Swarm Intelligence (2023) 17:1–4
https://doi.org/10.1007/s11721-023-00223-6

Cross-disciplinary approaches for designing intelligent swarms of drones

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Accepted: 20 January 2023 / Published online: 14 February 2023

The idea of preparing a special issue of the *Swarm Intelligence* journal dedicated to the *distributed control and adaptive collective behavior in swarms of drones* has emerged after a workshop on this topic held in Toulouse on November 13–14, 2017. This workshop was intended to promote an interdisciplinary approach of collective behavior both in swarms of drones and in natural systems like fish schools or flocks of birds and also to favor cross-disciplinary interactions between various communities: quantitative and computational ethology, computer science, information technologies, swarm robotics and statistical physics. The workshop took place at the Université Toulouse 1 Capitole and was supported by The Fondation de Coopération Scientifique Sciences et Technologies pour l'Aéronautique et l'Espace, the National School of Civil Aviation (ENAC), the Toulouse Institute for Complex Systems Studies, the Toulouse Institute of Computer Science Research and the Research Center on Animal Cognition.

Designing swarms of autonomous mini or micro-drones able to self-organize, sense their environment, coordinate their movements, and cooperate to perform collective tasks in real-world situations is a major challenge in swarm robotics. This problem has been tackled from different perspectives in many research fields that often follow different strategies and objectives.

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In quantitative and computational ethology, recent advances in the study of collective motion and information processing in animal groups such as swarms of insects, schools of fish, or flocks of birds have offered new sources of inspiration to design distributed control algorithms for swarms of drones. In these animal groups simple social interactions facilitate the transfer of information between individuals and their ability to quickly respond to changes in the environment. In computer science, a major challenge resides in the provision of robust and truly decentralized control of a swarm at different levels in the architecture.

Micro-drones are extremely limited at the individual scale, since they cannot carry highly accurate, heavy, and power hungry sensors and have very limited onboard processing capabilities. Swarming can allow micro-drones to transcend these limitations, allowing them to achieve complex tasks outside of the reach of the individual. Still, there are many challenges on the way to realizing the potential of swarming in real-world settings. A crucial issue is the relative perception problem when it comes to implementing flying swarms in real life. Handling a swarm with a global infrastructure (e.g., GPS, radio beacons, or global communication) might be convenient in many cases but it is not a suitable solution in all scenarios. The focus of this special issue is on decentralized approaches to swarming. This poses challenges of robot-to-robot perception. When solved in a scalable way, such perception can be suited for reliable and fast agile maneuvers such as those performed by flocks of birds or schools of fish. Additional challenges lie at the individual level. For example, on micro-drones ego-motion estimation, obstacle avoidance, and navigation are active research areas due to the drone's restricted sensing and computation resources.

This special issue aims to provide a platform for research studies focusing on the design of autonomous drone swarms, highlighting the current state of the art and the challenges ahead.

In "Noise-resistant and scalable collective preference learning via ranked voting in swarm robotics", Qihao Shan and Sanaz Mostaghim consider the classical site selection problem, where a swarm of robots have to rank areas of interest with limited computational and memory resources. They propose a novel algorithm using the Borda Count approach that shows better decision accuracy while reducing the required memory, computation, and communication bandwidth compared to belief-fusion based approaches. Most notably, the proposed approach is even more advantageous for large swarm sizes or high sensing noise that ultimately occur in micro-drones. The method has been rigorously validated in simulation on a model that is valid for differential-drive ground robots or drones that survey an area.

The paper "A field-based computing approach to sensing-driven clustering in robot swarms", by Gianluca Aguzzi, Giorgio Audrito, Roberto Casadei, Ferruccio Damiani, Gianluca Torta, and Mirko Viroli, considers robots that have to assign themselves to clusters that they can sense in the environment, such as environmental monitoring of temperatures. Their approach uses the field-based programming paradigm, which is a formal and platform-agnostic approach to specify and implement swarm-based algorithms. The resulting program has been deployed to a small embedded low-power hardware platform such as those that can be carried by micro-drones. The extensive simulations demonstrate that environment monitoring is feasible even if the underlying distribution changes or robots randomly fail.

The paper "Drone flocking optimization using NSGA-II and principal component analysis", by Jagdish Chand Bansal, Nikhil Sethi, Ogbonnaya Anicho and Atulya Nagar, applies a multi-objective optimization paradigm to the drone flocking problem and gives an in depth analysis of the bottlenecks and trade-offs of collective phenomena one has to face when designing a flocking algorithm for swarms of robots. By applying the principal component analysis methodology to existing flocking algorithms, authors reveal the two most basic and mutually compromising behavioral expectations of swarm movement: "agility/reactivity/responsivity" and "cohesion/stability/persistence". The authors propose a quantitative method to show how different instantiations of the used algorithm can move the solution on the pareto front, with a different mixture of these two desired features.

In the article "Wildfire detection in large scale environments using force based control for swarms of UAVs", Georgios Tzoumas, Lenka Pitonakova, Lucio Salinas, Charles Scales, Tom Richardson and Sabine Hauert study the application of swarms of drones to wildfire detection, a problem that is getting more widespread due to global warming. Based on a real drone platform, the "Windracers ULTRA", a novel algorithm is presented to monitor an area the size of a major forest region in the state of California (133,546 km^2). The proposed *dynamic space partition* (DSP) algorithm is able to cope with varying numbers of drones, and allows repartitioning in a distributed way, aligning with real-world conditions in which drones will only be able to communicate locally. A comparison in simulation with three other distributed search methods from the literature shows a higher percentage of fires detected by DSP.

In the article "Collective gradient perception with a flying robot swarm", Tugay Alperen Karagüzel, Ali Emre Turgut, Ágoston E. Eiben and Eliseo Ferrante study the problem of emergent sensing with a swarm of drones. They introduce two methods in which individual drones modulate their desired distance to their neighbors or modulate their speed depending on their interactions with their neighbors and obstacles. Combining numerical and physics based simulations with experiments with a swarm of real nano-drones, they show that both methods can achieve collective gradient sensing without the individual drones having to estimate the gradient. These results open new perspectives to develop real-world applications to localize radioactive sources or gas leaks with a swarm of drones that individually have limited sensing capabilities.

Finally, the vital and basic capability of perceiving and relatively localizing other drones in a swarm is investigated in "Three-dimensional relative localization and synchronized movement with wireless ranging", by Sven Pfeiffer, Veronica Munaro, Shushuai Li, Alessandro Rizzo and Guido C. H. E. de Croon. Specifically, the article focuses on improving relative localization with the help of Ultra Wideband (UWB). Three-dimensional relative localization without external infrastructure is enabled by combining wireless ranging with the communication of flight velocities. Moreover, the method is implemented for the first time on flapping wing drones, which fly with larger attitude angles and hence have more difficulty determining their velocity. The real-world experiments show the potential of this relative localization method but also illustrate the remaining challenges in terms of scalability and estimation robustness.

In summary, the special issue shows the clear progress of the swarming approach towards deeper scientific insights and towards real-world systems and applications. However, it also makes apparent that there are many theoretical, algorithmic, and practical hurdles to be taken before we will see large swarms of highly robust and autonomous drones performing real-world missions in challenging, unknown environments. We hope that this special issue serves as a small stepping stone towards this final goal.

Funding N/A.

Data availability N/A.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent for publication Yes.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.