Swarms of flying robots in unknown environments

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An optimal planning algorithm enables swarms of flying robots to explore unknown environments autonomously and safely.

Aerial swarms have the potential to make profound socioeconomic changes. Delivery in the healthcare sector and warehouse operations that were previously performed manually are already being replaced or assisted by teams of flying robots (*1*, *2*). It is only a matter of time before swarms of flying robots are a common fixture in our environment. Unlike wheeled vehicles, aerial swarms can avoid environmental barriers by flying in three dimensions, they can access places that are inaccessible to humans, and they can survey an area from many viewpoints simultaneously. This makes them uniquely suitable for many applications, including medical delivery, emergency transportation, aerial mapping, and disaster mitigation. However, their large-scale adoption will only be possible once this technology is mature enough to ensure public safety and security (*3*). Currently, most swarms act based on the orders of an external computer, their individuals are blind and passive, and they cannot avoid unforeseen obstacles or adapt to new environments, which makes them unsafe for operating in public spaces.

Recent research in aerial robotics has concentrated its attention on decentralized coordination models, where every drone is endowed with the necessary intelligence to make decisions on its own using local information (*4*, *5*). These swarms are safer because they do not rely on a central coordinator, and they are robust to individual failures. In decentralized swarm systems, drones are equipped with several sensors for perceiving other drones and the environment. In some swarms, neighboring drones wirelessly communicate their relative positions, which are obtained from a global navigation satellite system (GNSS) (*4*). Other swarms use a purely sensor-based approach to avoid the potential issue of unreliable data links in wireless communication, such as package drops or delays. For example, using sensors drones can detect and localize their neighbors in the output images of RGB or UV cameras (*5*, *6*). An open research challenge is to combine the coordinated flight of the swarm agents with an obstacle avoidance behavior that can let the swarm fly safely even in previously unknown environments (*7*). Although existing swarms are deployed in laboratory environments, where either there are no obstacles (*4*, *6*) or their morphology and location are known a priori (*5*, *7*), real-world applications require the swarm to sense and interpret more complex and uncertain environments, such as dense forests and narrow corridors.

Writing in *Science Robotics*, Zhou *et al.* (*8*) address these issues by proposing a swarm of micro flying robots that can reliably navigate real-world cluttered environments based only on onboard sensors (Fig. 1). Their custom platform weighs less than 300 g and has an embedded depth camera for obstacle and neighbor detection and localization, an ultra-wideband sensor for positional drift corrections, a flight controller for low-level control, and an extra onboard computer for high-level control and planning. A path planner computes local trajectories by solving a spatio-temporal joint optimization, which combines inter-agent and obstacle collision avoidance with task-specific requirements, such as multi-point tracking and maintaining formation. The algorithm was successfully validated in impressive outdoor experiments, where the swarm flew without hitting trees or people in a wild forest. Being the first swarm system capable of decentralized, autonomous flight in an unstructured environment, this work presents a notable contribution to the robotics community and an important step toward the application of drone swarms beyond the constrained environment of a laboratory, not only for exploration in forests but also for a range of safety-critical missions in human-made environments, such as urban areas with humans and buildings.

By enhancing the sensory perception and autonomy of aerial swarms, the work of Zhou and colleagues will inspire new research venues that will further expand this technology's functionality and versatility (*9*). Because real-world environments dynamically change, a question that will need to be answered is how the swarm can effectively interpret environmental changes and cope with unexpected events. What needs to be understood is how the drones in these swarms can autonomously prioritize behaviors that make the team achieve tasks faster or more effectively based on varying external conditions. Such systems will require online individual decision-making and information sharing for propagating the behavioral change consistently from one or few individuals to the entire swarm. This workflow would leverage the intelligent nature of individual robots to perceive and interpret environmental stimuli and the group consensus to converge to the optimal

Fig. 1. A swarm of micro aerial vehicles flying in a forest. A composite image of the aerial swarm in a bamboo forest (**left**). A close-up view of the drone used for the experiments (**right**).

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behavior. Moreover, the work by Zhou and colleagues (*8*) focuses on homogeneous swarms, where all robots are the same. In the future, it would be compelling to deploy heterogeneous swarms where drones have different morphologies and sensors, and they can specialize for specific subtasks based on their characteristics and skills.

Finally, current interfaces for human control of aerial swarms are generally designed for expert users and are unintuitive for novices. It is yet to be determined how the swarm can be effectively influenced by a human while maintaining a high degree of autonomy (*10*). A solution to this problem could substantially improve the usability of these systems, allowing for enough swarm flexibility without overburdening the cognitive faculties of a person. It is also not clear how the human commands should be propagated through the swarm. Research in these directions will give additional momentum to the commercialization and usage of aerial swarms for real-world applications at an unprecedented pace.

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