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

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Abstract. *Coordinating UAV swarms 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 using 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.*
Keywords: *Swarm Robotics. Pathfinding. Dynamic Environments. Wildfires.*

1. Introduction

Over the past decade, swarm robotics has become a well-established topic in robotics research [Shahzad et al. 2023], and its relevance is expected to grow exponentially in the current century. Although the term first appeared in the early 1990s [Beni and Wang 1993], 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 both simulation platforms and real-world applications.

In simplified terms, swarm robotics is defined as a collective of simple robots that work collaboratively to achieve a common goal [Şahin 2004]. Unlike multi-robot systems, swarm robotics is characterized by the autonomy of individual robots, which execute local objectives without direct collaboration from other robots. However, as noted by [Navarro and Matía 2013], 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, encompassing potential aerial applications.

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Pathfinding techniques are widely applied to UAV swarms across various tasks [Shahzad et al. 2023]. 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, particularly for evacuation, its practical application remains limited [Wu and Zheng 2023]. Deploying UAV swarms 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 [Tinoco 2024] proposed a pathfinding technique for swarm robotics, enabling cooperative identification of paths through local interactions, making it adaptable to both 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 UAVs swarms assisting in wildfire evacuations, where UAVs collaboratively identify and signal escape routes while adapting to environmental dynamics.

2. Related Works

This section presents the related literature on swarm coordination models, with a focus on wildfire-related tasks[1]. It is noted that UAVs are becoming increasingly popular in the public safety sector. Specific applications, such as fighting wildfires, highlight the critical need for the implementation of intelligent techniques.

Early work by [Srinivasan et al. 2012] highlights the use of UAVs to track fire boundaries as a viable monitoring strategy, while [Chmaj and Selvaraj 2015] demonstrated the operational advantages of distributed swarm cooperation. Recent studies address pathfinding in dynamic wildfire spread prediction [Radmanesh et al. 2021], real-time fire perimeter monitoring [Tzoumas et al. 2023], and task allocation for firefighting resource distribution [Chen et al. 2023], proposing optimisation algorithms and adaptive strategies. Moreover, [Vaidyanath et al. 2020] 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. Within this context, the thesis proposition focused specifically on a cooperative strategy for identifying safe evacuation routes – *a targeted contribution to swarm adaptability for dynamic disaster scenarios*. Future research must address other limitations in robustness, field validation, and system interoperability to allow practical swarm-based disaster response solutions.

[1] Compilation of works that use swarms in wildfire response (refer to Table 2 [Tinoco 2024, p. 57]).

3. Proposition

Considering the thesis hypothesis (refer to Section 1.2 [Tinoco 2024, 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), along with a coordination model for robot swarms, denominated Swarm-Assisted EVacuation sYstem (SAEVY), which implements this technique.

The SW* enables distributed pathfinding, making it well-suited for implementation in robot swarms. Cooperation between robots allows the dynamics of the environment to be efficiently reflected in the local maps of each robot. Consequently, each robot's map is more likely to represent a real-time state of the environment.

In order to find a possible path, the SW* takes a start and end point as input, initially prioritizing the shortest route. However, in environments where specific areas must be avoided, the optimal paths may differ from the shortest ones. This is due to the fact that certain tasks may require paths with specific characteristics, such as minimal curves or maximised safety. The proposed heuristic constructs a restricted area around the area to be avoided. Considering that the environment is represented as a lattice, cells within this area receive the highest restriction penalty. From these cells, successive layers are iteratively constructed to expand the restricted area, based on a pre-established restriction radius. The penalty intensity of these layers decreases the farther they are from the cells to be avoided, i.e., the farther from the restricted area, the lower the restriction effect. Figure 1 illustrates the application of the proposed heuristic, showing how the swarm avoids predefined areas. The expansion of the restricted area is determined through the Equation 1, which calculates the restriction penalty for each cell of the lattice.

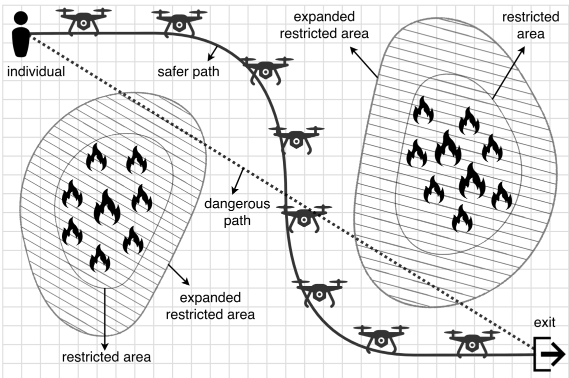


Figure 1. General scheme of the proposed heuristic to search for safer paths.

