SZAKMAI ZÁRÓ BESZÁMOLÓ

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Pályázó: **Vásárhelyi Gábor, PhD**

Table of Content

Foreword

The K_16 grant was a great follow-up opportunity to continue our mission declared in 2009 during the EU ERC COLLMOT grant (2009-2015, PI: Tamás Vicsek) to demonstrate how bio-inspiration can help us to build large-scale autonomous aerial robotic systems. The K_16 grant also brought us much closer to our vision to step over the boundaries of basic research and establish innovative practical applications based on the coordination, cooperation and collaboration of large drone swarms. Even though we kept the original track of the defined K_16 workplan and methods and have achieved most of the basic research goals that have been set five years ago, the practical vision turned out to be much more complex than planned is several aspects and thus this line remains incomplete, even though we work hard to go forward on this route in the upcoming years.

Besides, a structural challenge also arose along these deviating goals that needed to be addressed properly. We realized that we need to separate our research-oriented mindset with basic research goals (with a fitness function of more and higher impact publications) from our entrepreneur-oriented mindset with practical goals (with the overall fitness function of a successful commercialization process). Going towards practical applications as university-based researchers consumes our resources, deviates scientists from key research aspects towards technical problems and usability-oriented development which results in less or lower impact publications, while the practical realizations with the mindset of a researcher will never exceed the research prototype level that is still very far from commercialization or true innovation and thus do not generate sufficient positive feedback in any form. Therefore, we decided to keep the research focus on basic science as much as possible and channel all practical realizations into CollMot Robotics, the startup founded in 2015 by researchers at ELTE Department of Biological Physics with the aim of commercializing drone swarm research results.

The separation and channeling of our goals into the proper background structures (university and spin-off) did not only enhance our chance to succeed in both directions (basic research and commercialization), but also gave us synergistic benefits as the two entities could and can support each other optimally. This is what happened during the K_16 years: while research results and drone swarm experience and knowledge could be channeled into unique commercial applications of our spin-off though the proper agreement between ELTE and CollMot, the commercial revenue in the company could be dedicated to increase the autonomous drone fleet size and its overall technology readiness level, stability and usability. This resulted in much higher impact experiments with up to 100 autonomous drones with much less technical problems to deal with during the experiments as they have been resolved previously by well-paid and professional IT developers of the spin-off for the more demanding industrial requirements.

I find it very important to write about these issues in detail as this decision to keep the threads for research and innovation separately and in parallel is in direct conflict with my original goals in the K_16 project that included both in the research plan. However, I hope that the results presented below, and their potential further impact will be convincing enough to understand and accept this structural reconsideration of the original research plan.

Description of the main results

Throughout this final report I will use the original structure of the research plan and go over each of its key hypotheses and goals to describe what have been achieved.

Heuristic and adaptive optimization of collective control algorithms

We have used bio-inspiration for achieving our research goals related to automating drone swarms in three distinct forms:

1. mimicking the basic flocking/control algorithms of animal swarms;
2. understanding the optimal strategies and structures (egalitarian, hierarchical, adaptively hierarchical) for collective decision making;
3. optimizing the control algorithms with artificial evolution.

This last point is a very important aspect of any complex system that has several tunable parameters and thus its dynamical properties and overall behavior gets dependent on the actual parameter setup it is tuned to. Finding a good parameter setup for a system with up to or more than 10 parameters is a true challenge as any brute-force scanning method gets practically impossible with increasing dimensionality. Therefore, heuristic optimization is needed, for which artificial evolution seemed to be a very promising general concept that can be used for basically any optimization problem.

For our research goals of creating scalable and stable flocking and traffic algorithms for drones we designed a realistic simulation framework (available at https://github.com/csviragh/robotsim) that included all kinds of disturbances, errors, stochasticity and dynamic constraints so that the outcome of the simulation should have the least amount of reality-gap when going out on the field to test. While the simulation can be executed on any computer and its GUI is very useful to visualize the overall collective patterns and possible deviations from optimal behavior, which is very important for manual tuning of the algorithms, we also routinely used the ATLASZ computer cluster of ELTE to perform large populations of simulations in parallel.

For optimizing the control algorithms, we incorporated the CMA-ES solution (https://www.lri.fr/~hansen/cmaesintro.html) into our workflow and by now use it for every single problem we target with the simulation framework. The evolutionary optimization turned out to be very useful that produces absolutely acceptable results, when the fitness function of the problem is defined properly.

From the publications [1], [2], [3] and [4] use this evolutionary optimization layer and the evolutionary process is explained first in detail in [1].

