling the vehicle and other such operations.

B. *Mixed-reality by Sensor and Communication Spoofing*

The mixed-reality capabilities of the DT can be realized by sensor and/or communication spoofing, as depicted in Fig. 5. The conceptual introduction of these concepts in a typical UAS sensory data flow is illustrated in Fig. 6.

Sensor spoofing reflects the ability of the DT to inject additional information into the sensing path of the UAS's perception system, enabling the vehicle to detect objects in its vicinity that are physically absent. If a virtual entity is introduced within the digital environment, two types of sensor spoofing techniques can be used. When the sensory data required cannot be provided by any on-board sensors, sensor spoofing involves injecting the readings from a virtual sensor into the flight controller of the physical UAS. Conversely, data of existing on-board sensors can be manipulated according to virtual entities when a stream of useful on-board sensory data already exists.

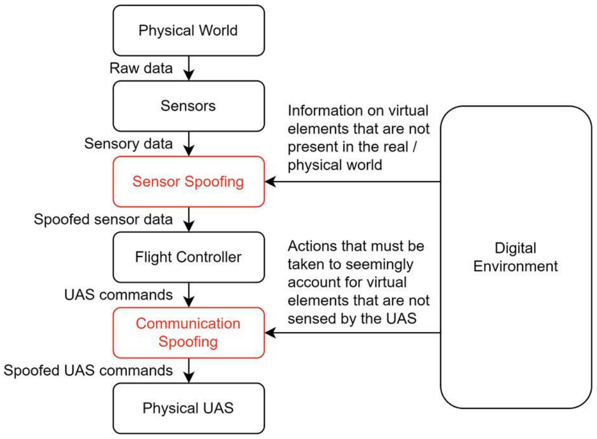

Fig. 6. Flow of on-board UAS data with communication and/or sensor spoofing.

The data of virtual entities can be directly extracted from the sensory data streams of a virtual twin of the UAS, under the assumption that the two UASs retain identical poses in identical environments. Alternatively, the expected sensor data can be deduced according to the pose of the physical UAS, and the pose and characteristics of the virtual entity. Despite requiring more complex and resource-demanding computations, the latter eliminates the need for a high-fidelity simulation model of the UAS, which is particularly useful as UAS and AAM vehicles become more heterogeneous.

By enabling the UAS to perceive virtual entities, such as obstacles or landing areas, this technique can significantly improve the situational awareness of the vehicle and enable more efficient mission planning and execution. Sensor spoofing also increases the UAS resilience to sensor failures, supporting safer and more reliable tests and demonstrations. If the spoofed data is not consistent with reality, however, the physical flight controller may take incorrect decisions that pose a greater safety risk and hinder the ability of the UAS to complete its mission.

Communication spoofing, on the other hand, refers to the manipulation of commands sent to a UAS, such that the vehicle seems to react to elements in its vicinity, even if they are not detected by its sensing system. This allows the mixed-reality system to bypass or modify the commands generated by the flight controller of the physical UAS, lending itself to a simpler implementation than sensor spoofing. Nonetheless, a high-fidelity model of the UAS and environment is required to avoid transmitting inaccurate and potentially unsafe commands that do not adequately account for the complex physical environment in which the UAS operates.

By allowing the UAS to respond to virtual stimuli, such as commands or alerts, communication spoofing increases the autonomy and decision-making capabilities of the vehicle. It further supports UAS operations in complex environments, where sensory data cannot be easily obtained, deduced, or simulated. Additionally, this technique is easier to realize in practical operational environments and reflects the possibility of a ground control station or remote pilot overriding the on-board UAS flight controller in an emergency. Nonetheless, spoofed commands must be reliable and accurately synchronized with the entire system to mitigate the risks of spoofing incorrect commands.

III. DIGITAL WORLD

This section describes preliminary experiments that were conducted to demonstrate and evaluate the proposed methodology used to create the digital world. The Unreal 4.27 graphical engine is a powerful 3D creation and visualization software and was used in this study to develop and integrate the components of the digital environment. Detailed instructions for Unreal 4.27 can be found in [20]. Moreover, the static layers of the digital environment were built using the Cesium plugin for Unreal. The high degree of coupling between these two software packages allows the 3D geospatial capability of Cesium to be combined with the high-fidelity rendering power of Unreal Engine, unlocking a 3D geospatial ecosystem. An introduction to Cesium for Unreal and detailed instructions on its applications can be found in [21]. AirSim [22], on the other hand, is an open-source and cross-platform UAS simulator developed by Microsoft Research and was used to simulate the UAS and UAS operations within the digital environment. Additionally, a DJI RoboMaster TT Tello Talent Drone was used in the physical world. A detailed Tello user manual is included in [23].

