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Autonomous Mission Control of Drone Flocks

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Summary

The proposal aimed at creating a novel type of outdoor drone flock which was planned to be made of autonomous and hierarchically controlled aerial robots. Although not all of the goals have been achieved, we have been able to realize and publish exciting related results. The resources provided by the US AF and our university were generous and have provided an environment a financial support plus working place which enabled us to create a unique autonomous flock of 30 quadcopters capable of performing tasks which have not been carried out by any other outdoor drone flocks yet. Autonomy in this context meant that the drones were given a global "mission" and all of the other decisions regarding their trajectories were decided (calculated) by themselves without controlled by any central computer. It turned out that due to several limiting factors our most ambitious plan (hierarchical but still decentralized/distributed control of a flock) was beyond our capacities (more details about this are given in the conclusions). In short, we have been able to perform research in several areas either very directly or less directly related to the subject of the proposal and publish our results in prestigious journals and other media.

Introduction

In this introductory section I will focus on overviewing three aspects of the proposal: State of the art regarding research on drone flocks and alike (1.), and hierarchy (2.). Finally, I describe the main goals we addressed before starting the research (3.)

1. *Flocks, swarms and traffic of drones*

Drones have become a hot topic over the past half-decade for several reasons. I) There is a strong commercial interest in producing and selling small drones flying and controlling the gives considerable satisfaction to the customers. II) Drones have the potential of being used for a number of practical purposes, including agriculture, surveillance, making footages from the air and many more. III) Drones are used to fight terrorism plus have other military applications. IV) There is a quickly growing entertainment industry branch which involves dozens of hundreds of drones providing unique visual effects in three dimensions over a scale of hundreds of yards. Finally, but not last (since this is our most challenging goal) autonomously co-operating flocks of drones are likely to open important new avenues both concerning the above points as well as their usage for solving complex tasks needing many "intelligent" units. Most of these aspects were nicely reviewed in a recent Nature review focusing on the aspect of autonomy of small aerial robots (Floreano and Woods, 2015).

1.1 Collective motion of drones

It is commonly assumed that building and making fly many drones simultaneously is a much more challenging and potentially useful aspect of the research and commercial/military application of drones than building/studying a single flying robot. There are three main important directions in this kind of activity. A) Swarming robots in a strictly indoor environment (requiring a special video-technology) B) Outdoor displays of flying drones following a pre-programmed trajectory (without interacting with each other), C) Outdoor flocking of autonomous interacting drones sharing and processing information on their own. Our research concentrated on the last, most challenging and interesting solution. Our first efforts (supported by an EU science source) attracted some interest (Nature Newsteam, 2014), however suffered from being not optimized enough and being able to handle only about 10 drones. Using the support from US AF we could significantly improve our fleet of drones – see later.

The first autonomous outdoor flock of micro UAV-s was built by Hauert et al., 2011 and consisted of 10 fixed-wing units. Although this was a truly great achievement at that time, it had some limitations which came primarily from the constraint that the “winglets” had to maintain an absolute velocity in a relatively narrow range of values. Thus, for example, “staying/hoovering” at a given position was achieved by the winglets circling around the desired position (other problems had to be also treated by oversimplification).

1.2 Traffic of small aerial robots

Our group was the first to algorithmically and experimentally address this problem in the same research. The complexity of three-dimensional aerial traffic with ever-growing number of agents can go beyond that of ground traffic, even though the only infrastructure needed, air, is present everywhere and in general there is a lot more space in three dimensions than on one dimensional roads. At the same time, aerial traffic might also be constrained by virtual roads and restricted air spaces, close-to-ground air traffic has to handle obstacles in 3D, while motion and communication in the air is always much more challenging than on the ground. Centralized path-planning - e.g. game theory based or bioinspired - calculates close to optimal routes for a couple of agents, but the scalability of such approaches is questionable due to central communication and computational complexity. Self-organization is an excellent direction to address all these difficulties.

