

A Co-simulation Digital Twin with SUMO and AirSim for Testing Lane-based UTM System Concept

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Abstract—The UAS (Unmanned Aircraft System) Traffic Management (UTM) System Concept of Operations (ConOps) is the first formal design reference document of the UTM system, ConOps aims to bring Class G Airspace into government regulation. However, it should be noted that there are still some shortcomings in ConOps that require further discussion. For example, there are concerns about operational rights, privacy rights, and the potential interference caused by high-rise buildings in urban core areas. The Lane-based UTM systems could potentially help in solving the above issues. The flight paths of Unmanned Aerial Vehicles (UAVs) in urban areas or other areas will interact with the road network, which can facilitate airspace traffic development. Ground traffic flow simulation is generally conducted on three levels: macroscopic, mesoscopic, and microscopic. Some of the commonly used car traffic flow simulation tools include Vissim, SUMO, and MATSim. However, UAV traffic simulation is mostly at a single level, and all of the current mainstream simulation software for UAV, such as Gazebo, AirSim, and Flight Gear, are microscopic-level analyses of UAV operations, lacking uniform management of drone traffic flow and operations. In addition, these UAV traffic simulation studies do not consider the city traffic and road network. In this context, a lane-based co-simulation UAV traffic simulation method is proposed in this study. The co-simulation architecture will be based on the high-fidelity three-dimensional (3D) environment developed in the Unreal Engine, UAV simulation with AirSim, and two-dimensional (2D) road network simulation with SUMO. A standardized and universal co-simulation architecture and communication interface to ensure interoperability, compatibility, and synchronization will be developed in this study. The lane-based co-simulation method will effectively leverage the road network simulation capacities to turn complex 3D space planning into simple 2D planning, it could reduce computational load and improve system efficiency. The 3D environment will also enhance the simulation capacities with its unique and high-fidelity simulation capacities. Overall, the proposed co-simulation method will support the Digital Twin development by interfacing several simulation tools, incorporating different communications, and adding realistic visualization, which could create unprecedented opportunities for software tool combinations.

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1. INTRODUCTION

Background and Problem Statement

In 2020, the US FAA (Federal Aviation Administration) and NASA (National Aeronautics and Space Administration) published the UAS (Unmanned Aircraft System) Traffic Management (UTM) System Concept of Operations (ConOps) V2.0 [1]. This document aims to bring Uncontrolled Airspace- Class G Airspace, which is under 400ft, into regulation and put ‘the number of people and amount of property on the ground’ as the first indicator. The ConOps is the first formal design reference document of the UTM system, and it should not be overlooked that it still has some issues that deserve in-depth discussion.

A comprehensive analysis of ConOps V2.0 in 2020 [2] and the results state that the FAA authorizes the right of use to operators, and this action may risk the operator monopolizing the airspace. In addition, modern city building heights easily reach the maximum height limit of Class G Airspace. For example, New York City has over 6,000 high-rise buildings, and 274 skyscrapers standing over 150m tall [3]. These high-

rise buildings can be a potential risk for drone flights, especially if regulation is too lax.

In this context, Sacharny and Henderson proposed lane-based traffic management for large-scale unmanned aircraft systems in 2022 [4]. This research used the city road network as a reference for UAS traffic routes. This method optimizes the scheduling of safe flight paths, simplifies the analysis of transportation flow, and thousands of drones can be simulated throughout the city. This paper focuses on developing a study on co-simulation digital twin (DT) with SUMO and AirSim for lane-based UTM systems, providing support for DT development by interfacing multi-simulation tools.

Related Works

The DT collects the state data from the physical entity through sensors, and uses the virtual counterpart to replicate the physical entity. The general framework of DT architecture consists of three main parts: the physical world, the virtual world, and the connection between them.

The level of realism of virtual world models can be extended from basic two-dimensional (2D) models to high-fidelity three-dimensional (3D) environments with autonomous operation and maintenance [5]. As shown in Table 1, as the level of DT increases, the data flow also shifts from the initial unidirectional flow (from the physical world to the digital world) to a mutual flow of data between the physical and digital worlds. In addition, human intervention is gradually decreasing as the maturity of DT increases. It is worth noting that most DT models to date do not exceed level 3 maturity, which means they lack real-time data integration.

Table 1. Digital Twin Maturity Levels [5]

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

The Development process of the UAS operation system could be divided into five parts [6]. In the Virtual Scenario, the agent environment is based on simulation servers, the drone simulation is done by simple software, equipped only with sensors. This setup best suits high-level system design and

verification in the early development phase when system fidelity is less important. Therefore, the proposed Co-simulation DT architecture thereby aims to include mixed-reality capabilities, to verify the theory of the lane-based UTM System.

