MAV-swarms: Unmanned aerial vehicles stabilized along a given path using onboard relative localization

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***Abstract*— A novel approach for stabilization and navigation of swarms of Micro Aerial Vehicles (MAVs) along a predefined path through a complex environment with obstacles is introduced in this paper. The method enables to control large MAV swarms (in literature also called UAV swarms) based only on onboard sensors and without any inter-vehicle communication. The proposed method relies on visual localization modules carried by all MAVs, which provide estimation of the relative positions of neighbours in the swarm. Guess on the positions of the neighbouring MAVs and information on the relative positions of obstacles are integrated into swarm stabilization via Reynolds' Boids model. The performance of the complex system is shown in various numerical simulations and in experiments with a fleet of MAVs in the paper. Presented experimental results with the multi-MAV swarm were conducted in indoor and outdoor environment, and without using any external global localization system such as Vicon motion capture system or GPS localization.**

I. Introduction

An algorithm for stabilization of swarms of Micro Aerial Vehicles (MAVs) in a compact shape and for their navigation through complex environment with obstacles is presented in this paper. The method relies strictly on onboard sensors, without any need for global localization or external motion capture systems, which enables utilization of the multi-MAV system independently of preinstalled infrastructure.

Miniaturization of MAVs and their low price enable deployment large groups of simple robots instead of one well equipped (and therefore expensive) vehicle, which increases reliability of the system. In case of a failure, the task of a broken MAV (or MAVs) can be simply over-taken by an identical robot being part of the team for redundancy. Furthermore, for antagonists, it is difficult to purposely decrease operability of large swarms of closely operating small vehicles, in comparison with a single vehicle that can be easily attacked, which is important mainly in security and defence applications.

However, deployment of multi-robot systems introduces numerous challenges that do not have to be solved in single-robot systems. Operation of swarms of closely cooperating MAVs involves inter-vehicle collision avoidance that requires precise and frequently updated information on relative positions between robots in the group. In most of the MAV-swarm applications, publicly available systems (such as GPS) can not be applied due to their limited precision and reliability. Position error of GPS is usually higher than the required relative distances between MAVs and any signal drop-out can be fatal for control of such highly dynamic system. Another bottleneck of distributed systems of multiple MAVs is the necessity of inter-vehicle communication, since the amount of transferred data grows with size of the team in most of the approaches. Moreover, any communication drop-out can be again fatal for swarm stability and collision avoidance within the team.

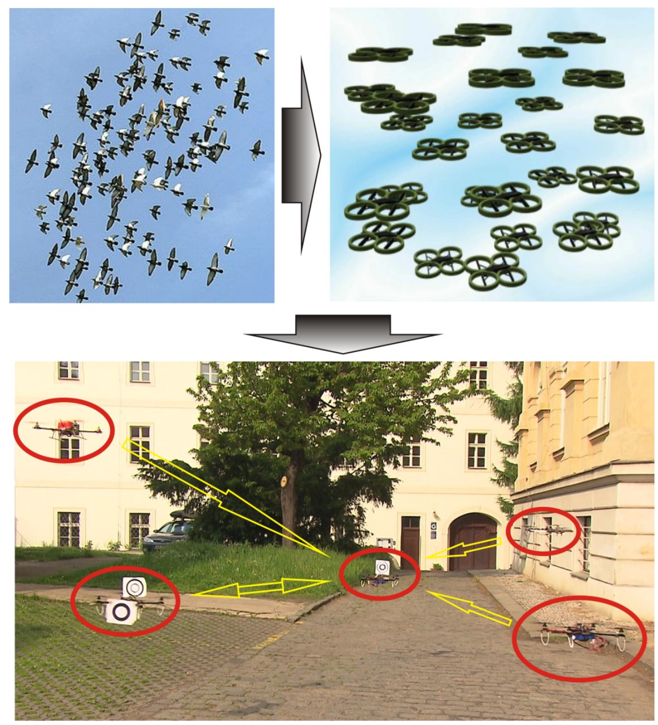

Fig. 1. Demonstration of the process from observation of the flock of birds through simulation of 3D flocking to the MAV swarm with depicted linkages between robots realized by the onboard relative localization.

All these issues are tackled in this paper using a system of visual relative localization of swarm particles, which is carried onboard of MAVs. Precision and reliability of the localization system is sufficient for swarm control and its stabilization, and using this localization does not require to install any kind of infrastructure in the environment, which significantly increases applicability of the MAV swarms (see Fig. 1 for motivation). The relative localization system uses monocular cameras carried by all MAVs and simple localization patterns attached on all MAVs for precise estimation of their mutual positions. This setup allows us to gain information on close proximity of each MAV in a similar way as it is done in swarms of animals in nature. The sensors

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of relative visual localization have similar characteristics as sense organs of birds and fish. Both these 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.