Formation flights in three dimensions

Throughout the years it cleared out that there are two main building blocks or extreme scenarios of group coordination we wished to exploit in detail and the field of "formation flights" is kind of a small intermittent segment or combination of these. One basic collective pattern arises when the goal of every single individual is the same and thus the motion of *all* agents is synchronized as much as possible – this we call "flocking", as bio-inspired flocking drones resemble in their motion to flocking birds, schooling fish, herding sheep, or swirling bacteria. The other extremum of coordination is when *none* of the agents are synchronized in motion as they all have individual goals. We call this scenario "traffic" as it is a generalization of pedestrian or automobile traffic on the ground without explicit lanes and possibly even in three dimensions. We believe that every other scenario of coordinated motion can be built up from the optimal combination of these, what's more, some emergent phenomena, such as self-organized lane formation comes from the direct combination of the interaction terms of these two scenarios. Formation flights are flocking flights with some extra but simple constraints on the relative positions, and the metamorphosis between different fixed formations is a traffic scenario to be resolved by a traffic algorithm autonomously.

Therefore, during the project we did not put much emphasis directly on formation flights as the scientific value of purely that did not turn out to be interesting enough, instead, we focused on perfectioning both our flocking and traffic algorithms as the most profound building blocks of collective motion and we truly succeeded in both, setting world records in the number of autonomous agents used in both scenarios. We could fly first 30, then 50+ drones in our newest flocking algorithms (see [1] and [2]) and we could also push the limits of our traffic algorithms from the initial 30 drones [4] to a yet unpublished world record of 100 agents.

A final note is that a third direction covering the field of formation flights is when formations are preprogrammed and optimized by a central entity. The direct utilization of such methods is in drone shows, which is the first worldwide application of large drone swarms (without self-organization). As this is less a scientific and more a technical achievement, we channeled our related efforts into our spin-off, CollMot Robotics, which became a pioneer in providing innovative drone show solutions (see https://collmot.com).

Self-organizing dense UAV traffic in three dimensions

With the quickly increasing number of drones that soon need to be integrated into the common airspace, the urge to find self-organized, decentralized methods for autonomous UAV traffic became a much larger expectation than what we thought of when we created our first traffic algorithm as a building block for local drone coordination.

Our first traffic algorithm throughout this project utilized our well working flocking interaction terms in modified form optimized to the traffic situation: repulsion between agents became anisotropic and velocity alignment became behavior driven. For traffic, we also needed a self-drive term, which we designed in a way that it points towards each agent's individual goal while it is also rotated and shrunk optimally when others are in the way to prevent trajectory conflicts (prevent getting into each other's repulsion range). This algorithm was suitable to drive up to 30 drones in real experiments and up to 100 drones in simulation [4], in a crosswalk and a queuing scenario.

By now we have enhanced this algorithm substantially. We replaced the self-driving term with a more sophisticated short-term path planning solution that linearly predicts all neighboring agents' motion and finds the optimal conflict-free route between them with a simple heuristic algorithm. We also extended the whole framework to handle any heterogeneous velocity regime and even priorities between agents, giving rise to a complete and general decentralized solution for any traffic situation one can imagine in 2D. Finally, we also extended the algorithm to 3D with introducing layers as ad-hoc overpasses to prevent agents from ending up in frontal collision conflicts.

This final algorithm is working very smoothly. We have tested it in simulation with up to 5000 agents and also demonstrated it with 100 autonomous drones out on the field.

Note: we have created an interactive visualization from this flight but as it is unpublished yet and the NKFIH website declares that this report will be publicly available, we cannot share its link here. If the reviewers are interested in the visualization, we can send it privately upon request.

We wish to submit the details of this final algorithm as a research article to Science Robotics. Article preparation is in progress.

Bio-inspired collective search, chase and escape

This topic got covered in one research article [3] in which we demonstrated that the cooperation of pursuers can result in catching even a faster prey if they interact and coordinate their motion according to simple, basically flocking rules. The key message here is the same as usual around collective motion: a group is more than just the sum of its individuals.

As the chase and escape topic has a direct military aspect, with our mostly pacifist team we did not go further on this route but kept ourselves to the limit of the theoretical basic research results.

Optimal behaviour with heterogeneous and hierarchical drone flocks

Heterogeneity and hierarchies are very interesting topics that we tried to introduce in all lines of research. The previously mentioned chase and escape scenario is by definition heterogeneous (both in rule, behavior and velocity), but that is kind of a triviality.

