Developing digital twins of swarms of UAVs for wildfire monitoring

Georgios Tzoumas*, Lucio Salinas*, Lenka Pitonakova*, Alex Horlock, Jonathon Waters and Sabine Hauert

***Abstract*— Deploying aerial swarm robotic systems in real-life scenarios can be challenging. Using them to monitor wildfires requires the system to be easily used by a swarm operator. To achieve this with the minimum associated costs, advanced frameworks must be developed to monitor, optimise, and control the swarm in real-time. One approach to achieve this is the creation of a digital twin where physical counterparts can be mirrored in a virtual world. Our aim was to create a digital twin of a swarm to allow simulation and optimization of control algorithms as well as real-time monitoring and control to allow swarm systems to be deployed in the field. Our framework is comprised of the following main sub-systems: Digital twin for optimization of swarm controllers, monitoring, and control of real time swarm deployments; a cloud infrastructure to allow data passing between our system components; and aircraft. We developed a Swarm Operator interface that allows a swarm operator to define missions for a swarm to monitor areas in search for a digital wildfire. We tested our system in field trials using three physical UAVs and three digital UAVs. During the trials a swarm operator was able to task the UAVs to perform autonomous search amongst three different search strategies, to loiter in a stack at a specific location, and finally to land.**

Keywords- UAVs, Swarm, Digital Twins, Human Swarm Interaction, Swarm Operator, Wildfires, Field Trials

I. INTRODUCTION

Wildfires appear more often than ever before as the effects of climate change create drier environmental conditions. Recent studies have shown that wildfire events are becoming more severe in terms of intensity and socioeconomic impact [1]. Over the past five 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]–[5]. Researchers have been investigating the use of swarms of 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]. Innocente et al. showed how a swarm of UAVs can self-organise utilising a particle swarm optimisation algorithm [3]. Seraj and Gombolay demonstrated a coordinated control system for UAVs to monitor a propagating fire front whilst taking into account the locations of the fire fighters [7]. The algorithm was demonstrated in simulation [8]. Our previous use case study with firefighters from around the world showed that an important aspect to deploy swarms in the field is the creation of a tool that a swarm operator can use so that they can interact with the swarm to patrol and identify potential fire fronts [9].

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. This creates limitations in their deployment in real life as the behaviour of the swarm is difficult to comprehend or control using standard aviation industry methods [10]. 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, it is possible to create a swarm of UAVs to first simulate large numbers of swarm to optimise a swarm behaviour for a given scenario, and then launch the mission in real-world, constantly receiving feedback from the real aircrafts 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. This data interconnection between the virtual and physical objects creates a true digital twin system [11], [12]. Digital twins can also be useful to understand how potential changes in the decentralized controllers will affect the overall performance of the system [13]. This can minimise production costs and can allow users to assess the effects of alterations in the parameters of the algorithms in the system before and during operations [14]. In the case of swarms of UAVs, digital twins can be used to reduce deployment costs, test new behaviours to enhance user interaction.

Results show initial field trials where a swarm operator can optimise, monitor, and control a swarm of up to 3 UAVs and 3 digital UAVs (total 6), changing amongst 3 decentralised search algorithms designed to search for wildfires. We used random walking, pheromone avoidance and dynamic space partition [15]. Using these algorithms we show that the Swarm Operator can locate a fire, and manage the swarm.

We explain our methodology and system architecture, we present the outcomes of our trials and conclude on the use of digital twins in field deployments of autonomous systems.

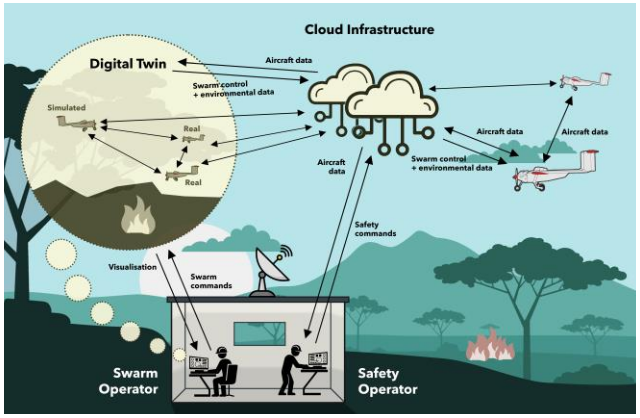

Figure 1. System architecture.

II. METHOD

A. System Framework

Our system consists of: Aircraft, Swarm Operators, Digital Twin and a Cloud infrastructure as shown in Figure 1. The digital twin is a desktop application that enables a swarm operator to launch a swarm of UAVs and to control and monitor their operation. A cloud infrastructure is used for data to flow between the UAVs, and between the UAVs and the Operators. Finally, the swarm consists of a number of physical and digital platforms that perform the swarm tasks cooperatively, and without knowing which platforms are real. Finally, in our field trials, a Safety Operator was included to ensure smooth testing and for regulatory reasons.

