Sim-to-real transfer of UAV swarms using digital twins

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Abstract— **Swarms of UAVs can be a useful tool to battle wildfires. Field deployments of swarms of UAVs though are not often seen as there are many challenges in controlling the aircraft effectively and to change their behaviour if needed after they are deployed. Thus, tools are needed to test, monitor and control the system to achieve effective and safe deployments. We have developed a digital twin user interface in an effort to create a software to facilitate both research and field deployments of swarms of UAVs. The interface is focused on fixed-wing aircraft providing two modes of operation: low and high fidelity. The low-fidelity simulation mode is used by developers to create and test control algorithms. The high-fidelity simulation mode uses simulators that run on AWS servers with a higher level of accuracy in the behaviour of the aircraft. This mode uses the same autopilot software that is used on real aircraft. In high fidelity mode a swarm operator is also able to monitor and control a real swarm. Moreover, virtual aircraft on AWS can run at the same time achieving real and virtual aircraft interaction. We have proven the functionality of our system in field trials and now aim to develop our software further in cooperation with firefighters as potential users to create interfaces to facilitate more robust field operations.**

I. INTRODUCTION

The effects of climate change result into significantly increased mean temperatures leading to drier environmental conditions [1]. Over the past six years, large fire outbreaks occurred around the world. In 2017 in Portugal and in 2018 in Greece more than 100 people lost their lives and more than 250 were injured [2], [3], [4], [5]. Researchers have been investigating the use of swarms of uncrewed aerial vehicles (UAVs) to assist in fire monitoring and information retrieval for firefighters. Using self-organised swarm systems can have numerous advantages such as scalability and robustness in rapidly changing environments [6], [3], [7]. Our previous use case study with firefighters from around the world showed that to deploy swarms in the field an advanced deployment tool is necessary to allow for effective human-swarm interaction [8]. Swarms of UAVs are not often seen outside of laboratory settings or controlled environments as these systems can be costly and user interaction is complex. A tool is therefore needed to permit swarm operators to test the deployment of swarms in simulation and to allow for real-time monitoring and control of the swarm.

Using digital twin technology [9] it is possible to first simulate large numbers of UAVs to optimise a swarm behaviour for a given scenario. The mission can next be launched in reality, constantly receiving feedback from the real aircraft for real-time monitoring, and then changing or re-optimising the swarm control as the need arises. Data is bidirectional between the simulated and real-world deployments. Furthermore, digital agents can also be injected in the real swarm deployments for experimental trials to augment the exploration capabilities of swarm mission control strategies.

Our work shows initial field trial results where a single operator was able to optimise, monitor, and control a swarm of UAVs (up to three physical and three digital aircraft, six in total), changing amongst three decentralised search algorithms designed to search for wildfires. We used random walking, pheromone dispersion and dynamic space partition [10]. This abstract briefly explains our methodology and results, an extended version of this paper has been recently accepted for publication in the 2023 International Conference on Unmanned Aircraft Systems (ICUAS).

II. METHOD

A. System architecture

Our system consists of: a Digital Twin user interface (UI), a Swarm Operator, a Cloud infrastructure and a Swarm of UAVs as shown in Fig. 1.

1) Digital twin: This system comprises of a desktop application UI and simulated agents running swarm-based control algorithms. The interface allows real and simulated UAVs to explore and collaboratively act within a virtual world in which points of interest like fires are located. The UI has two operational modes to develop and test swarms:

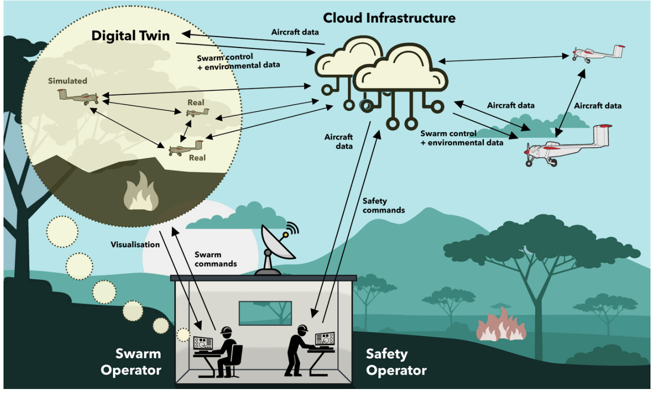

Fig. 1. System architecture showing the different elements of the developed framework.