1.3 Group chase and escape

We found that the so-called group chase and escape problem (a special kind of hierarchy) is closely related to the subject of my proposal. Therefore, we considered the challenge of building a more realistic model of this widely occurring phenomenon than the prior ones. In particular, we were interested in the problem of how slower predators are able to catch their faster prey. The answer is rooted essentially in the co-operation of hunters as well as in natural barriers such as, e.g., river banks. The variety of predator-prey systems is extraordinarily rich within birds, mammals, fishes or even insects. Wolves tend to hunt elk, while coyotes have been studied hunting for pronghorns in e.g. migrating corridors using landmarks as a strategic tool (reported in Yellowstone National Park). In both cases the prey is faster than the predator. The problem may have applications in other areas, such as catching unwanted intruders into an airspace.

2. Hierarchy

We considered the topic of hierarchy as a branch of science which has not been explored enough, especially considering its quantitative and experimental applications to phenomena ubiquitous in nature and society. Hierarchy is typically defined for systems of agents and can be advantageous to a varying degree. One of the main messages of our interpretation is that the main reason for the hierarchical structure of the relations among organism is that such a structure is more advantageous than a fully regular or a random or any other arrangement. It is widely accepted that we do not understand deeply enough the reasons behind the abundance of multi-level hierarches. However, there must be an advantage of such an organization, because of the permanent evolution of the corresponding systems preferring more efficient variants. But where is this advantage? Better adaptability? A more efficient, robust or stable structure? A faster spreading of relevant information? Or, perhaps, better controllability (think of, e.g., an army)?

3. Goals

The questions to be addressed/answered by investigating hierarchically controlled systems include the following: What are the best rules for a system of hierarchically controlled robots for exhibiting self-organized collective motion and perform other, more complex tasks (e.g., rescue operations)? Do these rules differ qualitatively depending on the conditions of the experiments? What is the algorithm providing for such a system the optimal exploration of information/resources distributed very unevenly in space?

We learned from our pigeon flock studies (Nagy et al 2010) that they tend to be hierarchically organized as far as concerning the leader-follower relationships determined for the pairs in a group. This means that the contribution of the individual pigeons to the final choice (in a particular moment or over larger time scales) can be very different. In a computer simulation there are several ways to account for such diversity in the leading role of the flock members. We plan to explore these possibilities and compare them with the experimental data we have so that we could make an educated guess which rule is the most likely to be at work for pigeon flocks.

