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Swarms of micro aerial vehicles stabilized under a visual relative localization

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***Abstract*— A stabilization and control technique developed for steering swarms of unmanned micro aerial vehicles is proposed in this paper. The presented approach based on a visual relative localization of swarm particles is designed for utilization of multi-robot teams in real-world dynamic environments. The core of the swarming behaviour is inspired by Reynold's BOID model proposed for 2D simulations of schooling behaviour of fish. The idea of the simple BOID model, with three simple rules: Separation, Alignment and Cohesion, is extended for swarms of quadrotors in this paper. The proposed solution integrates the swarming behaviour with the relative localization and with a stabilization and control mechanism, which respects fast dynamics of unmanned quadrotors.**

The proposed method aspires to be an enabling technique for deployment of swarms of micro areal vehicles outside laboratories that are equipped with precise positioning systems. The swarming behaviour as well as the possibility of swarm stabilization with the visual relative localization in the control feedback are verified by simulations and partly by an experiment with quadrotors in this paper.

I. INTRODUCTION

The possibility of deployment of large groups of unmanned Micro Aerial Vehicles (MAVs) closely cooperating together brings new potentialities for autonomous robotics. MAV swarms are beneficial in numerous applications including cooperative surveillance, reconnaissance and monitoring tasks, search and rescue missions, searching for sources of pollution, sensory data acquisition and various military applications. To be more specific, swarms of MAVs can be employed for monitoring of natural disasters (floods, forest fires), patrolling of objects or protected areas (ammunition depots, borders), surveillance of crowds (cultural and sport events, demonstrations), monitoring of industrial accidents (plume of toxic gas tracking, concentration of pollutants measuring), sensing in large environments (measuring of signal coverage, smog concentration) and many more.

Most of these tasks involve the utilization of swarms of MAVs in environments without any pre-installed infrastructure for precise localization of robots. Although available global localization systems (such as GPS) can be used for a rough positioning of the whole swarm, the precision of these systems is insufficient for relative localization of closely operating MAVs. Knowledge of the relative position of neighbouring MAVs in the swarm is crucial for collision avoidance within the team and for any coordination of MAVs, if it is required by the application (cooperative actions). The swarm control approach presented in this paper is suited for utilization of an onboard visual system for relative localization in large teams of unmanned micro quadrotors. The employed localization method provides precise information on relative positions of neighbouring robots with an update rate, which is sufficient for the swarm stabilization.

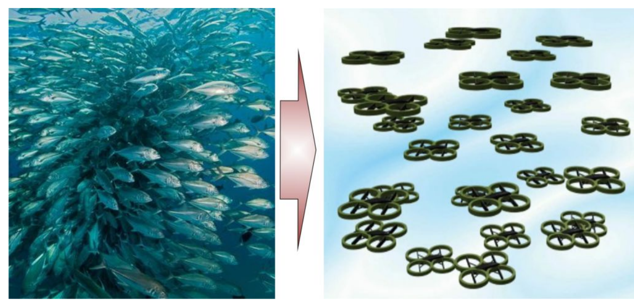

Fig. 1. Swarm of quadrotors controlled by rules derived from behaviours observed in schools of fish.

The presented algorithm designed for the swarm control with obstacle avoidance ability is inspired by the Reynold's BOID model [1], which was developed to simulate schooling behaviour of fish. In our method, the Reynold's basic rules (originally designed for control of 2D holonomic particles) are interpreted for stabilisation of swarms of MAVs under the relative localization as follows:

- Separation - avoid crowding neighbours (a short range repulsion to avoid collisions and to reduce mutual airflow effects caused by propellers).
- Cohesion - keep swarm compact to enable its stabilisation using the relative localization (a long range attraction to keep swarm particles in the range of the visual localization).

The alignment is realized via a target attraction, which steers swarm particles towards a common target. Besides, we consider another rule, which is important in applications in environment with obstacles or with possible human-swarm interaction, where the swarm has to keep a sufficient safe distance from people:

- External avoidance - avoid obstacles (a short range repulsion based on flight direction).