A. Experiments

To evaluate the techniques proposed for building the digital world of the DT framework, a preliminary digital environment with digital elements of UAS operations was built in the Unreal Engine. The digital environment was built using the Cesium plugin for Unreal, and the digital elements needed for UAS operations were built through AirSim.

In line with the workflow shown in Fig. 4, some 2D and 3D elements were obtained from third parties. In particular, the Cesium plugin enabled World Terrain, Bing Maps Aerial Imagery, and OpenStreetMap (OSM) Buildings to be obtained. Initially, World Terrain and Bing Maps Aerial Imagery were used to build the terrain layer of the digital environment. Similarly, OSM buildings provided the preliminary buildings layer of the digital environment. The developed digital environment at the Cranfield University campus (including Cranfield Airport) is shown in Fig. 7.

To create the digital elements needed to simulate UAS operations, the AirSim simulator built on Unreal Engine was used. For this study, the default flight controller, sensor models, vehicle dynamic model, physics engine, rendering engine, and public API layer provided by AirSim were used. A custom vehicle mesh, however, was introduced to better reflect the physical Tello drone. Additionally, the AirSim Python APIs were utilized to interact with the simulated UASs, and Python 3.7 was used to write all the scripts needed to programmatically interact with AirSim.

It is noted that the Cesium plugin for Unreal and AirSim have already been validated. An experiment, however, was conducted to evaluate the consistency and accuracy of the elements within the constructed digital world, particularly the consistency between Unreal and Airsim/Cesium. Throughout this experiment, the North-East-Down (NED) coordinate system, (i.e., +X is North, +Y is East and +Z is Down), was employed. Moreover, all quoted units are in SI units, and coordinates within Unreal and Cesium are normalized to NED coordinates.