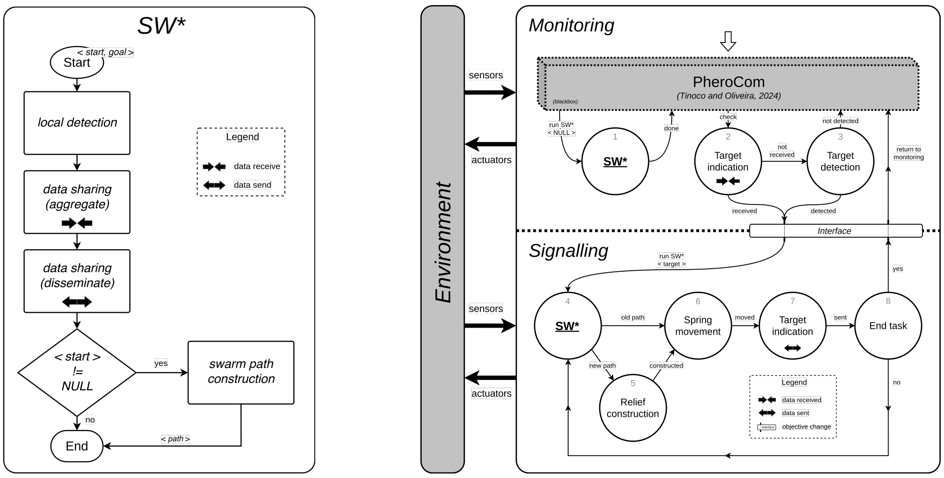
$$RST(c_{ij}, r_{rst}) = \begin{cases} 2.0^{(r_{rst} - dist(c_{ij}) + 1.0)}, & \text{if } dist(c_{ij}) \leq r_{rst} \\ 1.0, & \text{otherwise} \end{cases} \quad (1)$$

where: (i) RST is the restriction penalty for a given cell; (ii) c_{ij} is a specific cell in the position ij; (iii) r_{rst} is the pre-established restriction radius; and, (iv) $dist(c_{ij})$ is the distance from the cell c_{ij} to the nearest cell in the restricted area.

As shown in Figure 2a, SW* continuously updates its local map to improve pathfinding. The process begins by checking the robot's neighbourhood for changes in the map. Next, the robot verifies whether any information is being disseminated by others within its communication range. If such information is detected, it indicates that changes in the environment have been found and shared by other robots. Once the local map is updated, the robot contributes to the swarm by disseminating the data it gathered in the previous steps. The combination of data aggregation and dissemination leads to the emergence of a global behaviour in the swarm, enabling efficient pathfinding.

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. The model's versatility allows its application in various scenarios, such as search-and-rescue, formation of temporary communication relay chains, and the exploration of caves and storm drainage networks. It is defined by two swarm behaviours (Figure 2b): monitoring and signalling. In the monitoring-task, UAVs spread throughout the environment to identify pre-established targets and mapping. In the signalling-task, they indicate potential evacuation routes for individuals in affected areas.

The behaviours of the SAEVY are implemented through a Finite State Machine (FSM). The monitoring-task implements three states: (i) *01 - SW**: the UAV performs the SW* without a goal (SW* *(NULL)*); (ii) *02 - Target indication*: the UAV assesses whether any UAV within the communication radius is signalling the presence of fire spots or individuals; and, (iii) *03 - Target detection*: the UAV examines its detection neighbourhood for any fire spots. In turn, the signalling-task implements five states: (i) *04 - SW**: the UAV performs the SW* with a goal (SW* *[init, goal]*); (ii) *05 - Relief-map construction*: constructs a map that allows the UAVs to converge onto the evacuation path (refer to Section 4.3.2 [Tinoco 2024, p. 82]); (iii) *06 - Spring Movement*: the robot transitions from an origin cell c_{ij} to a target cell $c_{(i+a)(i+b)}$, such that $\{a, b \in \mathbb{Z}\}$, while maintaining distance from other robots (refer to Section 4.3.3 [Tinoco 2024, p. 84]); (iv) *07 - Target indication*: signal to other UAVs the necessity to contribute to the signalling-task; and, (v) *08 - End*: the FSM final state is activated when the UAV completes the proposed task.