In nature, flocks (fish schools) can avoid obstacles or escape from predators very fast in a cooperative way and without mutual collisions. In analogy to the school of fish, also MAVs equipped with the onboard sensors for relative

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localization are able to detect neighbours within a short detection range and to determine their position and change of the position. This information employed in the control feedback enables the swarm to keep compact and avoid obstacles without any explicit communication. Moreover, even if not all robots of the group are able to detect the particular obstacle, its avoidance is ensured via a sequential transfer of motion changes through the swarm by continual observing of relative positions of neighbours (the visual relative localization system that we have introduced in [2] is employed). The presented swarm stabilization approach is an extension of work in [3], which was designed for control of swarms of ground robots.

From the robotic point of view, such an approach based on flocking behaviour has two important advantages regarding the large MAV swarms: 1) It is strictly decentralized based only on the information gathered by onboard sensors and therefore it is scalable. 2) The swarming rules are computationally efficient and so the control algorithm can be run in a fast loop even using the computational power available onboard of simple MAVs.

1) State of the art: Recently, the research of swarms of autonomous vehicles covers broad areas of robotics including aspects of task allocation and strategies for solving multiple tasks [4], communication and maintenance of connectivity within the team [5], a modeling of the swarm behavior by predicting of individual behaviours [6], or a collision avoidance within the swarm [7]. The topic involved in this paper is related mainly to control and stabilization of swarms of MAVs [8], [9]. The most related to the research proposed in this project is presented in [10], where swarming behaviours of ground robots in a planar environment are investigated. The aim of our approach is also to stabilize swarms of autonomous robots (in our case MAVs) in a desired shape while maintaining a small distance among themselves. Beyond the research presented in [10], we design principles of swarming rules to satisfy requirements on the visual system of relative localization in 3D, which enables *to take swarms of flying robots outdoor*. This is one of the most important contributions of our method in comparison with the aforementioned algorithms that have been verified usually via numerical simulations or rarely using ground vehicles in laboratories. In literature, one can find also number of works based on the Reynold's model, e.g. [11], [12]. These algorithms are also mostly designed to steer ground robots or 3D particles, which are often considered as dimensionless points. There is lack of approaches considering limitations of MAV multi-robot systems or even investigating possibility of deployment of swarms of aerial robots in real-world missions.

II. Problem statement and preliminaries

Let us assume a group of N quadrotor MAVs equipped with omnidirectional vision system capable of relative localization of neighbouring robots and obstacles in a limited range. The robots are identical to each other (the localization does not provide the identification of neighbours) and there is no communication within the swarm available. The obstacles are considered as a set of simple objects (spheres in the experiments) with known relative positions from the MAVs. A complex map, could be represented by such objects with arbitrary precision, but this paper is not focussed on the environment representation/mapping.

The problem solved in this paper is to stabilize the robots in a compact swarm in an environment with obstacles and, if it is required by the application, to reach a target region. In the case of the target following, we also assume that the robots are able to detect the target position or a direction into the target. The control algorithm must respect both the relative positions of neighbouring MAVs and the constraints of the relative localization (local range). Clearance between neighbouring MAVs and between MAVs and obstacles must ensure a collision free movement.

A. Quadrocopter model and control

In this paper, we use a quadrotor vehicle model [13] with four identical propellers located at vertices of a square (see Fig. 2 b)). Each of the propellers j generate a thrust f_i^j along its axis. For each MAV i, we consider an inertial reference frame and a body-fixed frame with origin located at the center of mass of the MAV. The relative position of these frames is defined by the location of the center of mass $x_i \in \mathbb{R}^3$ in the inertial frame and by the rotation matrix $R_i \in \mathbb{R}^{3\times 3}$ from the body-fixed frame to the inertial frame. The inertial reference frame is different for each MAV since they cannot communicate with each other, which would be necessary for unification of the reference frames.