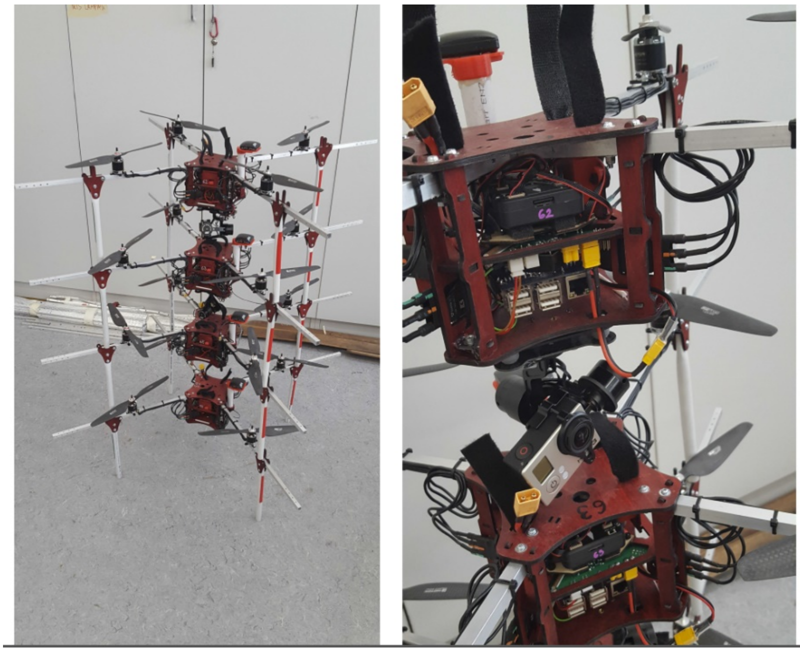
Methods, Assumptions and Procedures

Methods

1. Building the quadcopters

To achieve the goal of hierarchically controlled drone flocks we needed to create our custom designed/made aerial robots. The technological details can be summarized as follows:
Our quadcopters use the Pixhawk autopilot (55) for controlling the rotors with a slightly modified ArduPilot. We also used an onboard, Linux-based companion minicomputer (Odroid C1+) through which we gave desired velocity commands at 20 Hz to the autopilot. The desired velocity was calculated onboard using an improved flocking model presented as the control algorithm.

We used two independent, parallel wireless modules for inter-agent communication in the 2.4-GHz range, both broadcasting the same status packets. One is an XBee module broadcasting through its own proprietary protocol at 1 Hz; the other one is a small universal serial bus (USB) wifi dongle (Odroid Wifi Module 0) transmitting user datagram protocol (UDP) packets through a local ad hoc wireless network at 10 Hz. The two modules are complementary in bandwidth and range (XBee being small bandwidth and longer range and Wifi being large bandwidth but shorter range). Packets contained an absolute time stamp, geodetic position, and velocity principally measured by onboard GNSS receivers and other safety-related status info about the actual state of the drone that was not relevant to the main control algorithm. Relative position and velocity were calculated by the differences of GNSS-based absolute measurements. The net payload size of a status packet was 46 bytes.



The actual hardware (the body of the drones) was designed and built by ourselves (see Fig. 1). Our design is quite original, involves, e.g., parts that were produced by our 3D printer (acquired from a prior grant). The rotors and the propellers were carefully selected after testing a number of available ones on the market.

Fig. 1 Our drones showing how we store them and the many parts of the electronics we built into their control/sensor part.

2. Developing a program simulating the collectively flying drones

For testing any flocking algorithm in a realistic environment before actual flights, we used a simulation framework, which was originally developed for modeling special features of flying robots based on second-order ordinary differential equations. In this subsection, we present only the main features of this framework, without details. For further details, the simulation framework can be downloaded from https://github.com/csviragh/robotsim. The following general features of flying robots can be taken into account with our framework:
(1) Communication delay. The position and velocity data received by an agent from neighboring agents are old due to the necessary time for data transmission and processing. In the simplest case, we modeled this effect with a constant time delay.
(2) Inertia. A flying robot cannot change its velocity immediately because of its mass, aerodynamic effects, and specific features of its low level control algorithm. We assumed that the real velocity vi converges to the desired velocity exponentially with a characteristic time. A maximal acceleration of the units is also assumed.
(3) Refresh rate of the sensors. The agents cannot update their sensory data continuously, only with a nonzero time period. For simplicity, in the simulation framework, this parameter is constant and uniform for all agents.
(4) Locality of the communication. If two agents are too far from each other, they cannot exchange messages; that is, they do not see each other.
(5) Inaccuracy of the onboard sensors. We also had to model the fluctuating behavior of measured positions and velocities. This behavior can be described as a stochastic process.
(6) Outer noises. To take into account the environmental effects such as wind compensation of the low-level control algorithm, we added a delta-correlated Gaussian noise term with SD s to the acceleration of the robots.

Assumptions

Our basic assumption was that an advanced optimization of the algorithm determining the path of the drones can be improved to a degree which enables them to fly in a highly – and autonomously – coordinated fashion even in the presence of several types of barriers (like the virtual wall within they were allowed to fly or artificially placed – again virtual – areas they had to avoid within the flight zone.