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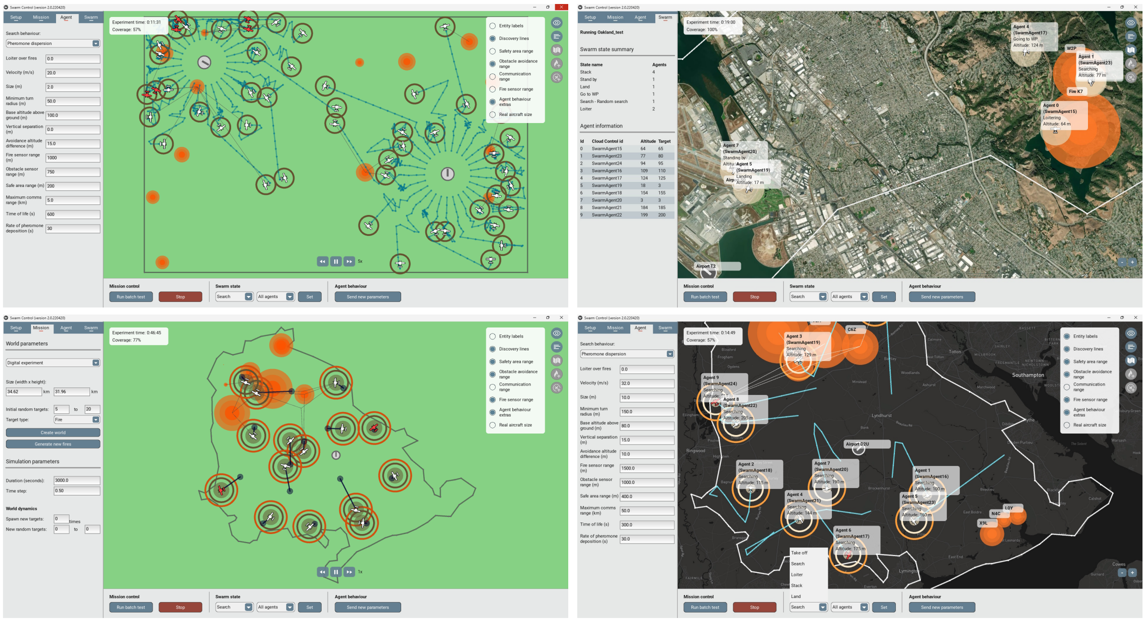

Fig. 2. The digital twin user interface (UI). Left: Shows two instances of the UI in low-fidelity simulation mode performing a search using pheromone dispersion (top) and dynamic space partition (bottom) algorithms. In this mode the user has the capacity to test the behaviour and the performance of the swarm with simplified flight dynamics. Right: Shows two instances of the UI in high-fidelity simulation mode using different search algorithms and map types. This mode shows the behaviour of the swarm with more accurate flight dynamics as the platforms use the same autopilot control and parameters (software-in-the-loop) and cloud infrastructure that are used in the field. The user can select different models of UAVs and modify the virtual environment (e.g. adding wind). The behaviour matches the flight of the real aircraft and is used to assess the behaviour of the swarm in a more realistic setting.

low fidelity and high fidelity. In low fidelity mode the user can evaluate the behaviour and performance of the swarm using multiple digital UAVs with simplified flight dynamics running in the same desktop application in real or faster-than-real time. In high fidelity mode, the digital UAVs are not simulated locally but distributed across multiple cloud instances using Docker containerized simulators provided by Distributed Avionics (DA, https://distributed-avionics.com/) and AWS servers. These high-fidelity digital aircraft use software-in-the-loop simulation of the hardware onboard the real platform (autopilot and companion computer) along a full dynamic model of the same platform. The digital twin UI can be seen in Fig. 2.