(a) SW* flowchart.

(b) SAEVY through a FSM.

Figure 2. Detailed description of the SW* technique and SAEVY model.

4. 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 [Tinoco 2024, 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 featuring natural elements, the experiments were performed in environments with dimensions equal to (20×30) and (40×60) cells. Sensing radius $(r_s = 1)$, detection radius $(r_d = 1)$ and communication radius $(r_c = 4)$. Variables $\mu = 0.3$ and $\nu = 0.3$, which are related to the decision-making process during the movement of the robots, and variables $\alpha = 0.5$, $\delta = 0.1$ and $\eta = 2.0$, which are related to the pheromone deposition process, a fundamental characteristic of this model. Additionally, the pheromone evaporation rate $\beta = 0.005$ and a swarm with 30 UAVs for environments (20×30) and $\beta = 0.001$ and a swarm with 100 UAVs for environments (40×60) (refer to Section 5.1 [Tinoco 2024, p. 89]). Finally, graphical elements were incorporated to depict each state of the cells, in order to facilitate the interpretation of the experiments. Figure 3 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
🔸	⭕	🔥	🟠	🟡	🔴	⚫

Figure 3. Graphical representations of the cell states applied in the simulations on the MaSS. Elements: mobile, vegetation, environment, trails and fire.

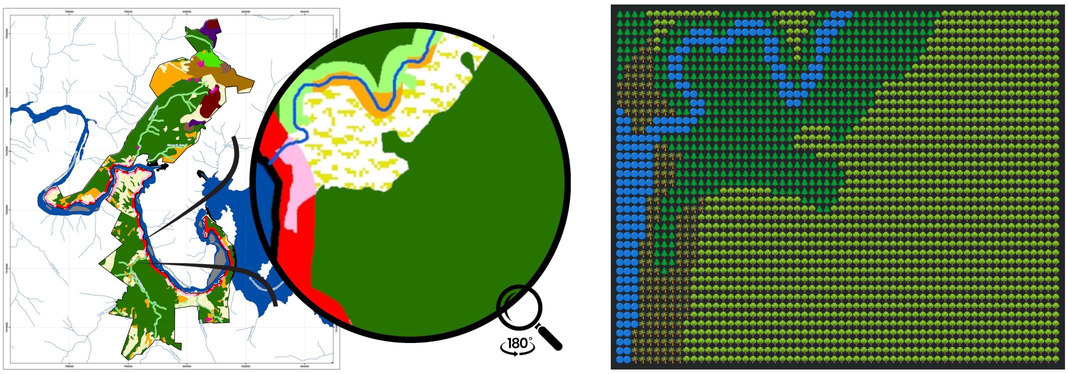
4.1. Pau-Furado State Park

The deployment of a swarm in a real-world environment is important for validation. To reduce the gap between simulations and reality, this experiment replicates real-world data and applies a wildfire simulation model[2]. These factors increase the dynamism of the environment, making the adaptation of the swarm more challenging. Figure 4 presents the map of the Pau-Furado State Park, a conservation unit located in the state of Minas Gerais, Brazil. Figure 4a shows an area of interest within the park where simulations were carried out. Figure 4b illustrates the discretization of this highlighted area.

Figure 5 presents the evolution of a simulation conducted in the highlighted area of Pau-Furado State Park (simulation videos available online[3]). The arrangement of the paths in a triangular shape facilitates the visualisation of the swarm's convergence towards

[2]This paper presents only the main results, while a series of preliminary experiments was conducted to calibrate the model's parameters (refer to Section 5.2.1 [Tinoco 2024, p. 92]).

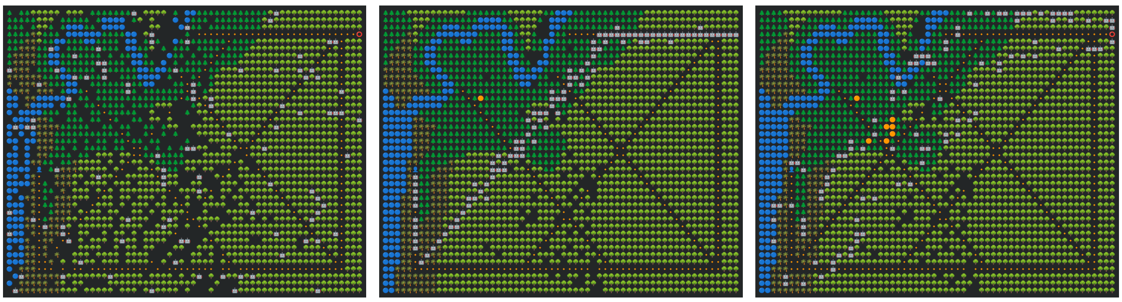
[3]Available: https://www.youtube.com/playlist?list=PLhS2nTblfgy4IqNcr8eHqCo3gIWbPMsKT, Accessed: June 28, 2025.