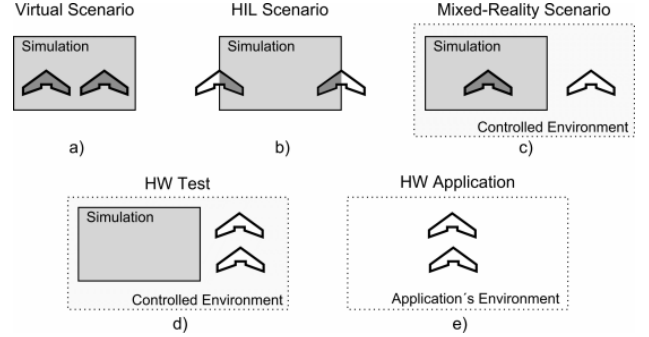


Figure 1. Consecutive scenario stages of a development process [6]

Traffic simulation is usually divided into three classifications, macroscopic, mesoscopic, and microscopic. The co-simulation in different classifications will accurately identify the Beyond Visual Line of Sight (BVLOS) Unmanned Aerial Vehicle (UAV) objectives and reduce calculation workloads, and improvement in efficiency is obvious. Co-simulation is a simulation technique integrating different simulators to create a unified and synchronized simulation environment. Logical time and exchange mechanism is the core of simulation. Currently, the main simulator for traffic simulation is shown in Table 2, with the classification of simulators from macro to micro, The simulation function contains traffic flow simulation, and UAS operation simulation.

Some of the commonly used car traffic flow simulation tools include Vissim, SUMO, and MATSim. However, UAV traffic simulation is mostly at a single level, and all of the current mainstream simulation software for UAV, such as Gazebo, AirSim, and Flight Gear, are microscopic-level analyses of UAV operations, lacking uniform management of drone traffic flow and operations. Since 2020, Airbus [7], JAXA [8], and Delft University of Technology [9] have launched UTM simulation tools. However, Airbus USim and JAXA UTM Simulator- SKALE are only available to collaborators. Bluesky is an open-source simulation, but it is mainly used for Air Traffic Management (ATM) simulation and is designed to consider the road and traffic environment within the city. In total, all simulation tools have limitations, there are no simulators that could meet all the requirements of a DT mixed-reality system. Consequently, co-simulation is required to leverage and integrate the capabilities of different software platforms.

In traffic co-simulation, there are many successful cases for reference, such as [10] and [11] developed the co-simulation in SUMO-CARLA, [12] developed MATSim-SUMO co-simulation framework. [13] analyze the UAV operation simulation tools, and [14] analyze the UAV operation

Table 2. Review of simulation tools

Simulator	Classification	Advantage/ Disadvantage	Function	Dimension	API	Example
Bluesky	Macroscopic	Higher computational capacity; lower data requirement; lack of detail	Air traffic simulation	2D	Y	[15]
Vissim	Macroscopic		Ground traffic flow simulation	2D/3D	Y	[16]
MATSim	Mesoscopic	Easy to achieve; more coarse than microscopic simulation	Ground traffic flow simulation	2D	N	[12]
SUMO	Microscopic	More details; lower calculate speed	Ground traffic flow simulation	2D	Y	[12]
AirSim	Microscopic		Drone and car operation simulation	3D	Y	[13]
FlightGear	Microscopic		Aircraft simulation	3D	Y	[17]
Gazebo	Microscopic		Robot simulation	3D	Y	[18]
OMNet++	Microscopic		Network simulation	-	Y	[19]

computing workload in 3D environment and 2D environment and present a co-simulation of UAVs between two different dimensions.

Contributions

In this context, a lane-based co-simulation UAV traffic simulation method is proposed in this study. The co-simulation architecture is based on the high-fidelity 3D environment developed in the Unreal Engine, UAV simulation with AirSim, and 2D road network simulation with SUMO. The main contributions are as follows:

- A universal co-simulation DT framework for testing Lane-based UTM concepts has been developed. SUMO and AirSim are co-simulated and used for UAV simulation with a standardized and universal co-simulation architecture and communication interface to ensure interoperability, compatibility, and synchronization.
- The road network simulation and the traffic simulation capabilities of SUMO can be fully utilized and integrated into the DT, which is two-dimensionalize the 3D simulation, reduce the computational load, and improve the system efficiency.
- The proposed DT co-simulation environment integrates road network information, 3D buildings, and 3D flight channel.

Overall, the proposed DT system enables the seamless integration of two different simulation tools to support the development and testing of Lane-based UTM concepts. It is also the first co-simulation of SUMO and AirSim, which has research and application value for Advanced Air Mobility concepts test and development.

Paper Structure

The remainder of this paper is as follows: Section 2 presents the proposed methodology to develop a co-simulation DT framework; Section 3 presents the enhanced DT environment of Cranfield University campus; Section 4 presents ground traffic simulation and UAV operation simulation, Section 5 discusses the integration, experiments and results on the enhanced DT capacities based on co-simulation with AirSim and SUMO. The final chapter presents the summary and conclusions of this study and introduces the future direction of this research.

2. METHODOLOGY

The co-simulation means that two or more simulation tools or models run interactively simultaneously and combine into a simulation system. Different tools represent and simulate the individual components to gain the advantages of other software and avoid the disadvantages.

A generic co-simulation DT framework of AirSim and SUMO is proposed in this paper. The DT framework is a platform that can test the feasibility of the lane-based UTM system. The entire co-simulation system also consists of traffic simulation and UAV operation simulation.