The motion model of MAVs according to [13] is

$$\begin{aligned} \dot{x_i} &= v_i, \\ m_i \dot{v_i} &= m_i g e - f_i R_i e, \\ \dot{R_i} &= R_i \hat{\Omega}_i, \\ J_i \dot{\Omega}_i + \Omega_i \times J_i \Omega_i &= M_i, \end{aligned} \tag{1}$$

where $v_i \in \mathbb{R}^3$ is velocity of the center of mass in the inertial frame, $m_i \in \mathbb{R}$ is weight of the MAV, $\Omega_i \in \mathbb{R}^3$ is angular velocity in the body-fixed frame, $J_i \in \mathbb{R}^3$ is inertia matrix with respect to the body frame. The hat symbol $\hat{\cdot}$ is defined by the condition $\hat{x}y = x \times y$ for all $x, y \in \mathbb{R}^3$, g is the gravity acceleration and $e = [0, 0, 1]$. The total moment $M_i \in \mathbb{R}^3$ along all axes of the body-fixed frame and the thrust $f_i \in \mathbb{R}$ are control inputs of the plant. The total thrust, $f_i = \sum_{j=1}^{4} f_i^j$, acts in the direction of the axis of the body-fixed frame which is orthogonal to the plane defined by the centres of the four propellers. The control inputs are obtained by the tracking controller presented in [13], which is employed to reach the new locations of MAVs given by the swarming approach described in section III.

B. Visual relative localization of swarm particles

The swarming principles investigated in this paper are designed for using the light-weight vision based embedded system of the relative localization of particles within the robotic group. The system developed within our team (see [2] for technical details and performance analyses) is based on a detection of black and white patterns with precision in units of centimeters for distances in units of meters. This operational range and precision are sufficient for the stabilization of groups of MAVs cooperatively acting in close swarms.

Although, this system is sufficiently robust and precise, it has a drawback concerning stabilization of large groups of MAVs, since its operational range is limited (depends on resolution of the employed cameras and size of the pattern). Therefore, it is crucial to incorporate the operational constraints into the swarming rules and to keep MAVs in appropriate relative positions regarding the relative localization. The operational constraints are described by a model of the localization arising from theoretical analyses of the vision system and experimental evaluation of the system performance in real scenarios presented in [2].

In addition, the localization system (in its simple version) may not identify which MAV is recognized in robot's neighbourhood. The possibility of particular MAVs identification would require more complicated patterns or patterns of different colours, which would be at the cost of decreased reliability, precision and operational range. The proposed nature inspired swarm control technique is especially appealing to deal with this limitation, since the swarm theory assumes utilization of homogeneous particles. Therefore, also the relative interaction of swarm particles (described in Section III-A) considers the neighbouring MAVs as anonymous entities.

III. Flocking behaviour with obstacle avoidance ability

A novel MAV flocking approach based on the Reynold's model of the coordinated animal motion is proposed in this section. Taking the steering behaviours of Reynold's boids as an inspiration, we have incorporated the local interactive forces from neighbouring robots into the dynamics of MAVs. We have also included effects given by proximate obstacles and a force pushing the overall swarm into the desired target region. This active force would not be necessary in case of employment of the algorithm as a component of higher level motion planning algorithms. Then the flocking MAV control can be used for swarm stabilization and for emergency intervention due to its avoidance and escaping behaviour, while the high level planner would solve the swarm navigation.

The proposed swarming approach, which provides control inputs based on surrounding quadrotors and near obstacles in a decentralized manner, enables employment of large swarms of relatively localized MAVs. This control scheme provides a sufficiently robust and fast solution, which requires minimal computational power and simple sensors available onboard of MAVs. The swarming behaviour is designed as a combination of the relative interactions of swarm particles, the attraction of the target and the interaction with surrounding environment as follows.

A. Relative interaction of swarm particles

The core of the proposed swarming behaviour is based on the relative interaction between particles of the group. The relative positions of neighbouring robots are composed into the separate rules for each of the individuals independently, which results in the required behaviour of the entire group. This decentralized concept is suitable for the proposed scheme, which is based on the relative visual localization of MAVs. In such a swarm, each robot is capable of localizing only neighbours in its limited surroundings. The effects of neighbouring robots are integrated into the MAV control by the individual force

$$\mathbf{F}_{ind_i} = \sum_{j,j\neq i}^{N} e_{ij}\mathbf{F}_{ind_{ij}}, \tag{2}$$

where e_{ij} is a distance weight function and $\mathbf{F}_{ind_{ij}}$ is an interactive force.

