

# Autonomous and Cooperative Pathfinding Technique for Swarms of Unmanned Aerial Vehicles in Dynamic Environments

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**Abstract**—Coordinating swarms of UAVs requires the integration of multiple subsystems, from flight control to cooperative task execution, making it a complex challenge. The thesis proposed a pathfinding technique for swarm robotics, designed for both static and dynamic environments. This technique enabled the robots to cooperate and incrementally find paths through the swarm’s emergent behaviour. It was validated through a coordination model focused on evacuating individuals from wildfire-affected areas, where the rapid identification of safe routes is critical. Experimental results demonstrated that UAVs collaboratively identified and signalled escape routes, exhibiting robust global behaviour during search and path delineation. Moreover, the thesis contributed to the application of swarm robotics to improve safety in high-risk scenarios.

**Index Terms**—Swarm Robotics. Pathfinding. Dynamic Environments. Wildfires.

## I. INTRODUCTION

Over the past decade, swarm robotics has become a well-established topic in robotics research [1], and its relevance is expected to grow exponentially. Although the term first appeared in the early 90s [2], it has gained significant attention only in recent years. This surge in interest is primarily driven by technological advances that have made the theory of swarm robotics feasible in real-world applications.

Swarm Robotics can be defined as a group of robots that work collaboratively to achieve a common goal [3]. Unlike multi-robot systems, swarm robotics is characterized by the autonomy of individual robots, which execute local objectives without direct collaboration. However, as noted by [4], when operating as a swarm, these robots exhibit an emergent global behaviour capable of performing complex tasks. Additionally, the deployment of UAVs – commonly known as drones – has expanded the scope of swarm robotics.

Pathfinding techniques are widely applied to swarms of UAVs [1]. These techniques employ different approaches, e.g., mathematical models, artificial physics, and bio-inspired methods. While intra-swarm cooperation can optimise the pathfinding process, many models still prioritise independent

path computation. Furthermore, beyond the cooperative path search, ensuring swarm convergence along the identified path presents an even greater challenge.

Despite the potential of swarm robotics in search-and-rescue operations, its practical application remains limited [5]. Deploying swarms of UAVs for this purpose presents multiple challenges, including flight control, intra-swarm communication, swarm coordination, and cooperative execution of tasks like pathfinding. In addition, unpredictable factors (e.g., wind currents and structural instability) further complicate real-time decision-making and route optimisation, both of which are critical for effective swarm-based evacuation strategies.

In this context, the thesis [6] proposed a pathfinding technique for swarm robotics, enabling cooperative identification of paths through local interactions, in static and dynamic environments. Although applicable to various types of robotic swarms, this technique is particularly effective for aerial robots due to their enhanced environmental perception. Potential applications include disaster evacuation, cave exploration, formation of temporary communication relay chains, and maze navigation. To validate the approach, the technique was applied in a coordination model for UAV swarms assisting in wildfire evacuations, where UAVs collaboratively identify and signal escape routes while adapting to environmental dynamics.

## II. RELATED WORKS

This section presents the related literature on swarm coordination models, with a focus on wildfire-related tasks<sup>1</sup>.

Early work by [7] highlights the use of UAVs to track fire boundaries as a viable monitoring strategy, while [8] demonstrated the operational advantages of distributed swarm cooperation. Recent studies address pathfinding in dynamic wildfire spread prediction [9], real-time fire perimeter monitoring [10], and task allocation for firefighting resource distribution [11], proposing optimisation algorithms and adaptive strategies. Moreover, [12] present a human-guided swarm system for evacuation tasks, although full autonomy remains limited.

Despite significant theoretical advances, the deployment of swarm robotics for wildfire response remains constrained. Limitations include insufficient robustness in unpredictable disaster environments, sensor and communication failures, and discrepancies between simulated and real-world performance.

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<sup>1</sup>Works that use swarms in wildfires response (refer to Table 2 [6, p. 57]).

### III. PROPOSITION

Based on the thesis hypothesis (refer to Sec. 1.2 [6, p. 31]):

- **H1:** It is possible to propose a cooperative pathfinding technique for swarm robotics to effectively operate in dynamic environments; and,
- **H2:** It is possible to integrate the proposed pathfinding technique into a coordination model, in order to evacuate individuals from wildfire-affected areas.