In the lane-based UTM system concept, drone flight paths are fixed over urban roads to improve planning ease and safety. In that context, drones are required to fly at designated altitudes, therefore UAV path planning in 3D space could then be considered as 2D path planning. The lane-based UTM system is based on the existing urban road system and could be viewed as a high-altitude upgrade of the vehicular road network.

As a co-simulator in the co-simulation DT framework, SUMO and AirSim can communicate and interoperate in real-time. Specifically, SUMO can provide traffic

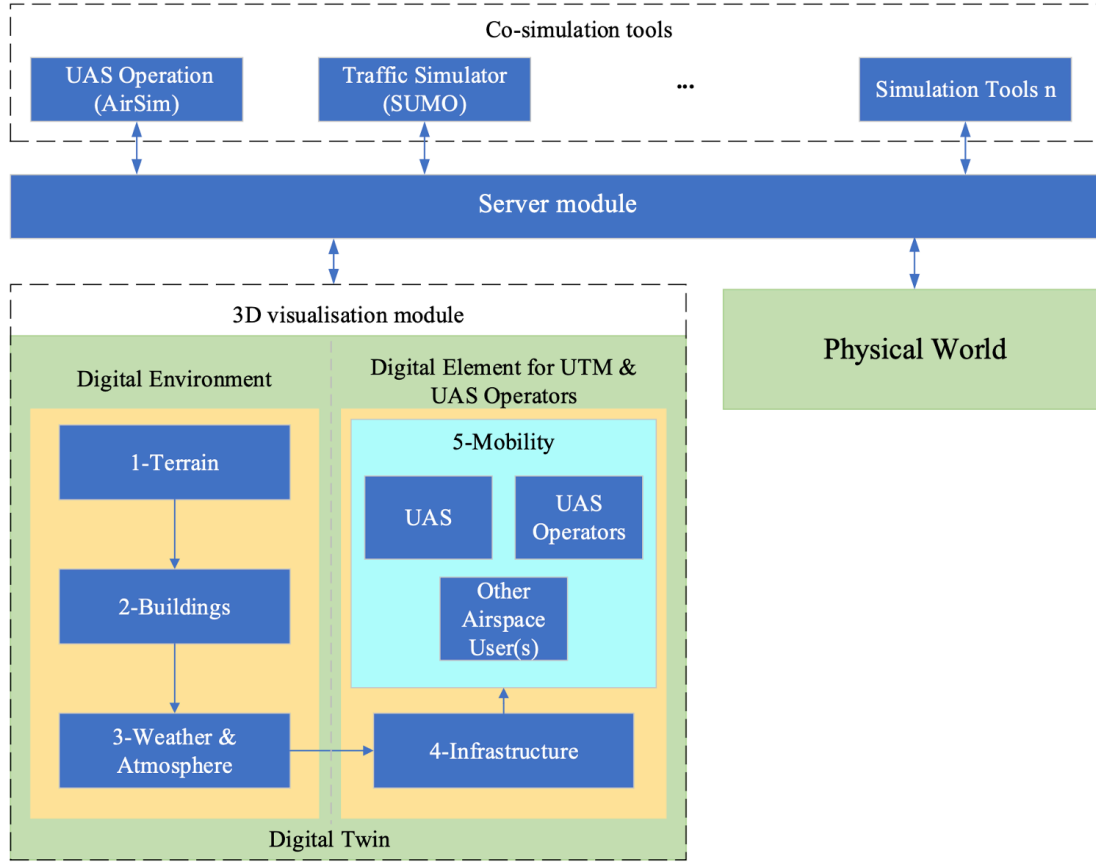


Figure 2. Generic co-simulation DT framework [20]

information such as coordinates. In turn, AirSim can display the data from SUMO in the 3D environment to enhance the simulation effect.

The co-simulation is a key enabler of the DT as well as a key capability of the DT framework for advanced air mobility development and testing. The proposed generic architecture is illustrated in Figure 2 and is composed of three main parts: co-simulation tools, the server module, and the 3D visualization module. The relationship and working of each simulator are shown in Figure 3. In the proposed co-simulation, AirSim and SUMO are the core of the framework, undertaking traffic flow simulation and UAV operation simulation.

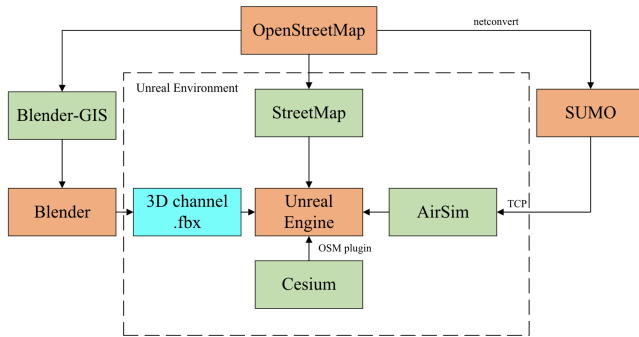


Figure 3. The software architecture of co-simulation

3. DIGITAL TWIN OF CRANFIELD UNIVERSITY CAMPUS

For testing UAVs more efficiently and accurately, it is important to build a high-fidelity DT environment. Creating 3D digital models is often time-consuming, especially creating the 3D models that are used in DT high fidelity is required. This project used Unreal Engine 4.27.2 to build a 3D digital environment, the plugin list is Table 3.