Taking this remark together with the fact that the swarming behaviour being seen in nature is very similar to the behaviour that is required by MAV swarm applications, we employ nature inspired approaches for control of entities in MAV swarms. In this paper, a Boids model of swarm behaviour is applied, which is derived from motion records of swarming in nature. This technique uses only limited information on local proximity of each swarm particle for design of a control law in distributed way. An important advantage of this approach is possibility of swarm stabilization without necessity of sharing any global knowledge between particles, and therefore the required communication is limited to broadcasting of a start command.

A. State of the art methods and progress beyond these methods

In swarm robotics, the following problems are currently investigated: communication and topology of communication networks [1], [2], multi-robot task allocation and swarm deployment [3], [4], [5], [6], collision detection and avoidance [7], [8], [9], motion planning [10], [11], [12], [13], coordination [14], [15], swarm localization [16], modeling of the swarm behaviour by estimation of movement of individuals [17], [18], and also control and stabilization of robotic swarms [19], [20], [21], [22], [23], which is the main topic of this paper.

The method proposed in this paper is designed with the aim to satisfy requirements of swarms as listed in [24]: scalability for large groups, high redundancy and fault tolerance, usability in tasks unsolvable by a single robot, and locally limited sensing and communication abilities. Therefore, examples of studies investigating these domains should also be mentioned in this literature review. A hierarchical framework for planning and control of arbitrarily large swarms is proposed in [20]. Aspects influencing a fault tolerance in teams of robots are discussed in [25]. Finally, controllers for swarms of robots with limited communication are described in [21].

The work in [21], which investigates swarming behaviours of ground robots in a planar environment, is the most related to the research proposed in this project. 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 [21], we investigate principles of swarming rules with requirements of visual relative localization in 3D. This enables to employ MAV swarms in environments that are not equipped by a precise external localization infrastructure. 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. Therefore, these approaches often omit constraints given by the real outdoor deployment of swarms, and they rely on a precise global localization systems that have to be installed in the workspace prior the robots utilization.

Finally, let us mentioned examples of works that use the Reynold's Boids model for swarm control [26], [27], [28]. These algorithms are 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, where the sensing and computational power has to be carried onboard of helicopters. Beyond the mentioned integration of the visual relative localization into the swarming principles, the contribution of this paper lies in design of novel swarming rules that are adapted for the fast dynamics of MAVs. This enables to achieve full potential of the Reynold's theory and realize impressive but also effective swarming abilities as demonstrated in various experiments in this paper.

This work is partially based on our approach presented in [29]. The contribution of this paper is the ability of the method to navigate the swarm through environment with complex obstacles. The approach enables utilization of any path planning technique (see [30], [31] for examples on our work dealing with path planning for groups of MAVs), which is able to obtain a collision-free path for a robot with given size. A proper method can be selected based on particular scenario, and there are no requirements on smoothness of the path or its shape. Moreover, the swarm stabilization approach is enough robust to deal with suddenly appearing obstacles without necessity of re-planning of the path and to navigate the group in corridors that are narrower than the size of the swarm in its stable shape.

II. Problem definition and enabling techniques

A. Problem statement

In the given task, a group of MAVs is navigated through a partly known environment from the actual location into a desired goal. We assume that the known structure of the environment and the unknown obstacles that are detected by MAVs during the mission are represented by 3D polygons. The known map is used for the initial path planning algorithm, which provides a path for the swarm stabilization and navigation method. Information on positions of detected obstacles is directly included into the swarming rules, which enables fast response and collision avoidance.

For the swarm stabilization and inter-vehicle collision avoidance, we assume that each MAV is equipped with vision system (described in section II-B) capable of relative localization of neighbouring robots and obstacles in a limited range. The number of MAVs in the group may be variable. The distributed stabilization principles, which use only local information on proximity of the particular robot and do not require any communication, make the approach robust to a failure of a team member, to splitting into independent groups, or contrariwise to integration of new team members. From the swarm stabilization perspective, each robot is considered as an identical particle, which is also advantageous for fast relative localization of swarm members. As analysed in [32], necessity of identification of particular vehicles in the group decreases update rate, range and reliability of the onboard relative localization.

Beside the onboard relative localization system that provides relative position of neighbours of each vehicle, we expect knowledge of a guess of position of the group (not necessarily precise) within the given map. In outdoor environment this information may be provided by GPS, even though its precision is insufficient for stabilization of swarms of closely flying MAVs. Indoor, any kind of localisation technique may be used (see e.g. our work on localization of MAV-UGV formations in [33]). For experiments presented in this paper, odometry obtained by integration of velocity measured by optical flow from down looking camera is used (see section V for details).