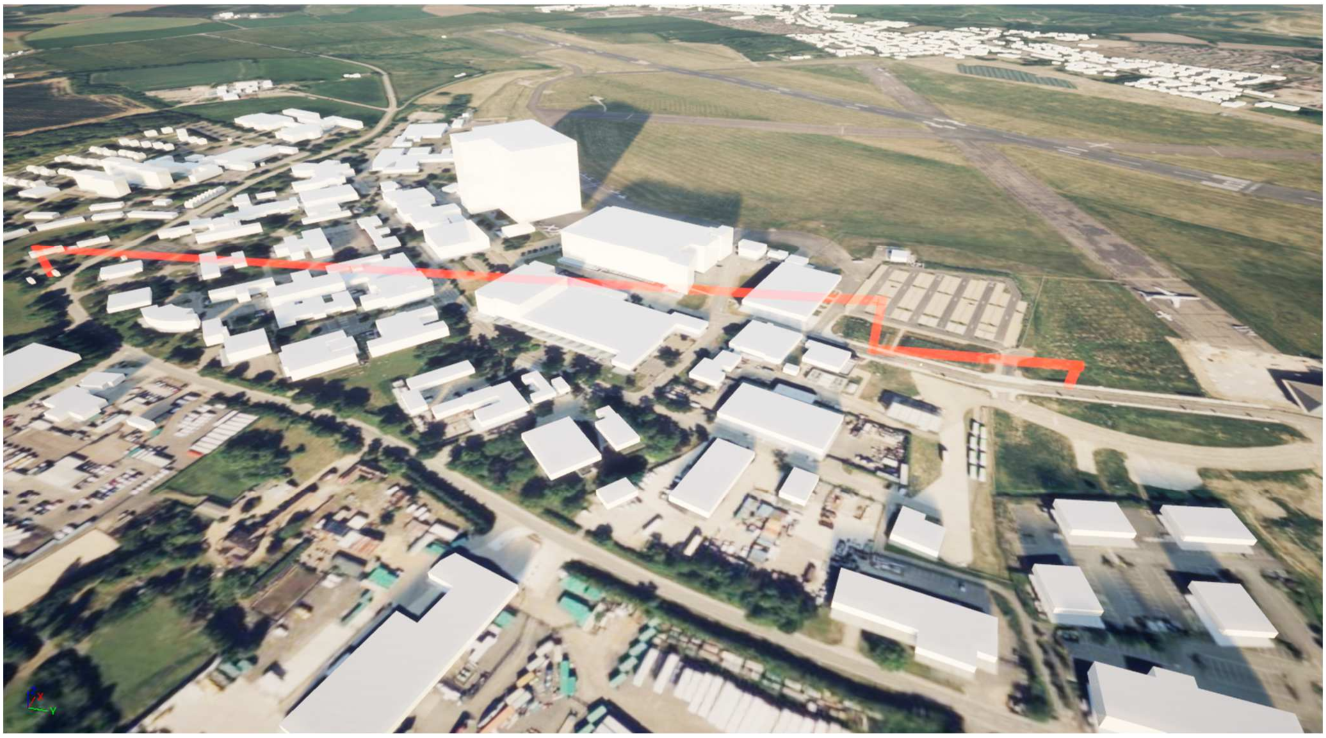

Fig. 7. Developed digital environment at Cranfield University campus (including Cranfield Airport).

The experimental area considered was Cranfield University Campus (including Cranfield Airport), as shown in Fig. 7. An infrastructure inspection mission was planned for a vehicle under test from a departure point near the Digital Aviation Research and Technology Centre (DARTeC) building to an arrival point near the Cranfield Main Gate bus station. Ten waypoints were appropriately selected within the coordinate system of the digital environment, built by integrating and consolidating the coordinate systems of Unreal, AirSim and Cesium. The vehicle under test was subsequently instructed to fly along the ten waypoints and return its position coordinates using a GPS sensor. As is shown in Fig. 7, the planned path of the mission is illustrated by the 3D spline in orange. By comparing the position coordinates from the digital environment to those obtained from the vehicle's GPS sensor, the consistency and accuracy of the elements within the digital world could be evaluated.

B. Evaluation Results

To quantitatively evaluate the accuracy of the digital world and the consistency between AirSim and Unreal/Cesium, the horizontal mean absolute error (HMAE), vertical mean absolute error (VMAE) and overall mean absolute error (OMAE) metrics were used. In general, the absolute error (AE) criterion is defined as:

$$AE = \sqrt{(x-\hat{x})^2 + (y-\hat{y})^2 + (z-\hat{z})^2} \quad (1)$$

This represents the Euclidean distance between an actual waypoint location in the digital world (x, y, z) and the waypoint location sensed by the UAS sensing system $(\hat{x}, \hat{y}, \hat{z})$. The HMAE is subsequently defined as:

$$HMAE = \sum_{n=1}^{N} \sqrt{(x_n-\hat{x}_n)^2 + (y_n-\hat{y}_n)^2} \,/N \quad (2)$$

Where N is the number of waypoints. This represents the average horizontal Euclidean distance between all actual and sensed waypoint locations. Similarly, the VMAE is given by:

$$VMAE = \sum_{n=1}^{N} |z_n - \hat{z}_n| \,/N \quad (3)$$

This represents the average vertical Euclidean distance between all actual and sensed waypoint locations. Finally, the OMAE is defined as:

$$OMAE = \sum_{n=1}^{N} \sqrt{(x_n-\hat{x}_n)^2 + (y_n-\hat{y}_n)^2 + (z_n-\hat{z}_n)^2} \,/ N \quad (4)$$

This represents the average 3D Euclidean distance between all actual and sensed waypoint locations.

The calculated results are shown in Table 3. The HMAE, VMAE and OMAE obtained throughout this experiment were 0.89m, 0.42m and 0.98m, respectively. This suggests a digital world accuracy of up to 0.98m, which is at a decimetre level.

TABLE 3. EVALUATION RESULTS OF THE DIGITAL WORLD

HMAE [m]	VMAE [m]	OMAE [m]
0.89	0.42	0.98

IV. MIXED-REALITY

This section describes preliminary experiments, results and discussions that were conducted to demonstrate and evaluate the proposed methodology on the mixed-reality DT features.

A. Demonstrative Experiments

To facilitate preliminary tests in a controlled environment, initial mixed-reality demonstrations were performed in the indoor flight arena at Cranfield University. Consequently, a high-fidelity digital environment in this arena was also developed within the digital world of DT. Since no existing elements or data were available, a 3D model of the arena was manually created and edited using Blender according to the digital environment building method shown in Fig. 4, while carefully considering the dimensions of all elements within the physical room. After creating the underlying mesh, Adobe Substance 3D Painter was used to create and closely match digital materials and textures to their physical counterparts. These resources were subsequently imported into Unreal for compatibility with the remaining DT environment.