Table 3. Unreal Engine plugins list

Plugin	Function
AirSim	UAV simulation
Cesium	Provide 3D digital environment (buildings, terrain, etc..)
StreetMap	Provide road network information

Firstly, an arbitrary area was selected in OpenStreetMap, this paper takes the Cranfield University campus (excluding Cranfield Airport) as the study object.

It is worth noting that the StreetMap plugin, which applies directly to the unreal Engine, is different from the plugin OpenStreetMap on Cesium. The StreetMap Plugin loads road

network and building information in the 3D environment of unreal by importing an OSM file. By StreepMap Plugin, a high-fidelity road network will be obtained in the 3D environment, but the building information is rough. By comparing with the 3D buildings generated by the OpenStreetMap plugin in Cesium, the quality of 3D building information in Cesium far exceeds the building quality of the StreetMap plugin.



Figure 4. Import OSM by Blender-GIS

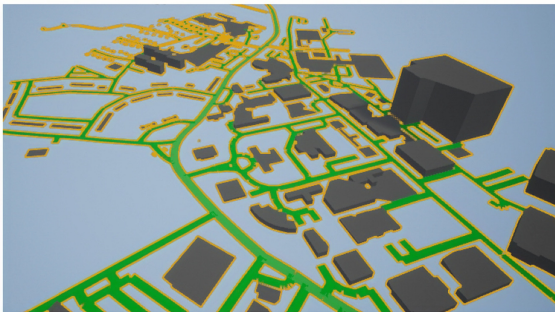
For verifying the flight trajectory of a UAV within a DT environment, a static 3D UAV flight channel is built by Blender. Blender-GIS is a plugin of Blender, this plugin integrates geographical information system (GIS) capabilities directly into Blender, allowing users to import geospatial information in a 3D environment. By Blender-GIS, Blender could import the road network information from OSM files (various sources include OpenStreetMap, Google Maps, Bing Maps, and more). The imported geographic information is shown in Figure 4.

It is important to note that Blender-GIS is a rudimentary and simple OSM analysis plugin, which makes mistakes when reading map information, such as reading city border, sidewalk, river, or other map signals as road network information. As shown in Figure 5, the reason for the messy route information in the Lanchester Hall area on the left side of Cranfield University is that Blender-GIS incorrectly reads the information of the rivers around the area as well as the shire line of Buckinghamshire and Bedfordshire and the Milton Keynes city border line. Therefore, when using GIS information as the basis for 3D fight channel design, extraneous information must be cleaned up.



Figure 5. The city border line, river, and other information of OSM in the Lanchester Hall area, (b): errors of Blender-GIS

Module integration is an important part of DT construction, Figure 6 shows this process. Figure 6 (a) shows OSM import



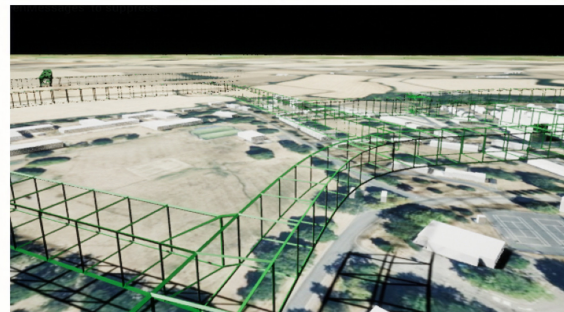
(a)



(b)



(c)



(d)

Figure 6. (a): Import OSM by StreetMap Plugin, (b): Cesium background environment and 3D buildings, (c): Import street map in Cranfield campus, (d): Integration of Cranfield campus DT environment

in Unreal by StreetMap plugin, the building height error in the picture is obvious. Figure 6 (b) shows Cesium plugin provides world terrain, Bing Maps, and OpenStreetMap buildings in Unreal. Figure 6 (c) shows the integration of the StreetMap plugin and Cesium plugin in Unreal, this methodology enhanced the digital environment of the Cranfield DT prototype. To make the 3D flight channel model more obvious, the model has a skeletonized frame structure in Figure 6 (d). Considering that there are no high-rise buildings at Cranfield University campus and that it is easy to observe, the flight channel was set at a height of 10 meters above ground level. The top and side views are shown in Figure 7.