Our traffic algorithm got extended to handle pairwise priorities, which generalizes the algorithm to any global hierarchy possible. The extension is very simple: when two agents get into direct trajectory conflict, if one has priority over the other, they get an asymmetric radius of avoidance instead of the default symmetric one, which affects both their repulsion term and self-driving term. In other words, one with priority avoids the other less, such as an ambulance car in normal traffic. Besides, since we have developed all interaction terms in a way to take into account the acceleration limit of agents, the traffic algorithm also became inherently resistant to heterogeneous velocities (and accelerations) of agents.

The most interesting novelty related to hierarchies is in our latest flocking algorithm [2]. During flocking a great challenge arises when the flock approaches any obstacle or wall. If agents are democratic, they are all equal and thus simply average their velocity to reduce all oscillations and noise in the system (which is a strong requirement for *stable* flocking), they will hit the obstacle as the agents in front will be dominated by the average opinion of others that are not yet aware or scared enough of the wall. This happens in human crowds and results in severe accidents and occasionally in the death of frontal individuals, e.g., in crowded football stadiums. On the other hand, if agents are individualistic, they react quickly to the constraints of their environment and do not accommodate their behavior to their neighbors so strongly, they will be able to avoid the obstacle/wall, however, the flocking pattern will become unstable, and instead of the wall they will hit each other more frequently. Animal flocks know both: they are stable *and* reactive at the same time, which is kind of against the notion of the fluctuation-dissipation theorem that governs non-self-propelled particles of standard statistical physics to choose in a compromise between these two. We found out that this hard constraint can be overcome with introducing adaptive hierarchies into the individual decision-making process. This means here that agents will become local bosses if they receive new information about the environment and the opinion of these local bosses will be weighted more momentarily in the velocity averaging process. With this simple but profound extension (which is the same structural solution as using braking lights on cars or shouting when something scary approaches us or demonstrating against climate change, the ecological collapse, or the local dictatorship) we actively increase our weight in the information-averaging process of our neighbors. Using this approach all kinds of standard flocking algorithms could be enhanced to keep their stability but become much more reactive at the same time. See [2] for more details.

Fully automated drone swarms for remote sensing and surveillance

As mentioned before, we could not cover this initial goal in the project as it turned out to be both too complex and too deviated from our basic research goals in terms of the required technology readiness level and the required amount of external knowledge needed related to any sensory system attached and used. However, we have experimented with different payloads that could later serve as the basis for such practical applications.

We cooperated with AEKI to develop a dosimeter (a small Geiger-Muller counter with extended dynamical range) that got attached to one of our drones. We performed initial experiments with the system, created nice heatmap visualizations of the radioactivity measured by the drone, but the research thread died out naturally after a conference publication [5] due to the lack of human and financial resources that would have been required to bring the thread forward to commercialization.

We have started to extend our research directions towards computer vision on drones. This is a very large topic, and it is not very feasible to gain outstanding new results in this field unless we build out a full dedicated research group focusing purely on AI and CV. Anyhow, one of my students wrote up his MSc thesis on the first results with a target following application (the drone got a camera payload, its companion computer detected simple circular objects on the images in real time, the coordinates of the objects got transformed back to geodetic coordinates and the drone moved above the detected target) and currently I have two students working on different aspects of the application of deep learning systems on drones.

Finally, we have started to integrate an air pollution particle detector on a drone but did not get ready so far with real-time measurements.

In the meantime, our spin-off, CollMot Robotics signed a contract with ELTE for the usage of some of the IP related to our drone swarm research and we are trying to pursue the first true industrial drone swarm applications in that context also (with no public results so far, because this again takes a lot more time than what we have imagined before).

Personnel involved

The following persons worked directly on the K_16 project:

- **Gábor Vásárhelyi** – PI of the project and co-founder of CollMot Robotics
- **Tamás Vicsek** – Professor Emeritus at ELTE Department of Biological Physics and co-founder of CollMot Robotics, who got involved in all key research questions related to chase and escape, flocking, hierarchy and traffic
- **Tamás Nepusz** – external researcher and co-founder of CollMot Robotics who helped a lot in developing stable IT solutions for the drones and ground control stations and worked on SITL simulations and data processing and visualizations
- **Gergő Somorjai** – external researcher and co-founder of CollMot Robotics who was mainly responsible for HW development aspects of the drone swarms and related field equipment
- **Balázs Badár** – technician who helped in preparing the drone swarm and other HW equipment for all experimentation
- **Gergő Vadász** – a researcher who got involved to the drone swarm projects in general, and helped a lot in the experimentation and drone development and data processing
- **Pedro Correa Pereira Vasco De Lacerda** – a researcher who got involved instead of Gergő Vadász to continue his job after Gergő left our department
- **Boldizsár Balázs** – a doctoral student and later post-doctoral fellow who became the core scientific partner in developing the latest flocking and traffic algorithms and solutions
- **Csaba Virágh** – a former BSc, MSc and doctoral student who was part of the core scientific team of both initial flocking and traffic research threads