Several obstacle avoidance demonstrations were used to showcase the mixed-reality potential of the DT. For simplicity, a single physical UAS and its virtual counterpart were considered, with both vehicles positioned to have identical starting poses within their respective environments. The two UASs were instructed to follow identical trajectories, comprising a simple straight-line path at a constant velocity and altitude. Additionally, both vehicles were programmed to use identical path-following and collision-avoidance algorithms. For demonstration purposes, experiments were conducted in a carefully regulated setting, with all obstacles designed to possess a distinct green hue, facilitating their detection and monitoring throughout the experiment.

Owing to the limited sensing capability of the Tello drone, a simple computer vision and rule-based obstacle avoidance algorithm was employed, with the camera of the virtual UAS configured to closely resemble that of its physical counterpart. Image processing techniques were used to extract the size of detected green obstacles and change the UAS heading when an obstacle was deemed to be too close to the vehicle, as illustrated in Fig. 8. This approach assumed that the true size of the obstacles was known, such that the correlation between the size of the object within the image frames and its distance from the UAS was known beforehand. While not conducive to real-world applications, this sufficed to demonstrate the mixed-reality capabilities of the DT.

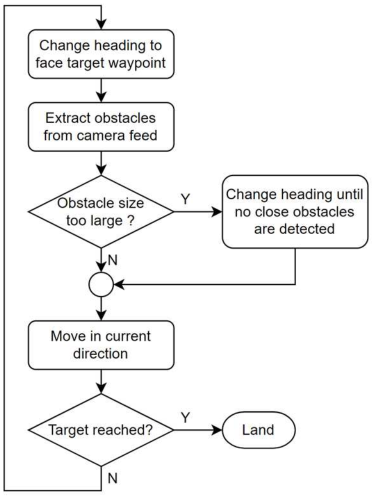

Fig. 8. Flow of the simple path following and collision avoidance algorithms used for preliminary mixed-reality demonstrations.

To illustrate the mixed-reality capabilities of the DT, no obstacles were included in the true physical environment. A virtual obstacle, however, was introduced in the digital environment, along the path of the virtual UAS. Sensor and communication spoofing could thereby be employed to enable the physical UAS to avoid the virtual obstacle.

Communication spoofing was used to realize a simple mixed-reality simulation, by manipulating the physical UAS instructions to match those generated by the virtual flight controller. Additionally, both identified sensor spoofing techniques were implemented and tested in a separate experiment. Firstly, the positional data obtained from the virtual UAS was fed to the physical flight controller, thereby introducing a feed of virtual sensory data within the physical UAS. This was necessary since the utilized Tello drone did not include a reliable positioning system. Additionally, obstacles detected in the virtual camera feed were extracted and injected into the camera feed of the physical UAS, such that the physical flight controller could appropriately react to the obstacles.

B. Results and Discussions

a) Indoor Digital Environment: The digital arena environment and simulated UAS closely resembled their physical counterparts, as shown in Fig. 9. Minor discrepancies in colour and textural information were identified, but these were deemed acceptable for the selected test case scenarios. In fact, the colour of the simulated virtual obstacle was selected to clearly contrast with its surroundings, as depicted in Fig. 10. This illustrates the simplest path that the UAS would take to reach the specified target waypoint and shows that an obstacle was inserted along this trajectory.