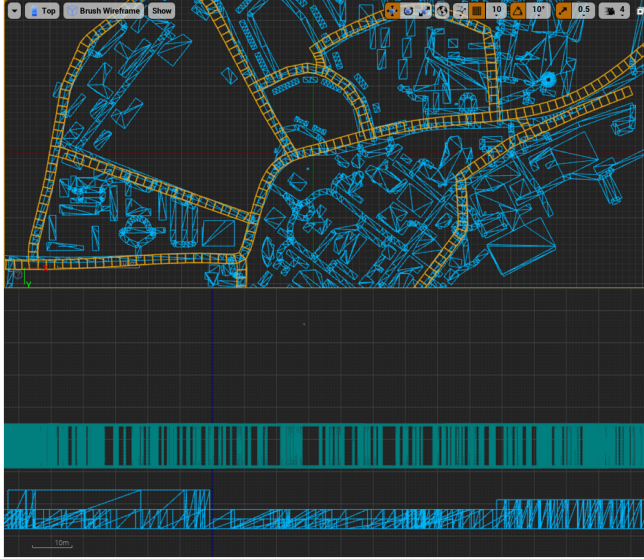


Figure 7. Flight channel in Unreal Engine

After integration, Figure 6 (b) is the Cranfield campus digital world for the lane-based UTM system concept, the environment replicates the Cranfield University campus with high fidelity. The co-simulation of SUMO and AirSim will be based on it, and UAV operation simulations will be developed within this digital environment. Buildings within the digital world created using this method lack texture but do not interfere with UAS operation. Furthermore, the 3D model can be improved by manually tweaking and editing it in Blender.

4. GROUND TRAFFIC AND UAV OPERATION SIMULATION

Ground Traffic Simulation

The lane-based traffic simulation by SUMO is a traffic flow simulation in a 2D environment. The configuration file of SUMO consists of road network files net.xml, rou.xml, and sumocfg files, where net.xml is the road network information file and rou.xml is the traffic information file.

The map could be downloaded through Open Street Map. In order to make the osm file readable and usable by SUMO-

GUI, it is necessary to convert the osm file using the netconvert command. Files generated by netconvert are in XML format and contain road network information in the form of nodes, routes, and relationships, which can be used for multi-modal microscopic traffic simulations with free software such as SUMO or proprietary software such as VISSIM. They can be opened directly by SUMO-GUI or Netedit. OpenStreetMap is a free open-source map, and the downloaded road network information suffers from inaccuracies, some road sections are not refreshed in time, so the road network can be modified using Netedit.

SUMO-GUI comes with a toolbox that includes a rou.xml generation package, which allows the production of traffic information files by using the Python file corresponding to the function. In addition to using a toolbox, there are two other methods for generating rou.xml files, one is to write the rou file directly by using a source code editor (such as Notepad++), and the other is to generate the rou file using Python. The advantage of the third approach is that the rou file can still be modified while the simulation is in progress, which is widely used in optimizing traffic simulations using reinforcement learning or optimization algorithms. When writing the rou file, the ID of the lane node is mandatory. The ID of the lane node can be found in Netedit.

The sumocfg file is a configuration file used by SUMO, it could run directly to enter the SUMO-GUI. Same as rou.xml, the sumocfg can be edited using the source code editor, the configuration file mainly includes input files (including rou.xml and net.xml) and time setup. In addition, when using Python to control SUMO simulation, you need to add autorun commands in the configuration file. The simulation framework for SUMO is shown in Figure 8.

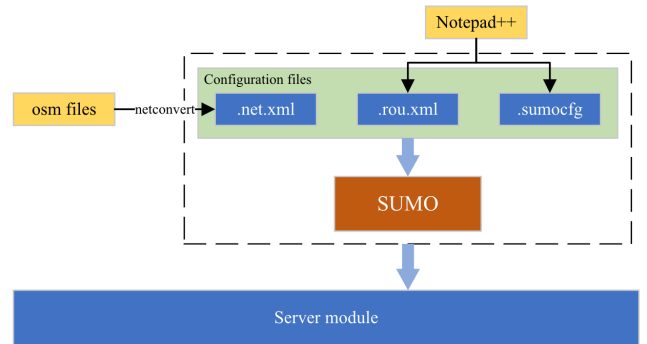


Figure 8. The architecture of ground traffic simulation

Figure 9 shows the SUMO display of traffic simulation. In the Cranfield University campus, to prevent blind alleys from interfering with traffic simulation, all blind alleys are set to be closed to traffic.

In the co-simulation process, APIs are used to control SUMO to collect vehicle information (such as speed, position, acceleration, etc.). The vehicle.getPosition is an API of TraCI, the function is to collect the position data of the vehicles in SUMO.

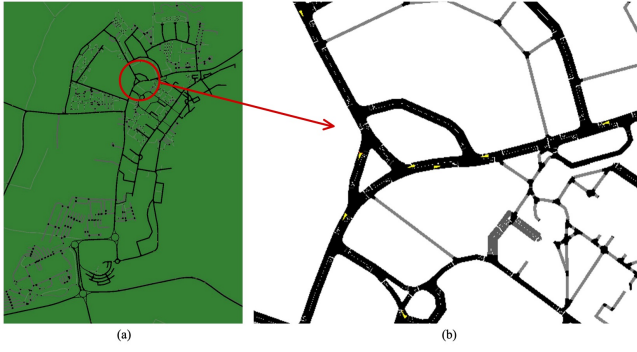


Figure 9. Cranfield campus traffic simulation

UAS Operation Simulation

Due to hardware limitations, it is more challenging to deploy a large number of UAVs in the Unreal environment, so five UAVs were simulated and analyzed in this project. Before integrating AirSim with SUMO, AirSim was tested using the Blocks and Cranfield DT environments.