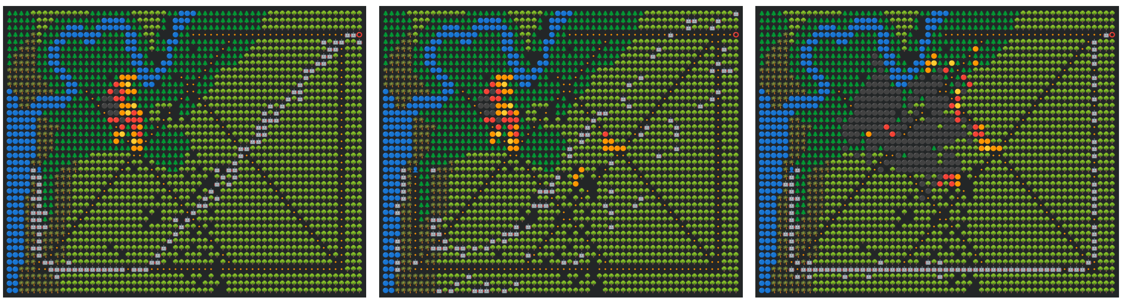
(a) Pau-Furado State Park. **(b)** Reproduced area.

Figure 4. Swarm rescue simulation in a reproduction of the highlighted area of the Pau-Furado State Park (Protected Cerrado area in Brazil).

the shortest path. During simulation, a fire outbreak is detected around time-step 208 (Fig. 5a). Information about this fire source quickly spreads within the swarm, and by time-step 250, the swarm converges to the shortest evacuation path (Fig. 5b). The swarm detects the approach of the flames by time-step 820 (Fig. 5c), and it reorganises and converges on a new path by time-step 865 (Fig. 5d). The fire continues to spread up to time-step 1870 (Fig. 5e), and by time-step 1910 (Fig. 5f), the swarm converges again towards a third possible path.



(a) Fire detec ($208ts$). **(b)** 1^{st} conv. ($250ts$). **(c)** Fire detec ($820ts$).



(d) 2^{nd} conv. ($865ts$). **(e)** Fire detec ($1870ts$). **(f)** 3^{rd} conv. ($1910ts$).

Figure 5. SAEVY simulation in the Pau-Furado State Park with the Wildfire Simulation Model proposed by [Tinoco et al. 2022a] and [Ferreira et al. 2023].

The number of UAVs in the swarm is greater than the number of cells on the evacuation paths, resulting in overcrowding during delineation. This overcrowding provides an opportunity to evaluate the behaviour of the UAVs when they are unable to access the path to be delineated due to the impossibility of finding free cells. Although it is easy to visually observe that the path is overcrowded, this information is not available to the UAVs, as they only have access to local information. Therefore, it is essential to observe whether a search behaviour emerges, i.e., even without finding an empty cell in their current neighbourhood, the UAVs should search for empty cells along the path. During the delineation of the evacuation paths, shown in Figures 5(b, d and f), this behaviour was clearly observed, as UAVs that could not approach the path due to overcrowding started a search process. This behaviour is primarily due to the UAVs' ability to store part of the cells they have already visited. Thus, in addition to being able to share information about past movements, this information is used to give a higher priority to cells that are not in the past-path memory (PPM) (refer to Section 4.1 [Tinoco 2024, p. 71]).

4.2. Murmuration Convergence Behaviour

Between convergences towards evacuation paths, it is possible to observe the UAVs moving away from the blocked path in different directions before converging on the new path (resembling diastolic and systolic movements). This behaviour is analogous to birds' murmuration in biology [Richardson and Chemero 2014]. Since UAVs do not have global knowledge, the murmuration period is important for quickly updating their local maps. This is because the UAVs do not explore the environment during the delineation phase, and their dynamism may have caused the local maps to become outdated. Thus, murmuration allows the current state of the nearby region to be reflected in the UAVs' local maps. Figure 6 presents a sequence of heatmaps illustrating, between two delineations, the murmuration convergence. The murmuration convergence allows the expansion of the swarm across the environment, increasing the probability of updating local maps and, consequently, enabling more accurate decision-making.