2) Swarm operator: The swarm operator defines the experiment parameters, such as the number of UAVs; the number, location and size of virtual fires; and the algorithm to search for the fires. Then, the UI can be used to optimise control algorithms, monitor the performance of the swarm and in real time control the behaviour of the swarm. The operator can control the swarm via sending swarm commands to take off, move to a specific waypoint, search a given area using a selection of swarm algorithms, and land.

3) Cloud infrastructure: The cloud allows the creation of simulated aircraft using Docker containers which then post their data to the digital twin. The digital aircraft use the same controllers and autopilot that are used by real aircraft to mimic their physical counterparts. Furthermore, the infrastructure allows data to be parsed between the virtual and real aircraft and at the same time passes information to the digital twin UI and to a web server with different levels of access that can be used by a safety operator or others. The cloud infrastructure is run by DA and it comprises a set of web APIs to handle different types of communication.

4) Swarm of UAVs: When performing low-fidelity simulations, swarm operators can use different virtual aircraft modifying some parameters like speed and minimum turn radius. In high-fidelity simulations we currently can select two digital aircraft models, Believer and ULTRA[1], each one with its flight dynamics and using the same autopilot control and parameters as its physical counterpart.

B. *Optimisation of swarm algorithms*

Field deployment of swarm systems require careful assessment of the controllers that are used. The development of novel controllers needs to follow a specific process that includes behavioural and performance testing before these controllers are deployed. Additionally, for long-duration operations the swarm operator should be able to test or change the behaviour of UAVs that are already deployed, if for example the operational environment changes. For this reason a rapid development and deployment process was developed (see Fig. 3). The user can design new behaviours and test them in low fidelity mode. Through batch testing over 100s of simulations, performance statistics can be generated to assess if the behaviour is more desirable. Next, the same behaviour can be tested in high-fidelity mode. Finally, it can be deployed to the aircraft that are already in operation allowing the user to modify the behaviour of the swarm.

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[1] ULTRA (Unmanned Low-cost TRAnsport) platform developed by Windracers, https://windracers.org/

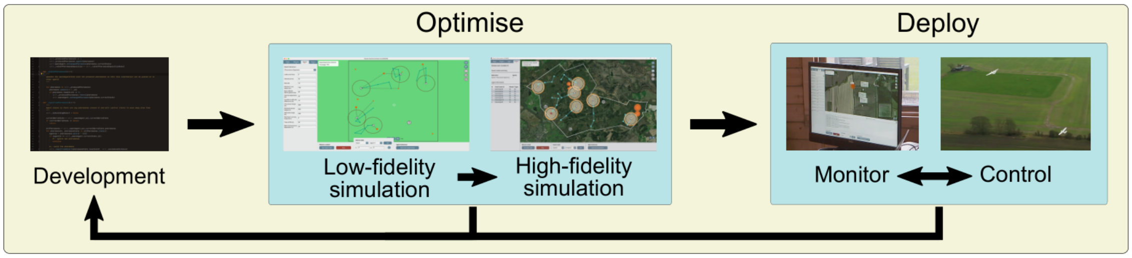

Fig. 3. The development process to optimise behaviours for a swarm of UAVs. First we use low-fidelity simulations to ensure that the desired behaviour is performed. The same behaviour is then tested in high-fidelity simulations, adjusting parameters of the algorithms and simulated sensors to verify proper operation under more realistic flight conditions. Next, the behaviours can be deployed to the swarm in the field. The type and parameters of search algorithms can also be changed whilst UAVs are in operation, hence new behaviours can be quickly tested and deployed to aircraft in real time.