APIs of AirSim were used to interact with UAV in Unreal, and all scripts were written in Python 3.11. The flow chart of the AirSim operation is in Figure 10.

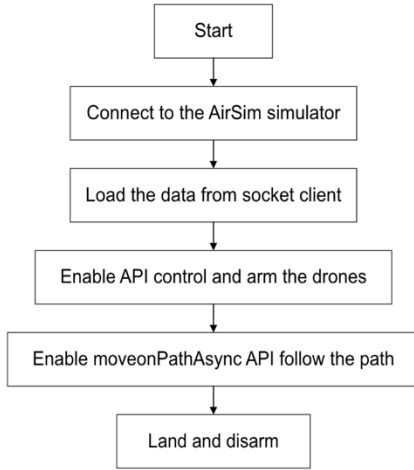


Figure 10. Flow chart of AirSim operation

5. LANE-BASED UAS CO-SIMULATION DIGITAL TWIN INTEGRATION AND EVALUATION

Co-simulation Integration

The co-simulators include SUMO and AirSim. The UAV dynamic model included in AirSim is responsible for simulating the operation of the UAV in the air. The main functions of SUMO include path planning and displaying BLVOS UAVs. In order to achieve the co-simulation, this paper develops a set of procedures for the implementation of SUMO control, Vehicle information reading, communication establishment, information transfer, and path following of UAV in AirSim, the framework and software program are shown in Figure 11. The program is divided into three main

modules: the SUMO control, the communication module, and the AirSim control. The TCP communication protocol completed the data transfer between SUMO and AirSim.

In the co-simulation framework, the main challenges include establishing real-time communication and coordinating coordinates in SUMO-AirSim. The connection mode of the co-simulation framework includes protocol, client, and server. The protocol is a rule established for the exchange of data in a network. It is used for communication between entities in different systems.

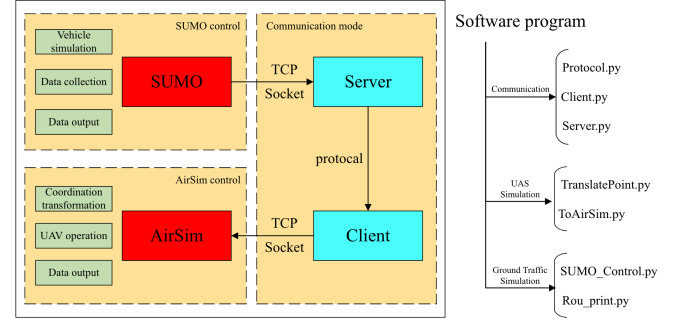


Figure 11. Software architecture of co-simulation

The establishment of communication between SUMO and AirSim consists of the following steps:

- Step 1: the vehicle position data comes from SUMO.
- Step 2: the data is transferred via the TCP protocol.
- Step 3: traffic data is processed in the client module.

As a reliable transport, TCP has two characteristics: the transmission channel is error-free, ensuring that the data is transmitted correctly; no matter how fast the sender sends data, the receiver always has time to process the received data. This paper uses UDP Broadcast to send the address and port number of the server to the client. When the client receives the UDP Broadcast, it will collect the IP address and port number. After that, UDP Broadcast will close, and TCP communication will start.

The communication between SUMO and AirSim is unidirectional, which means SUMO sends coordinate information to AirSim. SUMO is the data sender and Unreal is the data receiver, and the simulation uses synchronous transmission, in which SUMO transmits the data to AirSim every time SUMO completes one step of the simulation. The number of coordinate data transmitted between each UAV and each vehicle within SUMO is between 4500 and 5000, which is too large. A blocking socket is used to transfer the data to prevent data loss.

AirSim, Cesium, and OpenStreetMap have been evaluated in Unreal Engine environment. However, the unification