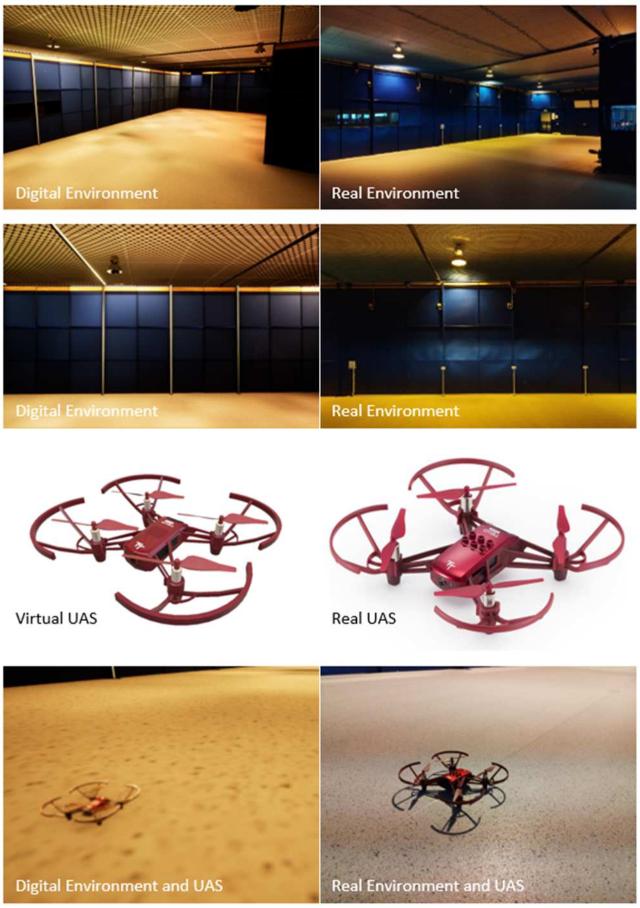

Fig. 9. Comparison of the digital environment and virtual UAS with their physical counterparts.

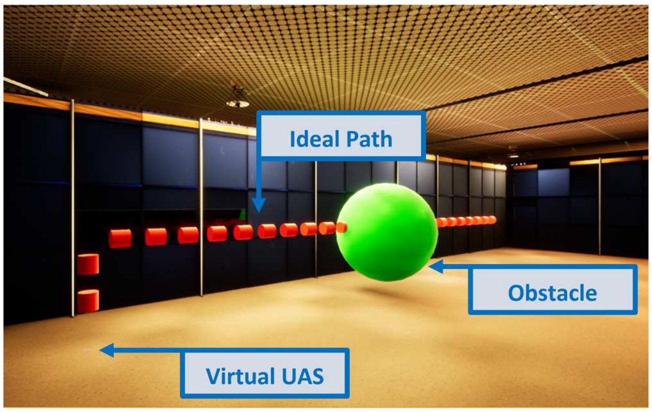

Fig. 10. Indoor digital environment with an obstacle introduced along the ideal UAS trajectory.

b) UAS Operations with No Mixed-reality: In the absence of communication or sensor spoofing, the real and virtual UASs acted independently of each other, as illustrated in Fig. 11. As expected, the virtual UAS diverted its path to avoid the simulated obstacle, while the real UAS flew along a straight line path, directly along its ideal trajectory.

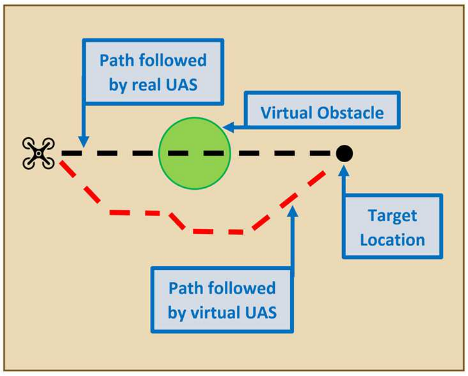

Fig. 11. Top-view of approximate paths followed by virtual and real UASs in the absence of communication or sensor spoofing.

c) Communication Spoofing: Fig. 12 illustrates the approximate paths flown by both UASs when using communication spoofing to manipulate the physical UAS flight commands. By ensuring that the physical UAS executed the same manoeuvres as the virtual UAS, both vehicles were observed to successfully avoid the region occupied by the virtual obstacle.

d) Sensor Spoofing: When spoofing the physical UAS camera, the virtual obstacle was successfully extracted from the virtual camera frames and injected into the real camera feed, as shown in Fig. 13. Moreover, the implemented high-level flight controller for the physical UAS was successfully spoofed to reflect the virtual UAS position data. This suggested, that the real vehicle would successfully react to the virtual obstacle, provided it retained the same pose and location as the virtual UAS. In fact, both vehicles avoided the virtual obstacle, as illustrated in Fig. 12.

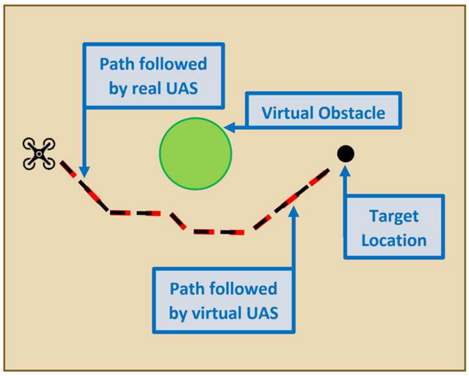

Fig. 12. Top-view of approximate paths followed by virtual and real UASs when using communication or sensor spoofing to realise a mixed-reality simulation.