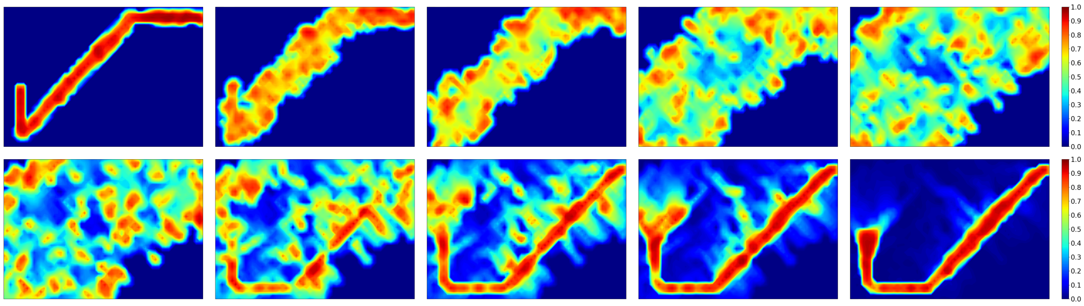


Figure 6. Switching path delineation via murmuration-convergence ($T = 60ts$).

4.3. Bandwidth Measurement

In order to determine whether the required bandwidth would dictate the communication medium (e.g., infrared, Bluetooth, Wi-Fi), a quantitative study was conducted to define how much data is disseminated and aggregated (for details on data aggregation, refer to Section 5.2.2.3 [Tinoco 2024, p. 106]) by each robot as well as by the swarm.

Figure 7 presents a chart of total data dissemination. According to the results, in a simulation with 100 robots and $T = 10,000$ time-steps, there are, on average, 1.0003×10^6 transmissions and 3.5×10^7 data units (in this case, each data unit represents a cell of the lattice, i.e., a structure defined by its coordinates and its value). On average, 1.0003×10^6 transmissions represent $(\approx 10,000/robot) \rightarrow (\approx 1/cycle)$; and, 3.5×10^7 data units represent $(\approx 350,000/robot) \rightarrow (\approx 35/cycle)$. The number of data units transmitted per robot represents approximately the size of the past-path memory applied (30 data units in this case), plus five data units for information related to the robot's current positioning, behaviour control, and versioning. Furthermore, both in the number of transmissions and in the number of data units, it is possible to observe a low variance in the data, since data dissemination does not depend on probabilistic events, always occurring at predefined intervals. Therefore, given that each data unit is approximately 6 bytes (6 characters), the total data size per transmission is ≈ 210 bytes. This volume of data can be easily handled by any of the described communication mediums, a fact further confirmed by the total data aggregation analysis. The consistent results from this analysis affirm the suitability of these mediums for handling the transmitted data.

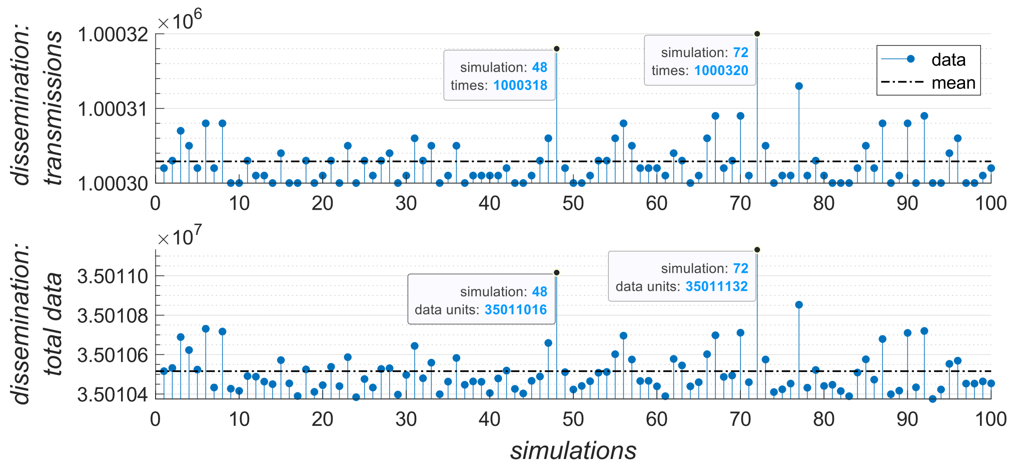


Figure 7. Bandwidth required for real-world implementation: data dissemination.