C. Real-world deployment

The experimental scenario was developed in cooperation with three firefighters from the UK. They believe that a swarm of UAVs can be used to patrol an area for potential wildfires and if a fire is seen they should be able to inform the swarm operator about a potential threat to investigate the incident further [8]. Our trials took place at Draycot aerodrome located in England, UK. During the trials three real UAVs were used and more digital aircraft were created to develop a swarm. The aircraft used were Believers, these are fixed-wing UAVs that are mostly used for aerials surveys. They are powered by a LiPo battery and can be airborne for 2 hours. The aircraft were equipped with DA's autopilot system, a small companion computer and a 4G LTE modem which enabled them to connect to 4G networks. The airfield and the Believer aircraft are shown in Fig. 4.

The aircraft were required to identify a virtual wildfire generated within the digital world. The UAVs were equipped with virtual sensors with 100 m sensory range. Different searching patterns were used and deployed in real time altering the behaviour of both real and virtual aircraft. The decentralized controllers deployed by the swarm operator tasks the UAVs to avoid each other, explore an area and at the same time remain within the required search space. Random walking, pheromone dispersion and dynamic space partition were used as exploration techniques [10].

III. RESULTS: FLIGHT TRIALS

To test the swarm operator's ability to monitor and control the swarms in reality, three Believer UAVs were used. Safety pilots were tasked to manually take off the aircraft, position them at different locations in the airspace and then change the autopilot flight mode to loiter. Next, a safety operator took over control of each individual aircraft and set it to fly at the required altitude, one at a time. Finally, the swarm operator took over control of the aircraft tasking them to stack or search the area. Additionally, while searching, the operator was able to change the behaviour of the swarm using the three different search algorithms that were developed. Lastly, the swarm operator sent a land command indicating the location and altitude of the landing point and runway heading, then an on-demand landing routine and mission were calculated on board and followed by each aircraft.

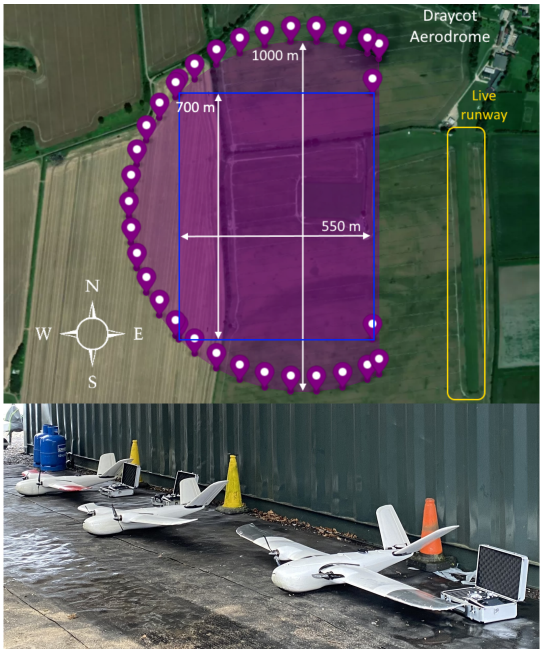

Fig. 4. Draycot Aerodrome airspace (top) and the Believer aircraft used in the trials (bottom). The civil aviation authority approved VLOS flights for three aircraft in an airspace defined by a maximum distance of 500 m horizontally and 120 m vertically from the safety pilots location. To ensure that the aircraft would not move outside of the approved airspace, considering the platforms' minimum turn radius, a live runway close by and windy conditions, a more restricted airspace was used, which is shown with a blue rectangle of 550 m x 700 m.

Figure 5 shows flight data registered by each Believer during a short mission. Despite the fact that the vehicles reached ground speeds of approx. 30 m/s, the swarm geofencing algorithms and DA's avionics system worked excellent keeping the vehicles within the small airspace. The trial was successful showing that the swarm operator was capable of controlling multiple aircraft in these challenging conditions.

