Project Report: The success criteria was clearly defined by two factors in the project proposal; by the successful peer reviews of submissions to journal and conferences (which indicates contribution of the work to the scientific community), and by three milestones. The accepted publication plan: “At least two conference papers and one journal article are expected in each year.” (i.e. together 6 conference and 3 journal papers) has been successfully implemented and even overcome. 16 conference papers and 4 journal articles with project results were published until now, additionally 1 journal article is accepted and 1 is conditionally accepted (minor revisions). In addition, 4 other journal articles were written and submitted into top ranked robotic journals in the last year of the project solution, where the most intensive publication activities were planned (the submitted journal papers with latest results of this project are available in attachment). To sum up these, together 10 journal articles with results of the project were published/accepted/submitted in impacted robotic, control, and AI journals.

In addition, we should highlight that the contribution of research realized within this project was positively evaluated by reviewers of International Journal of Robotics Research, the top ranked robotic journal in WoS at the time of submission, where the article [4] describing results of this project was published, and by Awards Committee of the International Conference on Unmanned Aircraft Systems, which awarded the paper [9] with results of the project by the prize for the best paper. Finally, the committee of the Lakeside Research Days selected the project investigator for an invited talk based on experimental results of the project.

The workload of the project was divided into three parts, each part aimed at one objective with three milestones. All proposed objectives and milestones were fully achieved as follows.

Objective 1: To establish and analyse a theory for swarm stabilization under requirements given by visual decentralized relative localization.

Milestone 1.1: A novel concept of decentralized relative localization will be integrated to swarm stabilization with an aim to keep the reciprocal visibility between neighboring particles.

Milestone 1.2: Adaptively evolving swarm behaviors will be established using evolutionary principles to minimize relative localization uncertainty.

Milestone 1.3: A proof of swarm stability with identified assumptions of stability will be designed.

The system of decentralized localization of the swarm entities was studied, designed and implemented as a key enabling technique for swarming behavior being solved in this project. The method is based on identification of white patches with defined shape and size. Details on the image processing were published in [5]. The technical solution that uses an embedded camera system (Gumstix Overo board, Caspa camera board, and two developed custom boards providing power and interfaces to Gumstix Overo) carried by Micro Aerial Vehicles (MAVs) were published in [18]. The development of the algorithm of the visual relative localization surpassed content of this project, and it was successfully extended [16] and implemented for different research projects of other universities (University of Lincoln, University of Buenos Aires, The Karlsruhe Institute of Technology).
As proposed in the project (Milestone 1.1), the visual relative localization was integrated into the swarm stabilization [1,6], [mov3]. Beyond the original proposal, four streams of the swarm control were successfully solved within the project. 1) Escape behavior based on bio-inspired Boids model of swarming was implemented as an important safety mechanism in applications with human-swarm coexistence [15], [mov2,mov5]. 2) Swarm deployment and coverage under the relative visual localization in surveillance applications were designed, implemented and experimentally verified [17,20], [mov6,mov7]. 3) Evolving swarm behaviors were established using evolutionary principles to solve applications of cooperative searching in the 3D environment using Particle Swarm Optimization (PSO) and Fish School Search (FSS) algorithms [19], [mov1, mov4, mov9] (Milestone 1.2). 4) A control mechanism for heterogeneous formations of MAVs and Unmanned Ground Vehicles (UGVs) and formations of MAVs was designed and implemented [mov10, mov15]. The concept of the decentralized relative localization integrated into a model predictive control technique, which ensures that the reciprocal visibility between neighboring particles is kept, was published in [2, 3]. A proof of stability of the method was published in International Journal of Robotics Research [4] (Milestone 1.3) and adapted for UGVs in [8]. The method was adapted for using in dynamic environments in [10].

**Objective 2: Maintenance of desired shapes of swarms**

Milestone 2.1: A theory for determining desired shapes of MAV swarms will be investigated and experimentally verified.

The various swarming techniques that have been designed for using with the developed visual relative localization within the first objective were extended with a possibility of optimizing desired shapes of swarms for particular applications.

In the swarm deployment and coverage for surveillance tasks, the desired shape of the spread swarm is found together with trajectories from initial configurations to this target shape. The plan of swarm distribution in the environment satisfies constraints given by range of the relative localization, and it respects mutual UAVs heading and movement constraints [sec. VI.C in 21], [20], [mov8].

A Fish Search School (FSS) based algorithm (called Tangible FSS) is modified for control the shape of MAV swarm, and it again respects motion constraints and limits of the visual relative localization (each MAV must see at least one neighbouring MAV all the time) [sec. VI.B in 21].

For applications of cooperative smoke plume tracking based on simple Particle Swarm Optimization (PSO) rules, a PSO searching process is modified for control the shape of the swarm with the aim of odor source localization. The entire MAV group is represented by the PSO swarm with a fitness function corresponding to a measured concentration of a smoke plume [19].

In the Leader-follower formation approach, the shape of the swarm (fixed formation in this case) is optimized regarding the visual relative localization employed in the control feedback. The core of the method consists in a representation of the entire 3D formation as a convex hull projected along the trajectory of the group. Such an approach provides non-collision solution and respects requirements of the direct visibility between the team members [13,14,7], [mov11,mov13,mov14].

Milestone 2.2: A novel concept of priority functions defining weights of sub-regions will be integrated for proper MAVs deployment in various areas of interest.
The concept of priority functions with defined weights of sub-regions selected for the visual surveillance has been designed for the above mentioned environment coverage by MAVs [20-22]. The proposed approach of weighted sub-regions, which respect priority of their surveillance, is one of the key outputs of the project. It enables to deploy the swarm of UAVs in a real world scenario, where the UAV group tries to autonomously satisfy vague requirements of human operators of the mission. Such a tool expands applicability of autonomous swarms to numerous safety, security and defense applications.