The distance function emulates the sensor range of the employed visual relative localization. It ensures that the interactive force is considered in the MAV control rule only if the neighbouring vehicles are in relative positions that enable their confident localization. The distance function is important mainly for realistic simulations of the MAV swarm behaviour. In the experiments with real quadrotors, this function is replaced by a tag indicating validity of the sensory data. Such a tag is provided by the utilized visual relative localization system [2]. The magnitude of the distance weight function depends on the relative distance $\mathbf{L}_{ij}$ between two neighbouring quadrotors, i and j, as:

$$e_{ij} = \frac{1}{e^{a\mathbf{L}_{ij}-b}+c} + \frac{1}{e^{0.5a\mathbf{L}_{ij}-b}+c}. \tag{3}$$

The weight function is used with constant values $a = 5$, $b = 4$, $c = 0.6$ in this paper. The interactive force

$$\mathbf{F}_{ind_{ij}} = K_d(\|\mathbf{L}_{ij}\| - L_r)\mathbf{L}_{ij} + D_d\frac{\mathrm{d}\mathbf{L}_{ij}}{\mathrm{d}t} \tag{4}$$

is designed as a spring-damper model. It enables stabilization of the robots in a relative distance equal to a desired intra-robot distance L_r. The constant L_r has to be chosen smaller than the range of the relative localization to ensure the stabilization of the group. On the contrary, too small value of L_r can increase possibility of collisions and mutual disturbances by air streams from propellers. $\mathbf{L}_{ij}$ is a vector between robots i and j, which is given by the visual relative localization. The constants, which are used as $K_d = 1.5$ and $D_d = 2$ in experiments in this paper, affect the rate of the convergence into the equilibrium. The required derivative of the relative position of neighbours is obtained by Kalman filtering of the data from the relative localization system [2].

B. Swarm attractivity

The rule of the swarming behaviour presented in this subsection deals with the attraction of the swarm to the target position. This ability of the swarm movement into the desired goal position is achieved by integration of an attractive force

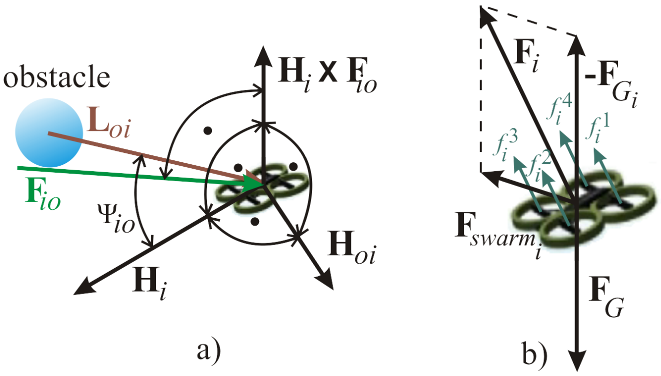

Fig. 2. a) Forces of interaction with surrounding environment. b) Integration of the total swarming force into the MAV control.

to the MAV control scheme. The attractive force is pointing at the goal and again it works as a spring-damper model:

$$\mathbf{F}_{goal_i} = K_g \frac{\mathbf{L}_{ig}}{\|\mathbf{L}_{ig}\|} + D_g \frac{\mathrm{d}\mathbf{L}_{ig}}{\mathrm{d}t}. \tag{5}$$

Here, the required equilibrium that has to be achieved is a zero relative distance between i-th robot and the goal position. $\mathbf{L}_{ig}$ is the relative position vector from the i-th MAV to the goal. The constants, which are $K_g = 1.1$ and $D_g = 2$ in experiments in this paper, control the rate of convergence of the group. In comparison with the eq. (4), where the force magnitude is changing based on the relative distance to the neighbours, the attractive force is normalized to ensure the same swarming behaviour along the whole trajectory to the goal.

As it is well known in robotics, such a simple attractive force suffers from local extremes in complex environments with obstacles, which may result in undesirable oscillations or a dead-lock. Nevertheless, this navigational approach is sufficient for the verification of swarming principles based on the relative visual localization, which is the main purpose of this paper.