The thesis proposed a pathfinding technique for swarm robotics in dynamic environments, named SW\* (SW-Star), and a coordination model, called the Swarm-Assisted EVacuation sYstem (SAEVY), which implements the SW\* technique.

The SW\* calculates paths between start and end points, initially prioritizing the shortest route. However, in environments where specific areas must be avoided, optimal paths may differ from the shortest ones, particularly when tasks demand specialised path characteristics (e.g., enhanced safety). To address this, the proposed heuristic establishes a restricted zone around prohibited areas. Since the environment is modelled as a lattice, cells directly within this core zone incur the highest restriction penalty. From these core cells, the method iteratively constructs successive layers to expand the restricted area outward, governed by a predefined restriction radius. Crucially, the penalty intensity diminishes incrementally with distance from the core restricted cells, i.e., cells farther from the avoidance zone experience weaker restriction effects. This approach is visualised in Figure 1, demonstrating swarm navigation around predefined hazards.

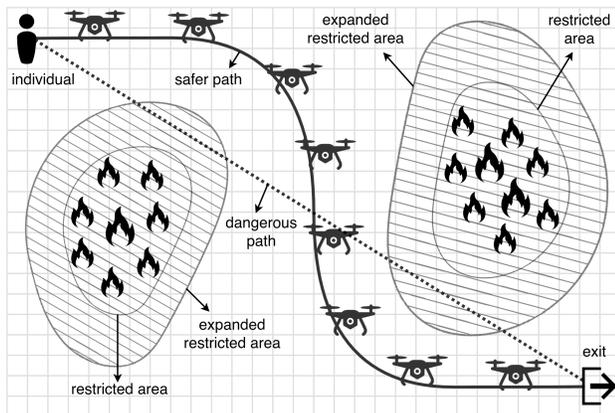


Fig. 1: General scheme of the swarm pathfinding heuristic.

The SAEVY model was proposed to coordinate UAV swarms in searching for and mapping paths. Beyond cooperative pathfinding, the swarm must also converge to delineate these paths. Its versatility enables applications like search-and-rescue operations, temporary communication relay chains, and cave exploration. SAEVY defines two core swarm behaviours (refer to Section 4.3, [6, p. 79]): the monitoring-task, where UAVs spread throughout the environment to identify targets and map environments, and the signalling-task, where they indicate evacuation routes for individuals in affected areas.

### IV. EXPERIMENTS AND ANALYSES

The thesis adopts a quantitative, exploratory, and experimental approach, employing technical procedures for validation. Simulations were conducted on the MaSS platform (refer to Section 3.3.2 [6, p. 65]), where experiments applied the SAEVY model to a search-and-rescue task in wildfire-affected areas. In this scenario, robots disperse throughout the environment to monitor conditions and, upon detecting a wildfire, identify and signal potential evacuation routes.

Representing outdoor areas, the experiments were performed in environments with dimensions equal to  $(20 \times 30)$  and  $(40 \times 60)$  cells. Graphical elements were incorporated to depict each state of the cells, in order to facilitate the interpretation of the experiments. Figure 2 details the possible states of the grid alongside their respective graphical representations.

Graphical Representation of the Cell States						
Mobile		Vegetation			Envir.	
robot	indv.	generic	meadow	savannah	forest	water
Trails		Fire				
path	exit	generic	initial	stable	ember	ash

Fig. 2: Graphical representations of the cell states. Elements: mobile, vegetation, environment, trails and fire.

#### A. Pau-Furado State Park

The deployment of a swarm in a real-world environment is important for validation. Figure 3 presents the map of the Pau-Furado State Park, a conservation unit located in the state of Minas Gerais, Brazil<sup>2</sup>. Figure 3a shows an area of interest within the park where simulations were carried out. Figure 3b illustrates the discretization of this highlighted area.

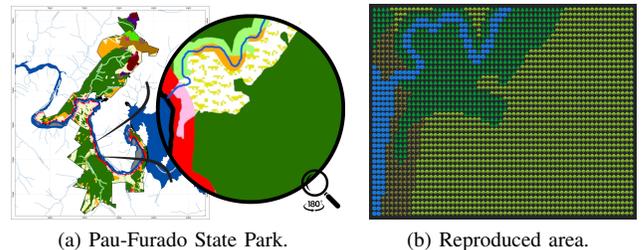


Fig. 3: Reproduction of the highlighted area of the Pau-Furado State Park (Protected Cerrado area in Brazil).