1) Aircraft

The aircraft used in the trial were Believer UAVs. Believers are fixed winged UAVs that are mostly used for aerials surveys. They are powered by a Lipo battery and can be airborne for 1.5 hours. Fixed winged aircraft are preferred as they can travel at greater velocities and for longer periods of time. The aircraft was equipped with a raspberry Pi computer and a 4G LTE modem which enabled the aircraft to connect to 4G networks. This allowed data to pass between aircraft and to the operator using a cloud infrastructure powered by 4G. Additionally, a radio serial link was used to send data in case the 4G signal is lost.

TABLE I. TECHNICAL CHARACTERISTICS OF THE BELIEVER PLATFORM

Minimum air speed	16 m/s
Maximum air speed	20 m/s
Minimum turn radius	50 m
Wingspan	2 m

2) Swarm operator

The swarm operator defines the experiment parameters, such as the number of UAVs, the fire search algorithm, etc., and uses a UI to optimize control algorithms, monitor the performance of the swarm and in real time control the behavior 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 and to land using their decentralized controller.

3) Digital twin

This is a desktop application that receives data about the current state of the real and virtual world, such as information about the platforms, virtual pheromones, and virtual fires. Virtual platforms are spawned in cloud-based containers, and they use the same controller that is used in real aircraft. Data is received and processed by the aircraft using a 4G connection to the cloud in an asynchronous manner, and they are visualized in 2D by a UI. The digital twin allows an operator to interact, monitor and control a swarm of UAVs for fire monitoring purposes.

4) Cloud infrastructure

The cloud allows the creation of simulated aircraft using containers which then post their data to the digital twin. The simulated aircraft are using 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 UI that is used by the swarm operator and the safety operator.

B. Experimental setup

The experimental scenario was developed in cooperation with firefighters. They believe that a swarm of UAVs can be used to patrol an area for potential wildfires and if a fire is seen then they should be able to inform the swarm operator about a potential threat to investigate the incident further [9].

We conducted our test flights at Draycot Foliat. The location provided an area to hand launch physical aircraft. Three safety pilots were present to ensure the safe operations of the tests. The size of the search area was 550m x 700m and a digital fire was generated for the swarm to identify. Digital fires were identified if the real or virtual aircraft would fly on top of their location. Once the aircraft were airborne by the safety pilots, the swarm operator took over control of the 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 avoidance and dynamic space partition were used as exploration techniques [15].

III. RESULTS

Figure 2. Digital twin UI showing 6 aircraft 3 real and 3 virtual performing an area search with the dynamic space parititon controller.

A. *Algorithm optimisation*

The swarm operator can run batch simulations to test the performance of the system given specific parameters such as the size of the world or the size of the swarm. Thus, we were able to test the performance of the searching algorithms to control our swarm to identify wildfires. Our results show that the dynamic space partition outperforms other exploration techniques and thus, it was chosen as the exploration strategy of our swarm.

B. *Swarm monitoring and control*

We were able to control the swarm via changing the searching strategy and the behaviors of the UAVs. Using the digital twin the operator could monitor the location of the UAVs and also the altitude that the UAVs were flying. The agents were tasked to stack on top of each other so that the swarm operator could then begin the search operations. The agents were then tasked to search and their search behavior was changed by the operator from random search to pheromone dispersion and then to dynamic space partition to test the ability of the operator to change the exploration strategy of the swarm. These behaviors were tested and performed successfully showing that the operator can monitor and control the UAVs in the swarm.

C. *Six aircraft fire identification*

The largest swarm that was controlled had six aircraft. Three physical aircraft and three virtual. The six aircraft were able to perform all the required functionalities (stack, loiter, search and land) successfully. All of the searching behaviours were tested and the digital fire was also identified by the swarm. During the trials the real aircraft avoided their digital counterparts, showing that the digital and real aircraft interaction was achieved. Lastly, the aircraft were tasked to perform a swarm land. In this case the real aircraft landed first as they were flying at a lower altitude than the virtual ones. Each aircraft performed the landing procedure if they were the lowest flying aircraft.

IV. Discussion

During the experiments, we discovered the importance of sufficient bandwidth in a swarm system where individual agents need to know up-to-date information about the positions of other agents, as well as of virtual objects like digital fires and pheromones. Even though we use Protocol Buffers [16] encoded in JSON strings to minimise the size of the data payloads, the allowed bandwidth was not enough to send the full state of the aircraft.

Additionally, the 4G LTE network was not as reliable as expected. In many occasions the signal was lost which created issues in communication with real aircraft. As it is impossible to have perfect communications in field operations it is important to design systems with built-in reliability. It is also needed to test our system with more aircraft in larger scenarios. Their deployment in larger scenarios in the virtual real are already in development.