C. Interaction with environment

The obstacle avoidance behaviour is essential for the real-world deployment of autonomous robots. Incorporation of an obstacle avoidance function directly into the swarming rules enables a very fast response to changing environment. In the proposed approach, the avoidance manoeuvre is realized by a translational reshaping of the swarm, which is caused by the interactions between particles of the group. Thus some individuals in the group may perform obstacle avoidance even without sensing the obstacle directly. This results in the required evasive action of the entire swarm without any centralized command.

The arising reshaping of swarms of quadrotors caused by detected obstacles is initialized by incorporating the equation

$$\mathbf{F}_{obs_i} = \sum_{o \in \mathcal{O}} \delta e_{oi} \frac{\mathbf{H}_{oi}}{\|\mathbf{H}_{oi}\|} \tag{6}$$

into the steering rules of each MAV. Each obstacle o in the set of detected obstacles $\mathcal{O}$ is considered in eq. (6). The magnitude of $\mathbf{F}_{obs_i}$ depends on the direction dependence function δ and the exponential distance function e_{oi}.

The function e_{oi}, which is designed as

$$e_{oi} = b_o e^{a_o \|\mathbf{L}_{oi}\|}, \tag{7}$$

is exponentially growing with decreasing distance $\|\mathbf{L}_{oi}\|$ between the $i-th$ MAV and the obstacle. The parameters of the exponential function are used as $a_o = -3$ and $b_o = 100$ in experiments presented in this paper.

The direction dependency function δ,

$$\delta = (1 + \cos(\Psi_{io})), \tag{8}$$

is important due to the fast dynamics of the MAV swarms. This function enables to generate a repulsion according to the relative angle Ψ_{io} between the vector $\mathbf{L}_{oi}$ and the direction vector of the i-th MAV. $\mathbf{L}_{oi}$ is the relative position vector between the MAV and the obstacle. MAVs flying towards a collision with the obstacle or in a direction which is close to the collision are influenced by the avoidance function more intensively.

$\mathbf{H}_{oi}$ is vector perpendicular to the direction vector of the i-th MAV, which is pointing away from the obstacle as shown in Fig. 2 a). The vector $\mathbf{H}_{oi}$ is defined as

$$\mathbf{H}_{oi} = (\mathbf{H}_i \times \mathbf{F}_{io}) \times \mathbf{H}_i, \tag{9}$$

where $\mathbf{H}_i$ is the direction vector of the MAV. The force $\mathbf{F}_{io}$ is employed to keep the MAV in a sufficient distance from the obstacle. Also, it enables us to incorporate a prediction of the obstacle movement into the avoidance function. The force, which is defined as

$$\mathbf{F}_{io} = K_o \mathbf{L}_{oi} + D_o \frac{\mathrm{d}\mathbf{L}_{oi}}{\mathrm{d}t}, \tag{10}$$

deviates slightly from the vector $\mathbf{L}_{oi}$ oriented from the center of the obstacle to center of the mass of the quadrotor, as denoted in Fig. 2a. The deviation correlates with the movement of the obstacle (included in the first-order derivative of $\mathbf{L}_{oi}$). Again, the constants, which are used as $K_o = 1.5$ and $D_o = 2$ in experiments in this paper, influence speed of the respond to detected dynamic or static obstacles.

The total force that acts on the i-th MAV is determined as a sum of particular contributions as:

$$\mathbf{F}_{swarm_i} = \mathbf{F}_{ind_i} + \mathbf{F}_{goal_i} + \mathbf{F}_{obs_i}. \tag{11}$$

For the stabilization of the quadrotor in the required orientation, a ray from the center of mass of the MAV in the direction of $\mathbf{F}_i$ is employed as the reference for the single MAV low-level control. The control approach addressed in [13] is used to achieve the new orientation of the MAV in the direction of $\mathbf{F}_i$. The low-level control is used to follow the direction of $\mathbf{F}_i$ until the update of the swarming rules is initiated, based on the frequency of the high level control loop of the swarm stabilization.