Figure 4 presents the simulation conducted in the Pau-Furado State Park (simulation videos available online<sup>3</sup>). The arrangement of the paths in a triangular shape facilitates the visualisation of the swarm's convergence towards the shortest path. During simulation, a fire outbreak is detected around time-step 208 (Fig. 4a). Information about this fire source

<sup>2</sup>This paper presents only the main results, a series of experiments was conducted (refer to Section 5.2.1 [6, p. 92]).

<sup>3</sup>Avail.: <https://www.youtube.com/playlist?list=PLhS2nTbfigy4IqNcr8eHqCo3gIwBPMsKT>, 10-07-2025.

quickly spreads within the swarm, and by time-step 250, the swarm converges to the shortest evacuation path (Fig. 4b). The swarm detects the approach of the flames by time-step 820 (Fig. 4c), and it reorganises and converges on a new path by time-step 865 (Fig. 4d). The fire continues to spread up to time-step 1870 (Fig. 4e), and by time-step 1910 (Fig. 4f), the swarm converges again towards a third possible path.

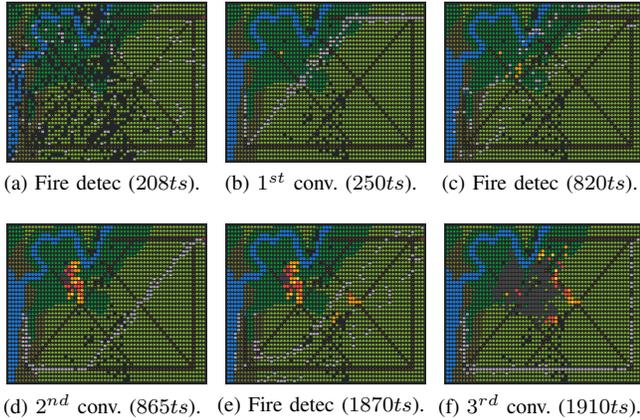


Fig. 4: SAEVY simulation in the Pau-Furado State Park with the Wildfire Simulation Model proposed by [13] and [14].

When the number of UAVs exceeds available cells on evacuation paths, overcrowding occurs, preventing some agents from accessing paths. Despite this congestion being visually apparent, UAVs operate solely on local information and cannot perceive global overcrowding. Crucially, a search behaviour emerged where UAVs unable to locate immediate vacancies actively sought unoccupied cells along the path. This adaptive response, observed during path delineation tasks, stems from the UAVs' Past-Path Memory (PPM) system. By storing previously visited cells and prioritising unexplored areas, UAVs efficiently navigate congestion while leveraging shared movement history (refer to Section 4.1 [6, p. 71]), demonstrating autonomous adaptation to constrained conditions.

## V. CONCLUSION AND FUTURE WORK

The thesis proposed the SW\* pathfinding technique and SAEVY coordination model for robot swarms operating in dynamic wildfire evacuation scenarios. SW\* provides decentralised, adaptive, and heuristic-driven pathfinding, while SAEVY enables self-regulated inter-robot distances, multi-objective handling, and interference resilience. Their combined implementation successfully demonstrated real-time path identification, environmental adaptation, and decision-making capabilities, confirming hypotheses H1 and H2. Key contributions encompass emergent swarm coordination behaviour, optimised path delineation, efficient distribution of agents, and reduced communication bandwidth requirements. The associated source code and data are publicly accessible under AGPL-3.0<sup>4</sup>. Future research will refine SAEVY parameters using

<sup>4</sup><https://github.com/claudiney-tinoco/SAEVY-SWStar>, Accs.: 10-07-2025.

evolutionary computation, optimise swarm information exchange, enhance deployment strategies for varying conditions, investigate impacts of failures and threats, explore heterogeneous swarms for simultaneous monitoring and signalling, and validate the model through realistic simulation platforms (e.g., Webots or ARGoS) for real-world implementation.

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## DEDICATION

This work is dedicated to the memory of Prof. Gina Maira Barbosa de Oliveira, professor, adviser, and dear friend.

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