Using digital twins it is possible to scale up numbers of the aircraft that the swarm consists of. This is done via introducing digital agents in the swarm and gives the capability to the operators to stress-test the system without risking damaging more aircraft.

V. Conclusion

In our trials we conclude that 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 real trials as our system was able to optimize, monitor and control six mixed reality aircraft. The aircraft were able to change their behavior in real time, to interact with virtual fires and both virtual and real aircraft of the swarm. The swarm operator could change the state of the swarm to different behaviors in flight. We understood that 4G LTE networks can be used but not as reliably or as a sole mean of data transferring. Thus, it is crucial for the agents to be equipped with other modules of communication so that they can interact with each other and the swarm operator in a distributed way.

Figure 3. Believers platforms.

VI. FUTURE WORK

Comparison metrics will need to be developed that will enable us to evaluate the latency between real aircraft and their digital representations. This will enable us to evaluate how well real and virtual aircraft interact. Additionally, we will need to test our system with a larger swarm as the limit to six aircraft was set due to the small area of the test space and not from the capabilities of our system. We are currently performing tests using our framework to control 30 virtual aircraft to monitor an area the size of California in a 24-hour operation.

Finally, and most important, it will be key to perform more thorough tests with swarm operators to assess the useability of the interface for future swarm deployments for wildfire monitoring and mitigation. In our case we have planned to test our system with firefighters to develop a qualitative and quantitative analyses assessing how effectively the operators can use our digital twin.

ACKNOWLEDGMENT

We would like to thank everyone involved in the test flights from safety pilots to operators for their invaluable help. We would also like to thank Windracers ltd. And Distributed Avionics ltd. for their help, information and provided equipment. This work has been funded by Innovate UK grant N 75392.

REFERENCES

[1] F. Tedim *et al.*, "Defining extreme wildfire events: difficulties, challenges, and impacts," *Fire*, vol. 1, no. 1, p. 9, 2018.

[2] A. M. Gill, S. L. Stephens, and G. J. Cary, "The worldwide 'wildfire' problem," *Ecol. Appl.*, vol. 23, no. 2, pp. 438–454, 2013.

[3] M. S. Innocente and P. Grasso, "Self-organising swarms of firefighting drones: Harnessing the power of collective intelligence in decentralised multi-robot systems," *J. Comput. Sci.*, vol. 34, pp. 80–101, 2019.

[4] D. M. Molina-Terrén *et al.*, "Analysis of forest fire fatalities in southern Europe: Spain, Portugal, Greece and Sardinia (Italy)," *Int. J. Wildl. fire*, vol. 28, no. 2, pp. 85–98, 2019.

[5] D. Bowman *et al.*, "Wildfires: Australia needs national monitoring agency." Nature Publishing Group, 2020.

[6] K. A. Ghamry, M. A. Kamel, and Y. Zhang, "Multiple UAVs in forest fire fighting mission using particle swarm optimization," in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2017, pp. 1404–1409.

[7] E. Seraj and M. Gombolay, "Coordinated control of uavs for human-centered active sensing of wildfires," in *2020 American Control Conference (ACC)*, 2020, pp. 1845–1852.

[8] E. Seraj, A. Silva, and M. Gombolay, "Safe coordination of human-robot firefighting teams," *arXiv Prepr. arXiv1903.06847*, 2019.

[9] G. Tzoumas, C. Scales, S. Wright, T. Richardson, and S. Hauert, "Developing use cases for swarms of high payload UAVs for firefighting using mutual shaping," *Submitted*, 2021.

[10] F. Fabra, J. Wubben, C. T. Calafate, J. C. Cano, and P. Manzoni, "Efficient and coordinated vertical takeoff of UAV swarms," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, pp. 1–5.

[11] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informatics*, vol. 15, no. 4, pp. 2405–2415, 2018.

[12] M. Batty, "Digital twins," *Environment and Planning B: Urban Analytics and City Science*, vol. 45, no. 5. SAGE Publications Sage UK: London, England, pp. 817–820, 2018.

[13] A. El Saddik, "Digital twins: The convergence of multimedia technologies," *IEEE Multimed.*, vol. 25, no. 2, pp. 87–92, 2018.

[14] R. Rosen, G. Von Wichert, G. Lo, and K. D. Bettenhausen, "About the importance of autonomy and digital twins for the future of manufacturing," *Ifac-papersonline*, vol. 48, no. 3, pp. 567–572, 2015.

[15] G. Tzoumas, L. Pitonakova, L. Salinas, C. Scales, T. Richardson, and S. Hauert, "Wildfire detection in large scale environments using force based control for swarms of UAVs," *Swarm Intell.*, 2022.

[16] Google, "Protocol Buffers." https://developers.google.com/protocol-buffers (accessed May 24, 2022).