Another important assumption was that if the flock is controlled by a suitable algorithm based on the principle of hierarchically arranged communication and control will result in a flock that can perform tasks more efficiently (e.g., faster, see also Zafeiris and Vicsek 2018). To achieve this, we tried a few hierarchical algorithms assuming specific rules in each model, (Y. Jia and T. Vicsek, in preparation).

We also tried to design a model which was based on the assumption that a group of chasers can catch evaders even if the former ones move slower. For this an appropriate strategy and the presence of barriers was needed (Janosov et al, 2017)

Procedures

In our case the texts corresponding to the Methods and the Procedures would have overlap so much that I reported about these two items in the Methods section.

Results and discussion

First of all, I would like to point out that virtually all of the results we achieved within this project (or being in a very close relationship with it) have been published very recently, most of them in very prestigious journals, proceedings or publisher (book in a Springer series): Balázs and Vásárhelyi 2018, Janosov et al, 2017, Vásárhelyi et al., 2018, Zafeiris and Vicsek 2018 (book on hierarchy), Zamani and Vicsek Sci. Reports, 2017. There is also a manuscript being written up (about 90% ready) by Jia and Vicsek, 2018. Below I shall concentrate on the results we obtained by investigating two basic situations arising when a flock of autonomous drones has to perform realistic tasks: i) flying smoothly in a confined environment and ii) trafficking within an area so that the targets' positions change in time (after a target is reached).

At this point (as mentioned in the summary) I have to point out that we have not been able to meet all of the goals laid down in the proposal. I shall get back to the reasons of this development in the discussion part.

i) We addressed a fundamental issue of collective emotion of aerial robots: how to ensure that large flocks of autonomous drones seamlessly navigate in confined spaces. The numerous existing flocking models are rarely tested on actual hardware because they typically neglect some crucial aspects of multirobot systems. Constrained motion and communication capabilities, delays, perturbations, or the presence of barriers should be modeled and treated explicitly because they have large effects on collective behavior during the cooperation of real agents. Handling these issues properly results in additional model complexity and a natural increase in the number of tunable parameters, which calls for appropriate optimization methods to be coupled tightly to model development. We proposed such a flocking model for real drones incorporating an evolutionary optimization framework with carefully chosen order parameters and fitness functions. We numerically demonstrated that the induced swarm behavior remained stable under realistic conditions for large flock sizes and notably for large velocities. We showed that coherent and realistic collective motion patterns persisted even around perturbing obstacles. Furthermore, we validated our model on real hardware, carrying out field experiments with a self-organized swarm of 30 drones. This is the largest of such aerial outdoor systems without central control reported to date exhibiting flocking with collective collision and object avoidance. The results confirmed the adequacy of our approach. Successfully controlling dozens of quadcopters will enable substantially more efficient task management in various contexts involving drones. For related video see the URL-s at the end of this section.