IV. CONCLUSION

Digital twins can be used as a tool to assist human operators to optimise, monitor and control a swarm in real time. This was demonstrated in flight trials as our system was able control six mixed reality aircraft. The aircraft were able to change their behaviour in real time, to interact with

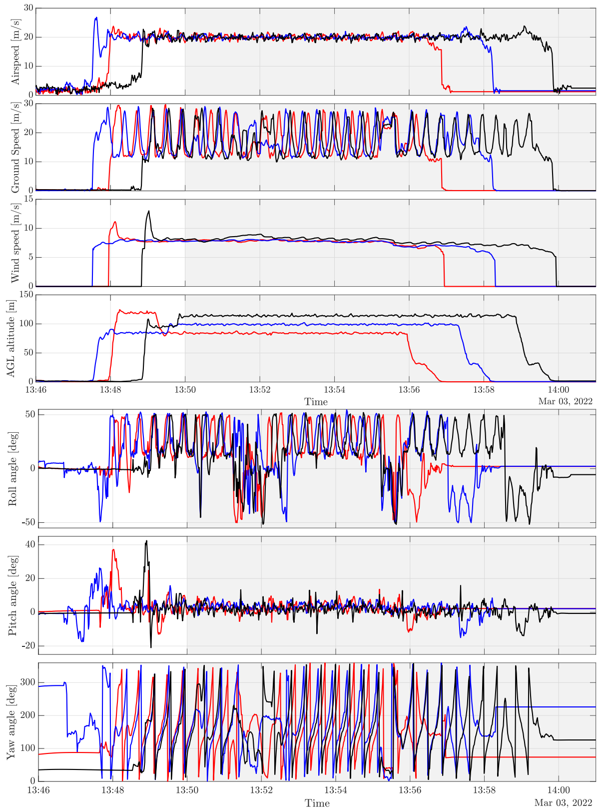

Fig. 5. Flight data registered by the Believer UAVs during a short mission. At 13:50 the swarm operator takes over control of the swarm.

virtual fires and both virtual and real aircraft of the swarm. The swarm operator could change the state of the swarm to different behaviours in flight.

Our digital twin accomplished two significant goals: it effectively replicated the swarm algorithms results obtained in simulation all the way through real-world deployments, and it reduced the sim-to-real gap successfully transferring capabilities learned in simulation to reality.

V. DISCUSSION AND FUTURE WORK

Digital twin systems can enable real-time optimisation, monitoring and control of UAV swarms by swarm operators. To reach its full potential as a digital twin, it is important to develop more realistic features. In the field of firefighting, realistic fire models must be developed so that firefighters can visualise how the fire fronts might expand and how a swarm system can be used to map and potentially extinguish wildfires. This can have an interesting effect on the controllers that can be further developed to both monitor for fires and extinguish them using an extinguishing agent. Additionally, the usage of different aircraft must be explored as small off-the shelf UAVs do not have the payload capability or the battery capacity to support long duration operation. For this reason UAVs that can carry large payloads should be explored such as the ULTRA platform developed by Windracers. Incorporating the characteristics of the new airframe must also be performed to create a tool that can be used by firefighters in the future.

Furthermore, human trials must be performed to assess how this tool can be integrated into current firefighting services. User studies can also provide us with new ideas on improving the digital twin from the perspective of the end users. To achieve this we are in the process of contacting firefighters around the UK to perform three stages of user studies. Initially, we aim to perform a contextual inquiry to understand further practical components in UAV deployments that have not been addressed yet such as their operational behaviour after a fire has been identified. Additionally, we aim to understand if the developed software can operate in real-life firefighting operations so that we can develop further our software. This will be achieved with different user studies starting with a key, attitude and perception questionnaire and focus groups. This will be followed by a "Wizard of Oz" study where participants will use our tools without being limited with the current functionality [11].

SUPPORTING VIDEO

A video demonstration and description of our work can be found here: `https://youtu.be/t1m7ucuwEmM`

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