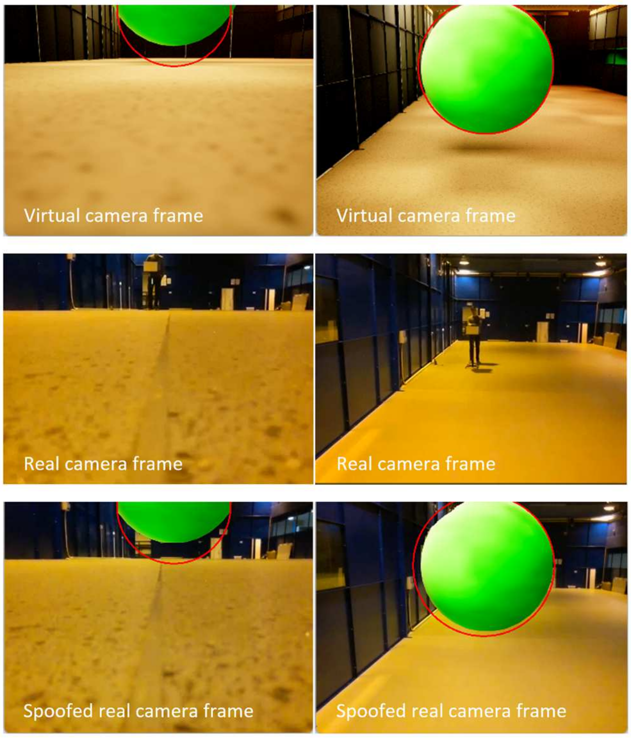

Fig. 13. Effect of spoofing the physical UAS camera feed.

e) Discussions: Despite effectively showcasing multiple approaches to realize a mixed-reality DT environment for UAS operations, the implemented spoofing algorithms require further development before they can be employed in complex simulation environments. Notably, all algorithms currently require each physical UAS to have a virtual counterpart, with both vehicles continually maintaining identical poses in their respective environments. The limited ability to accurately simulate the physical flight controller and real-time variations in environmental conditions, however, limits the extent to which these assumptions hold. A more effective sensor spoofing technique could independently determine the expected sensor data according to the pose of the real UAS and virtual obstacles, eliminating the dependency on a high-fidelity virtual UAS counterpart. Nonetheless, accurately determining the absolute position of the physical UAS remains a challenging requirement, particularly if the physical UAS does not house an accurate on-board localisation system.

V. CONCLUSIONS

This study proposes a DT mixed-reality prototype for improved safety, flexibility, efficiency and effectiveness throughout the entire development process of autonomous UAS operations. The proposed prototype is evaluated through several experiments and shown to exhibit promising results. The conclusions drawn from this study are as follows:

- Rather than solely relying on a synthetic test environment, the proposed DT mixed-realty framework supports the integration of the synthetic and physical worlds with a high degree of correlation. This improves the efficiency, flexibility, and reliability of conducted UAS test experiments.
- A systematic stepwise method for building the five layers of a digital world for autonomous UAS operations is proposed. A prototype world is created using this workflow, and shown to exhibit decimeter-level accuracy.
- Mixed-reality capabilities are realized within the proposed DT architecture, based on sensor and communication spoofing. These are demonstrated by injecting virtual obstacles into physical test environments such that a physical UAS successfully avoids the simulated obstacles.

Overall, the proposed DT mixed-reality prototype can support existing test systems by adding virtual test capabilities and blurring the sharp boundaries between reality and virtuality. In the context of digitalization and autonomy for AAM, the proposed DT system is envisioned to support the development, integration and testing of ATM/UTM ecosystems by enabling the seamless integration of simulation, physical test environments and real-time vehicle control. This will be pivotal to enabling the widespread certification and adoption of these emerging operations.

Several areas shall be further explored within this project. Within the DT environment, higher-fidelity static layers can be achieved by adding lidar point cloud and photogrammetry sub-layers, coupled with customized vehicle modelling, sensor modelling, and real-time communication protocols. Co-simulation with existing 2D simulation capacities can also be realized and tested, as well as interfacing with other UTM services through a set of APIs. In terms of mixed-reality, more effective spoofing techniques can be explored, to increase the utility and effectiveness of this functionality.

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A digital twin mixed-reality system for testing future advanced air mobility concepts: a prototype

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