Milestone 2.3: A proof of convergence to desired shapes and locations of swarms will be designed.

The proof of the stability of the swarm in a desired shape with the visual relative localization in the stabilization feedback has been designed for the leader-follower approach, as planned in the proposal. Additionally, a proof of convergence of the swarm movement into a desired target region has been built-up [4]. The proposed methodology relies on a model predictive control approach, which allows employing the Lyapunov theorems of stability to specify conditions of the convergence. The results of the convergence and stability analyses are also crucial for failure detection and recovery mechanisms (see [12]).

**Objective 3:** To establish and verify a collective decision making algorithm for control of swarms in complex multi-robot tasks.

Milestone 3.1: A novel decentralized collective decision making mechanism for MAV swarms will be established and experimentally verified.

The collective decision making in a decentralized way has been studied using an extended boids model as proposed in the text of the project. The nature-inspired technique based on the boids model that was designed, implemented and experimentally verified in the second year of the project [15] was extended with an ability of escape behavior. In accordance with fish schools, a decentralized mechanism was implemented into control laws of individual particles, which allows to collectively escape from a proximity of observed predators. This ability is especially appealing in applications with human-MAV swarm interaction. It protects people against injury from propellers of MAVs (e.g. regardless children) and also MAVs against damage by people, which is important in security and defense missions. In the developed method, each MAV that observes an object identified as a predator immediately starts an avoidance maneuver as a result of a multi-objective optimization taking into account only information on local proximity of the particular MAV. The neighboring MAVs that do not see the predator follow this maneuver using estimation of angular acceleration of the helicopters that are already in the escaping mode. See movie [mov12] from experimental evaluation of the method. Its description is under review of Autonomous Robots journal with expected result in 6/2015 (development of this method was planned for the last year of this project and therefore the paper could be submitted just shortly before deadline of this final report).

The second research stream realized with the aim of verification of the possibility to make collective decisions through individual control laws distributed within the swarm deals with the formation driving mechanism developed as a part of the Milestone 2.1. The collective decision making was implemented for autonomous splitting and subsequent merging of teams, where the collective decision where to split (merge) is done based on distributed optimal control mechanism (see [11] for details and [mov16] for movie from a simplified experiment with UGVs).
Milestone 3.2: A theory determining conditions of stability and convergence to new desired constellations will be designed with identified assumptions necessary for initiation of the switching between different swarm behaviors.

In the swarming mechanism based on escape behavior, the propagation of the information observed through observation of neighbors, which leads to the collective avoidance maneuver, was studied. It was experimentally shown and theoretically described that the fast propagation and consequently convergence into the new control mode significantly influences the integration of the angular acceleration estimate. The convergence is achieved faster than if using position estimation, and also probability of collisions within large swarms is lower.

In addition, a methodology that enables determination of conditions in which the swarm will be broken into separated parts by influence of multiple predators was designed. Minimal requirements on range of the employed relative localization, which ensure that the MAV swarm stays compact, may be specified based on number of predators and their motion abilities using this theory (this theory is currently being described together with experimental results achieved in the last months of the project for publication in IEEE Transaction on Robotics).

Regarding the formation splitting/merging method, a proof of convergence into sub-formations (in case of splitting) and into the merged formation (in case of merging) was designed. This methodology also enables to specify requirements on the control system (update frequency, length of prediction horizon, etc.) and limits on allowed disturbances of MAV sensors and actuators [11] (application of this methodology may be seen also in [16]).

Milestone 3.3: A study of observed autonomous behaviors of MAV swarms will be published with identified connections to hypothesis of biologists and evolutionary specialists.

As mentioned above, a study of autonomous propagation of the escape behavior within the MAV swarm, which was originally observed in fish schools, was analyzed and theoretically described. It was shown that the principles observed in nature swarms may be successfully applied for the proposed MAV swarm stabilization system, since the sensors of relative visual localization have similar characteristics as sense organs of birds and fish. Both species may observe only neighbors in swarms under limited viewing angle, acquired information on relative position of these neighbors is quite precise, but only a rough guess on their motion prediction is available.

Together with evolutionary biologists from university of Graz, a possibility of setting of range of communication between individuals was identified as very perspective way how to study unknown principles in nature using artificial swarms. Influence of variable communication on swarming behavior (swarm stability, maneuverability, etc.) is difficult to study with groups of animals. Usually, only the environment can be changed, but not perception of all members of the swarm. Therefore, beyond the project proposal, a communication module triggered by the relative visual localization was developed within the last year of the project solution. Now, it is ready for further swarm experiments together with the biologists, which was the main motivation of the development of the MAV system as proposed in the project proposal.

References:


Multimedia:

[mov1] 3D simulation of swarm movement according to PSO rules. Source: http://youtu.be/D8TRgul7zuM

[mov2] 3D simulation of swarm movement using the escape behavior method. Source: http://youtu.be/SZ7o7l_QlnI


[mov6] 3D simulation of swarm coverage using the PSO algorithm for the shape optimization. Source: http://youtu.be/i4hPYynykw0

[mov7] Experiment of swarm coverage realized in laboratory conditions (under Vicon motion capture system). Source: http://youtu.be/4S0vzYgFh8M


.mov16] Experiment of UGV formation splitting and consequent de-coupling. Source: http://youtu.be/2SJoNSpaqXo