IV. Experimental results

The experiments presented in this section have been designed to show performance of the proposed method and to analyse its key properties. The simulations shown in Fig. 5 and 8 demonstrate the ability of the algorithm to maintain a compact swarm of numerous MAVs and to avoid obstacles simultaneously. Movies of these simulations and two additional experiments are available in [14]. In the scenarios, 27 MAVs (experiments 1 and 2) or 10 MAVs (experiments 3 and 4) are initialized in a compact formation.

At the beginning of the simulation, the quadrotors autonomously increase their relative distances based on the swarming rules described above. The desired equilibrium is achieved very fast (in less then one second) as can be seen in the graph of distances from quadrotors to their closest neighbour shown in Fig. 4. Together with the swarm stabilization, the group is moving towards the desired goal position. After few steps of the first simulation (Fig. 5), the outer MAVs of the swarm detect an obstacle. The obstacle is positioned in the middle of the line connecting the start and goal positions. The quadrotors smoothly avoid the obstacle to keep the sufficient distance from the detected object during the whole manoeuvre. The distance between the obstacle and all MAVs is shown in Fig. 3. Once the obstacle is avoided, the group converges back into the flock shape, which is depicted in the last snapshot of Fig. 5, and continues towards the goal position. Reintegration of the sub-swarms is possible only if there exists at least one relative interaction between both groups. It means that the value of term $\|e_{ij}\mathbf{F}_{ind_{ij}}\|$ is greater than zero for at least one pair of robots i and j, which belong to different sub-swarms.

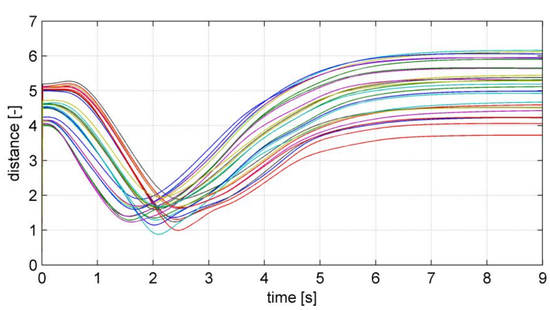

Fig. 3. Graph of distances from MAVs to the obstacle in the simulation 1.

The second simulation is initialized identically as the first one, but two additional obstacles are placed in the environment to show robustness of the approach. In snapshots of the experiment in Fig. 8 and in the video in [14], one can see that the swarm is again deformed due to the obstacles as the "avoidance signal" is propagated through the group. During the whole avoidance manoeuvre, sufficiently safe relative distances within robots of the team as well as between robots and all obstacles are kept. The values of distances between the obstacles and MAVs are plotted in Fig. 6 and the values of distances between MAVs and their closest neighbours in Fig. 7.

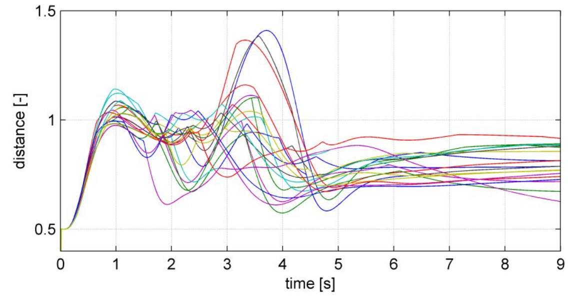

Fig. 4. Graph of distances between MAVs and their closest neighbour during the simulation 1.

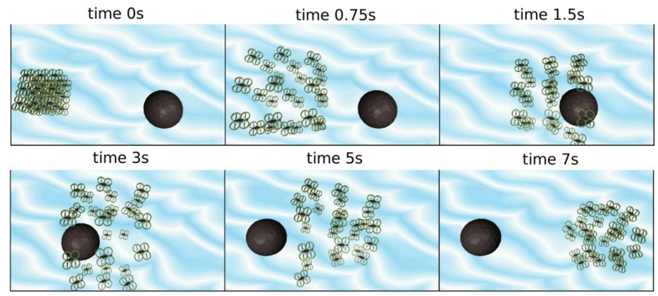

Fig. 5. Snapshots of simulation 1.