5. Assessment and Discussion

The evaluation of the proposed model addresses both hardware requirements and localisation challenges in real-world applications. Experiments conducted on the MaSS platform confirmed the effectiveness of the SW* technique and the SAEVY model in the coordination of UAV swarms. For further validation, the next steps include testing on realistic simulation platforms before deployment in real robots. Hardware considerations include agile UAV platforms, resilient communication systems, fire detection sensors, navigation mechanisms, onboard processing for real-time decision-making, long-lasting power sources, and protective materials against heat and environmental factors.

Individual spatial localisation remains a significant challenge in robotics, as existing techniques – odometry, landmark recognition, and radio-based localisation – often lack the required precision for complex applications. Although localisation mechanisms are beyond the scope of the thesis, prior research presents promising solutions, including a method that combines super multidimensional scaling with patch dividing/merging and GPS integration, alongside clustering-based cooperative relative localisation systems. These approaches adhere to the principles of Swarm Intelligence and have substantial potential for improving geolocation accuracy in future implementations.

6. Research Contributions and Dissemination

This section gives an overview of the work derived from the Ph.D. thesis [Tinoco 2024].

6.1. Bibliographic Production

The bibliographic contributions derived from the thesis are as follows:

Bibliographic production directly related to the thesis:

- [Tinoco and Oliveira 2019] (Qualis A1) Publication and presentation at the *"IEEE Congress on Evolutionary Computation" (CEC-2019).* The presentation was held in-person in Wellington, New Zeland;
- [Tinoco et al. 2020] (Qualis B2) Publication and presentation at the *"Int. Conf. and School 'Cellular Automata for Research and Industry' " (ACRI-2020).* Results of the interuniversity exchange, with the participation of the abroad-supervisor (Prof. G. Vizzari, Ph.D. - UniMiB);
- [Tinoco et al. 2022a] (Qualis B2) Publication and presentation at the *"Int. Conf. and School 'Cellular Automata for Research and Industry' " (ACRI-2022).* Results of the supervision of the undergraduate student H. F. Ferreira. The presentation was held in-person in Geneva, Switzerland;
- [Ferreira et al. 2023] (Qualis A2) Publication at the *"Int. Conf. on Artificial Intelligence and Soft Computing" (ICAISC - 2023).* Results of the supervision of the undergraduate student H. F. Ferreira;
- [Tinoco et al. 2024] Publication at the *"XVIII Workshop de Teses e Dissertações em C. Comp."* (WTDCC-2024). Titled: "Técnica de Busca de Caminhos Cooperativa e Autônoma para Enxames de VANTs em Ambientes Dinâmicos"; and,
- [Tinoco et al. 2025b] (Qualis A1) Publication and presentation at the *"IEEE Congress on Evolutionary Computation" (CEC-2025).* Preliminary results of the thesis. The presentation was held in-person in Hangzhou, China.
- [Tinoco et al. 2025a] (Qualis A1) Publication at the *"Swarm and Evolutionary Computation".* Available at: `https://www.sciencedirect.com/science/article/abs/pii/S221065022500241X`.

Bibliographic production from partnerships with other research groups:

- [Tinoco et al. 2022b] (Qualis B1) Publication and presentation of a paper at the *"Int. Conf. on Tools with Artificial Intelligence" (ICTAI-2022).* This work was a partnership between research groups from UFU and UFTPR; and,
- [Linhares et al. 2022] (Qualis B2) Publication of a paper at the *"Brazilian Conference on Intelligent Systems" (BRACIS-2022).* This work was a partnership with the Information Visualization Research Group (FACOM-UFU).

Prospects on bibliographic production: The thesis's outcomes enable multiple future publications: (i) a review for collective pathfinding with robot swarms; (ii) an extension of [Tinoco et al. 2025b]; and, (iii) the core contributions (SW* and SAEVY). Additional topics include the Expanded Restricted Area Heuristic, Murmuration technique evaluation, experimental results, and validation in realistic simulations.