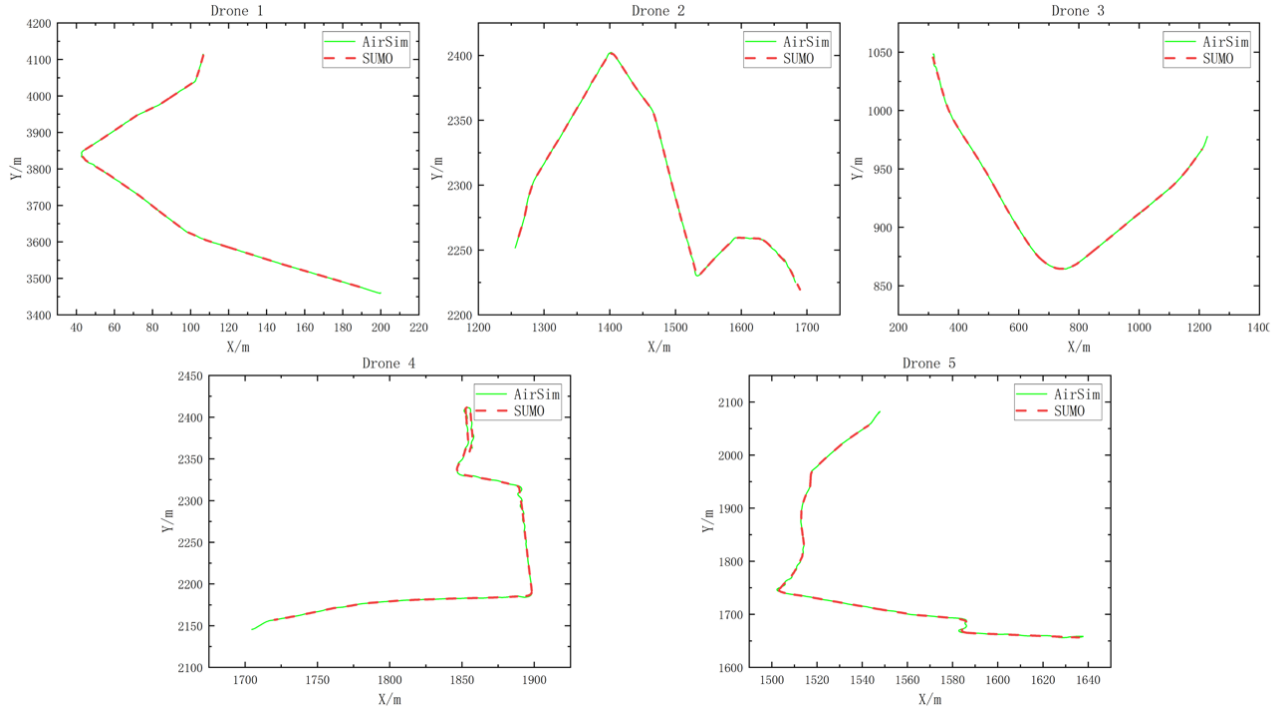


Figure 12. The comparison of UAVs flight trajectories in SUMO and AirSim

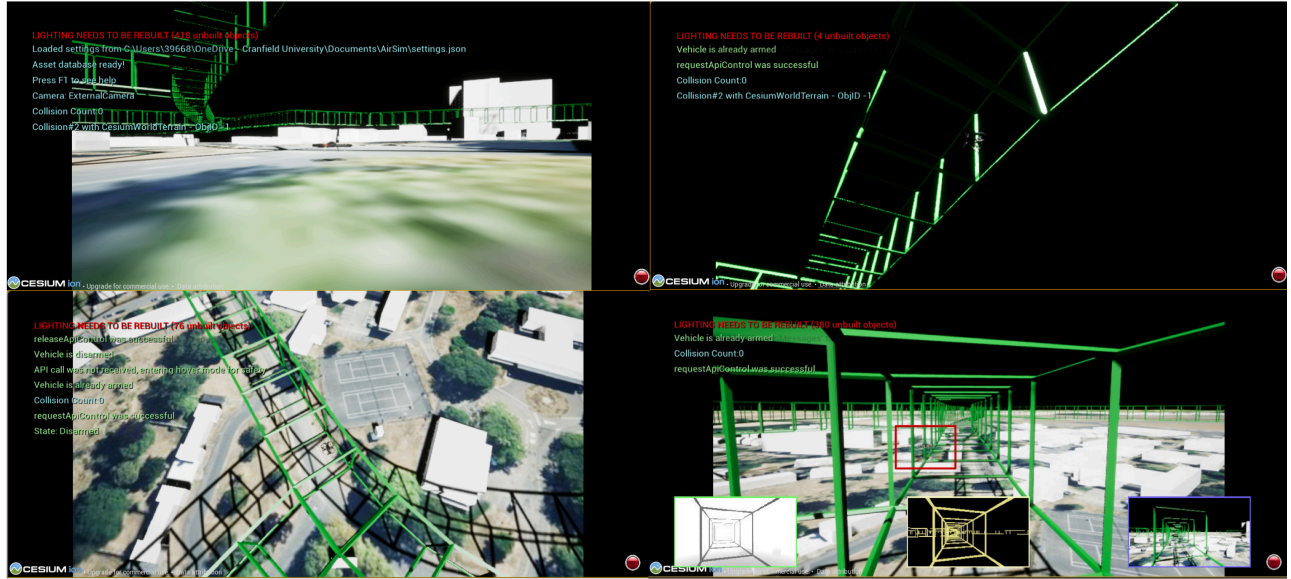


Figure 13. The flight test of drones in the Cranfield DT environment

between AirSim and SUMO regarding coordinates still needs further evaluation. The road network of SUMO uses Cartesian coordinates where the leftmost node is located at $x=0$ and the bottom node is located at $y=0$, the unit is a meter. Besides, AirSim uses the North-East-Down (NED) coordinate system, where $+X$ is north, $+Y$ is east, and $+Z$ is down, the unit is a meter. However, in Unreal Engine, $+Z$ is up instead of down, and the unit is centimeter. Therefore, a coordinate conversion program was developed along with the co-simulation program. In addition, because SUMO output is two-dimensional coordinate data, it cannot be directly read

and used by AirSim. Therefore, the coordinate conversion program should include the z -axis coordinate information addition.