The experiments with multiple MAVs show that the swarm of quad-rotors can be stabilized using the visual relative localization in the control feedback. In the experiment shown in Fig. 9, two MikroKopters L4-ME and one AR-drone are stabilized using only the feedback from onboard cameras.

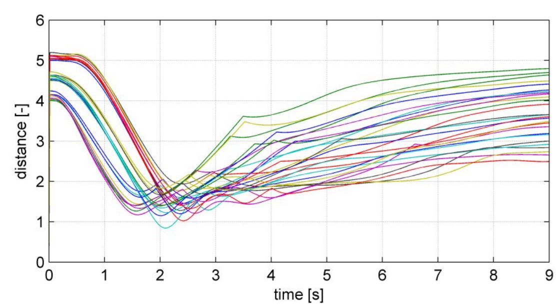

Fig. 6. Graph of distances between MAVs and the closest obstacle during the simulation 2.

V. Conclusion

A nature inspired approach for control and stabilization of swarms of unmanned micro aerial vehicles was presented in this paper. The proposed method is designed with the onboard visual relative localization of swarm members integrated into the MAVs control. The algorithm is based on simple swarming rules using an information on position of neighbours in the team and obstacles in limited sensory range without the necessity of communication. It was verified via simulations that the proposed swarming principle, computed onboard of MAVs in a strictly decentralized manner, enables

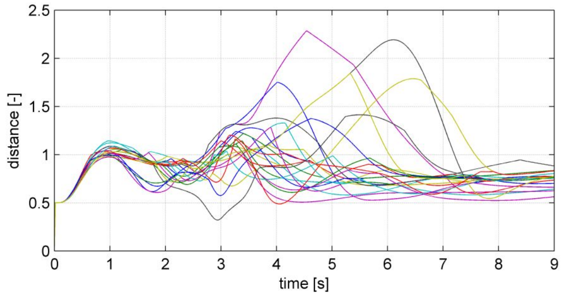

Fig. 7. Graph of distances between MAVs and their closest neighbour during the simulation 2.

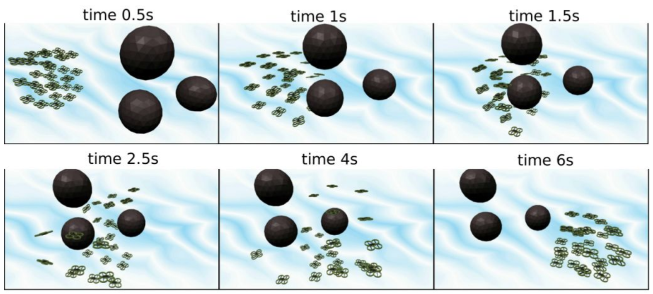

Fig. 8. Snapshots of simulation 2.

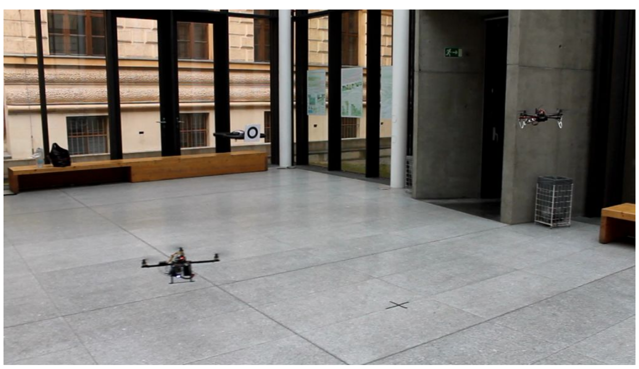

Fig. 9. Verification of the proposed swarm stabilization approach using only the relative interaction between swarm members.

stabilization of the swarm of micro quadrotors. With these desirable characteristics, the proposed approach could be an enabling technique for employing large swarms of MAVs outside laboratories equipped with a precise global position system. Such a swarming behaviour is appealing in scenarios in which a large team of robots has to move closely together: e.g. to form a distributed sensor for environment measurement, monitoring or surveillance.

VI. Acknowledgements

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