6.2. National and International Partnerships

The following partnerships are results of this thesis:

- Giuseppe Vizzari, Ph.D. of the Università degli Studi di Milano-Bicocca (UniMiB - Italy). Interuniversity exchange CAPES PrInt program (process 88881.311513/2018-01) [Tinoco et al. 2020];
- J. R. Ponciano, Ph.D. (ICMC-USP) and C. D. G. Linhares, Ph.D. (Linnaeus University - Sweden). Information Visualization Group [Linhares et al. 2022];
- Stéphane Júlia, Ph.D. (FACOM-UFU) and Leiliane P. Rezende, Ph.D. (UTFPR). Formalisation of Swarm Robotics Systems [Tinoco et al. 2022b]; and,
- Roseli A. F. Romero, Ph.D. of the São Paulo University (ICMC-USP). Developing the thesis proposal into a real-world application.

6.3. Awards

The thesis was awarded 1st place in the "Doctorate" category at the *XVIII Workshop de Teses e Dissertações em Ciência da Computação (WTDCC)*, an event organised by the Department of Computing (FACOM) at the Federal University of Uberlândia (UFU).

6.4. Lectures

Lectures invitations related to the thesis:

- "Coordenação Bio-inspirada de Enxames de Robôs para a Tarefa de Vigilância". In: *"LCBio Talks"*, 1st Lect. Circuit of the Bio. Comp. Lab. (LCBio-UFU);
- "Robótica de Enxames: A emersão do comportamento coletivo através de ações individuais". In: *"Hora do Café"*, Federal University of Jataí (UFJ), 2023;
- "Robótica de Enxames: O Poder da Inteligência Coletiva". In: *"TechTalks"*, Depart. of Computing (FACOM), Federal Uni. of Uberlândia (UFU), 2025;
- "Swarm Robotics: The Power of Collective Behaviour". In: *Coll. Electr. Electron. Eng., Shandong University of Technology (SDUT).* Zibo, China. 2025; and,
- "Robótica de Enxames: O Poder da Inteligência Coletiva". In: *"INFOWEEK2025 - O Mundo Conectado"*, Federal Institute of Triângulo Mineiro (IFTM), 2025.

6.5. Interviews and Media Mentions

This section highlights interviews and media mentions:

- **Interview:** "Doutorando da UFU utiliza feromônios para controlar robôs". In: UFU Comunica, 2021. Available: `https://comunica.ufu.br/noticias/2021/11/doutorando-da-ufu-utiliza-feromonios-para-controlar-robos`. Accessed: June 28, 2025;
- **Interview:** "O uso da IA é para facilitar a vida humana, não substituí-la". In: Senso in Comum - Ciência e Tecnologia, 53ª Ed., p.10, 2023. Available: `https://issuu.com/jornalismoufu/docs/senso_in_comum_-_53_issuu`. Accessed: June 28, 2025; and,
- ***University Admission*:** "Vestibular-Química". In: Universidade Federal de Santa Maria (UFSM), p.6, 2025. Available: `https://www.ufsm.br/app/uploads/sites/342/2024/09/PROVA-3-PROCESSO-SELETIVO-VESTIBULAR-UFSM-2025.pdf`. Accessed: June 28, 2025.

7. Conclusion and Future Work

The thesis proposed the SW* pathfinding technique for robot swarms in dynamic environments, evaluated within the SAEVY coordination model in wildfire evacuation scenarios. SW* enables decentralization, adaptive pathfinding, and heuristic-driven selection, while SAEVY provides self-regulated inter-robot distances, multi-objective handling, and resilience to interference. Their integration allowed real-time path identification, environmental adaptation, and decision-making (confirming **H1** and **H2**), enhancing efficiency in unpredictable scenarios. Contributions include emergent coordination behaviour, optimised path delineation, efficient swarm distribution, and reduced communication bandwidth. Source code and data are available under AGPL-3.0[4].

Future research directions include refining SAEVY's parameters using evolutionary computation, optimising information exchange within the swarm, and enhancing UAV deployment strategies based on environmental conditions. Further investigations can assess the impact of mechanical failures, communication disruptions, and external threats. Moreover, heterogeneous swarm simulations can explore simultaneous monitoring and signalling tasks, and improved signalling mechanisms to indicate path convergence. Finally, the model can be validated through realistic simulation platforms, such as Webots and ARGoS, to facilitate its transition to real-world implementation.

Acknowledgements

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