UAS Operation Evaluation

To evaluate the feasibility of the simulation framework, UAV operations were conducted in the constructed DT environment. Deploying five drones in the Unreal environment by modifying the setting.json file in AirSim, corresponding to the five vehicles in SUMO is Table 4. The SUMO data was collected through the simulation model

developed in Chapter 4 by randomly deploying five vehicles in the Cranfield campus road network, the path is random. Each vehicle flew along a different route, the ID, position, and speed are obtained through TraCI.

Table. 4 Relationship of SUMO ID and AirSim ID

Number	SUMO ID	AirSim ID
1	0	Drone1
2	1	Drone2
3	2	Drone3
4	3	Drone4
5	4	Drone5

In order to rigorously validate the reliability of the operation of the proposed simulation framework., this paper uses two ways to verify. One is to output the vehicle trajectories in SUMO and AirSim respectively and compare them. The other is to determine whether the UAV is flying according to the expected path by visually observing the overlap between the 3D channel and the UAV.

In the first evaluation method, the path of the vehicle in both simulation software is exported using TraCI and AirSim APIs. The flight trajectories in SUMO and AirSim are shown in Figure 12. By way of comparison, there is a high degree of overlap. The main reason is the huge position data, for vehicles in SUMO, the position data number is around 4000~5000. The position data of AirSim, except for Drone2 is 286, and other drones are around 600~900. Therefore, the large sample contributes to the high similarity between SUMO and AirSim trajectories. In the high-fidelity 3D Digital World, the drone experiences minor yaw in sharp and continuous turns, but the flight direction and trajectory are unaffected. This is more evident in Drone 4 and Drone 5.

The evaluation method through visual inspection is shown in Figure 13, the method is more reliable considering that the 3D channel model is a static module and vertically overlaps with the road network. the UAV flight trajectory in the Unreal interface overlaps with the 3D channel, in addition to the 2D path trajectories output by SUMO and AirSim. Therefore, the consistency and accuracy of the elements in the DT could be demonstrated.

Discussion

The proposed co-simulation DT framework uses StreetMap, Cesium, Blender, and Unreal to build a high-fidelity digital environment to improve the fidelity, accuracy, and efficiency of the DT model.

In order to fill the gap in the practice of the Lane-based UTM System, a methodology to build a generic co-simulation DT framework for the autonomous operation of UAS is proposed, which effectively integrates AirSim, Unreal Engine, and SUMO and builds a DT prototype, and this co-simulation DT framework has the following advantages:

This co-simulation DT framework is the first attempt to use

SUMO and AirSim to achieve co-simulation for UAV traffic simulation. In traditional traffic simulation, SUMO is used for automotive traffic simulation and AirSim is used for UAV operation simulation. However, in the context of Lane-based UTM, SUMO can give full play to the advantages of traffic simulation and improve the simulation capability of the UTM system.

Compared with AirSim, which focuses on UAV operation, the SUMO simulation is more macroscopic. In addition, SUMO comes with a TraCI API that can complement the shortcomings of AirSim, such as being used to directly obtain the traffic flow on the road. The co-simulation between SUMO and AirSim makes up for SUMO inability to realize three-dimensional simulation and AirSim inability to observe the traffic outside the field of view of the target UAV due to its limited display view so that the system simulation capability can be improved. The visualization view in SUMO can better show the traffic status in 2D view, while the 3D visualization view in Unreal Engine can better show the details of UAV operation.

6. CONCLUSION AND FUTURE WORK

Conclusions

This paper proposes a co-simulation methodology for the development of an accurate, efficient, and scalable DT environment throughout the development process of autonomous UAS operation. In this paper, the proposed two test methods for the DT co-simulation framework for the lane-based UTM concept are evaluated experimentally, and the results show that the method has good application prospects. Overall, the proposed co-simulation approach can support the existing DT framework by connecting multiple simulation tools. It is also the first co-simulation of SUMO and AirSim, which has research and application value for Advanced Air Mobility concepts test and development.

In the context of Advanced Air Mobility, the proposed DT system enables the seamless integration of two different simulation environments to support the development and testing of Lane-based UTM concepts. This is essential for exploring future UAV operations within urban areas.

Future Work

Several areas will be further explored in future research endeavors. In terms of co-simulation, the communication architecture currently used still needs to be enhanced and there is still room for improvement in synchronization. In addition, continuous turns and sharp turns during the test can lead to subtle yawing of the UAV, which does not interfere with the flight path but can still be enhanced.

Furthermore, many studies on automated vehicle driving, obstacle avoidance, and reinforcement learning path planning have been successfully implemented on SUMO and these results can be evaluated on this DT co-simulation framework, and further refinement of the co-simulation framework.

7. ACKNOWLEDGEMENT

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