- **Norbert Gál** – MSc student who helped in developing the first drone computer vision HW+SW framework
- **Milán Janosov** – Msc student working on the collective chase and escape algorithm
- **Botond Kalocsai** – a former BSc and currently MSc student involved in computer vision and deep learning for drones
- **Gáspár András Hegyi** – a BSc student involved currently in computer vision related aspects
- **Anikó Fribékné Farkas** – grant administration
- **Mária Kolozsvári** – grant administration

I wish to use this opportunity as well to emphasize that group work is more than the sum of individual efforts. I really enjoyed working in this nice, enthusiastic, and supporting personal context and would like to thank each member her/his great support and cooperation.

Related achievements

- **Botond Kalocsai** defended his BSc theses during the project with the title "Kvadrokopter automatikus precíziós leszállása képfeldolgozással – elmélet és szimuláció"
- **Boldizsár Balázs** defended his PhD theses during the project with the title "Natural Synergies in Collective Behavior for Smoothly Swarming Aerial Robots".
- **Tamás Vicsek** received the Lars Onsager 2020 Award (obviously for previous work and not for the contribution in this project, however, we are still very proud of him, as also expressed in [6]).
- The **Research Group of the Drone Lab** received the ELTE's Innovative Researcher 2021 Award

Other notes

During the project "I took one year off", i.e. I suspended the project after its third year for a whole year. I had many reasons for that, financial, personal, and even political, but looking back from now I think it was a good decision to keep the remaining resources for a time when I could better use them and take a kind of unofficial but very much desired sabbatical. I could not stop working fully in this year as I wished from my heart, but I kind of got forced to do so as this year got filled with almost continuous and severe health issues, including at least two COVID infections, two surgeries and one Lyme-disease that resulted in a serious heart inflammation. Anyhow, I survived, and I could also use these long periods spent in hospitals or laying in my bed to think about our long-term research results in more general contexts and in multidisciplinary analogies, and wrote up three educational articles at https://qubit.hu about mostly social collective phenomena spiced by and explained with the knowledge I gained from the many years of collective motion and drone swarm research. These are not strictly related to the project, but they are loosely related, and I find them important contributions, so I listed them also in the publication list below (see [7], [8] and [9]).

Publications

1. Vásárhelyi, G., Virágh, C., Somorjai, G., Nepusz, T., Eiben, A. E., & Vicsek, T. (2018). Optimized flocking of autonomous drones in confined environments. *Science Robotics*, *3*(20), eaat3536. (IF: 19)
2. Balázs, B., Vásárhelyi, G., Vicsek, T. (2020). Adaptive leadership overcomes persistence-responsivity tradeoff in flocking**,** *Journal of The Royal Society Interface*, *7*(167): 20190853. (IF: 3.224)
3. Janosov, M.; Virágh, C.; Vásárhelyi, G. & Vicsek, T. “Group chasing tactics: how to catch a faster prey,” *New Journal of Physics*, 19, 053003, 2017 (IF: 3.768)
4. Balázs, B.; Vásárhelyi, G., “Coordinated dense aerial traffic with self-driving drones,” *Robotics and Automation (ICRA 2018), International Conference on*, 2018, pp 6365–6372
5. Hirn Attila, Apáthy István, Deme Sándor,Donkó István, Endrődi Gáborné, Gerecs András, Nepusz Tamás, Somorjai Gergő, Tósaki László, Vásárhelyi Gábor: “Dozimobil, a sugárvédelmi felmérő gépkocsi”, 44 th *Annual Meeting on Radiation Protection*, 2019
6. Vásárhelyi, G., Nagy, M., & Zafeiris, A. (2019). Lars Onsager-díj – 2020, Vicsek professzor tanítványai az Onsager-díjjal jutalmazott munkásságról. *Fizikai Szemle*, *74*(10), 343–345.
7. Vásárhelyi, G. (2021). Késleltetett dinamika – a COVID-járvány, az ökológiai válság és a zuhanyzás összefüggései. *qubit.hu*
8. Vásárhelyi, G. (2020). Hogyan döntsek? Bevezetés a súlyozott döntéshozatal rejtelmeibe. *qubit.hu*.
9. Vásárhelyi, G. (2020). A 90 darabos 100-as papír zsebkendő, az evolúció és a biodiverzitás. *qubit.hu*