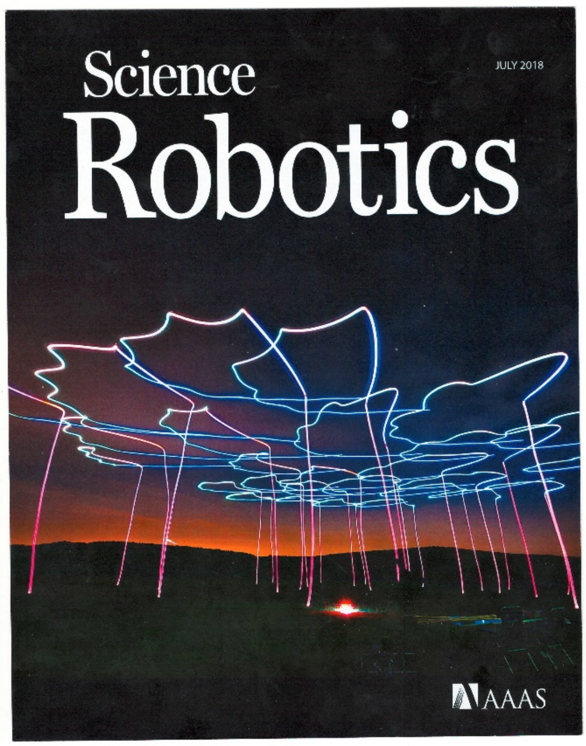
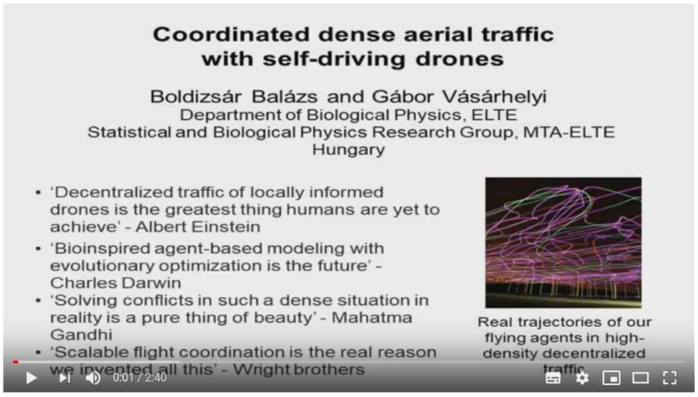


Fig. 2 Our above work was published in Science Robotics and was presented on the cover. The picture shows a long exposure photo taken after takeoff and the first seconds of self-organization.

ii) In our other work I discuss here we presented a general, decentralized air traffic control solution using autonomous drones. We challenged some of the most difficult dense traffic situations, namely, crosswalk and package-delivery scenarios, where intelligent collective collision avoidance and motion planning is essential for a jam-free optimal traffic _ow. We build up a force based distributed multi-robot control model using a tunable selection of interaction terms: anisotropic repulsion, behaviour driven velocity alignment, self-organized queueing and conflict avoiding self-driving. We optimize the model with evolution in a realistic simulation framework and demonstrate its applicability with 30 autonomous drones in a coordinated outdoor flight within a densely packed virtual arena.

The performance (the main features) of our flocks can also be visually examined by looking at the following youtube videos:

https://www.youtube.com/watch?v=E4XpyG4eMKE&t=



https://www.youtube.com/watch?v=v26Ohw9UpE0

Conclusions

The proposal aimed at achieving highly challenging goals. Indeed, we have been able to realize and publish exciting new results. The resources provided by the US AF and our university were generous and have provided an environment a financial support which enabled us to create a unique autonomous flock of 30 quadcopters capable of performing tasks which have not been carried out by any other outdoor drone flocks. However, establishing the kind of hierarchical control (having several levels of hierarchy) envisioned in the proposal has turned out to be not feasible. Fortunately, our drones have become so "smart" and autonomous that virtually every task which was planned to be solved by a hierarchical flock have been performed by our flock without a sophisticated hierarchical organization.

Here I would like to mention the main limitations of optimal performance of our research group. I shall briefly mention them, but I can document the below mentioned statements in detail if needed. Thus, we were limited by: i) an extremely slow public procurement process at our university (ELTE), ii) regulations which do not allow the recognition/acceptance of foreign degrees (except those obtained in the EU) and as a result the postdocs I planned to hire could not become employees of ELTE (and as such could not have health insurance), iii) due to the present policy in Hungary the government regards any young scientist from non-EU countries as potential immigrants and forces them to go through administrative procedures which discourage potential postdocs to accept positions in Hungary, i) finally, talented Hungarian students leave the country during their studies of even earlier. In summary, I have not been able to hire from the grant money proper postdocs, in particular, because robotics is a hot field and the “brain drain” from the EU and the USA works very efficiently.

In addition, the 18 months (partly because of the above) time span of the grant has turned out to be too short for achieving all of the planned ambitious goals.

In spite of the above mentioned difficulties, we have been able to perform research in several areas either very directly or less directly related to the subject of the proposal.

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