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 swarm particles. The system developed within our team (see [34] for technical details and performance analyses) is based on 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 stabilization of groups of MAVs cooperatively acting in the compact swarms. The core of the system consists of a Caspa camera and a Gumstix Overo board accompanied by a developed efficient image processing method for detecting the circular patterns. Although, the idea of the roundel recognition is simple, the developed system exhibits reliable and fast estimation of the relative position of the pattern up to 30 fps using the full resolution of the Caspa camera.

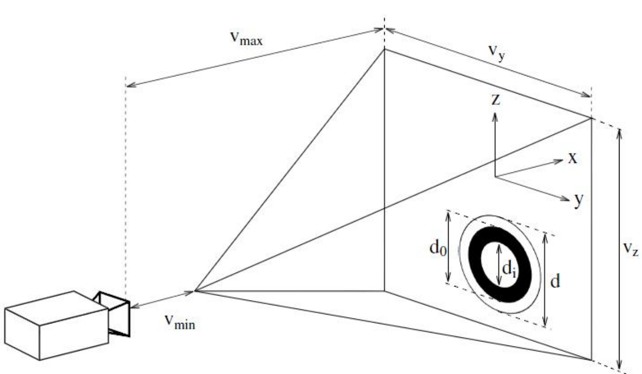

Fig. 2. Example of the localization pattern and operational space of the employed visual relative localization. Source: [34].

The blob detection is based on an image segmentation and finding two discs forming a black and white ring placed at a white background (see Fig. 2). The gathered data are used to determine position of the pattern relatively to the camera module. The pattern distance calculation uses the fact that length of the principal axis of the observed ellipse is invariant to the pattern spatial orientation and depends solely on its position relative to the camera. The pattern relative orientation is obtained from detection of pattern deformations (difference between axis of the detected ellipses and difference between position of centroids of ellipses). Although, this system is robust and well suited for robots acting in outdoor environments, 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 the pattern size). 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 [34].

In addition, the localization system (in its simple version) may not identify which MAV in the large swarm is recognized. 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) considers the neighbouring MAVs as anonymous entities.

III. Rules for swarm stabilization and navigation

In this section, the distributed flocking approach derived from the bio-inspired Boids model is presented. The method satisfies the motion constraints of MAVs, it respects the influence of airflow from the propellers of neighbouring vehicles, and it satisfies the constraints on relative positions of MAVs required by the visual localization of the neighbours.

Being inspired by the steering behaviour of Reynolds' Boids [35], we have combined the local interactive forces from neighbouring MAVs with effects given by proximate obstacles and with a force leading the MAV group along a feasible path into the desired target region. This integrates swarm stabilization, MAV control, obstacle avoidance, and group navigation into a stable control law in a decentralized manner. This control scheme provides a reliable solution, that requires a minimal computational resources and simple sensors available onboard of MAVs for deployment of large swarms of variable size. The flocking behaviour is designed as a combination of all these requirements as follows.

The main idea of the proposed MAV flocking behaviour lies in mutual interaction between particles of the group based on output from the relative localization module, which results in inter-vehicle collision avoidance and swarm stabilization. For each neighbour j, which is localised by the onboard system, a force $\mathbf{F}_{ind_{ij}}$ that influences movement of the i vehicle is composed based on their relative distance

$\mathbf{L}_{ij}$ as

$$\mathbf{F}_{ind_{ij}} = K_d(\|\mathbf{L}_{ij}\| - L_r)\mathbf{L}_{ij} + D_d\frac{\mathrm{d}\mathbf{L}_{ij}}{\mathrm{d}t}. \quad (1)$$

The main purpose of this force is to stabilize MAVs in relative distances that can be defined by the constant L_r. The proper value of this constant depends on the particular application, on the size of the MAVs, on their motion capabilities, and on operational range of the relative localization. MAVs flying in a too close proximity cannot be detected by the localization system as the localization pattern must be observed completely by the onboard camera, as explained in [32]. On the contrary, the equilibrium (required distance between neighbours) cannot exceed the range of the relative localization. The constants K_d and D_d influence convergence into the equilibrium and therefore also speed of the MAVs in the swarm[1].

Forces from all detected robots are integrated as follows:

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

where $e_{ij} = (e^{a\mathbf{L}_{ij}-b} + c)^{-1} + (e^{0.5a\mathbf{L}_{ij}-b} + c)^{-1}$ is a distance weight function. Parameters a, b and c are identified based on the range of the visual relative localization. In simulation of swarm movement, the weight function ensures that these forces are considered for MAV control only if the neighbouring vehicles i and j are in relative positions that enable their confident localization[2].

In addition to inter-vehicle collision avoidance, also obstacles in the MAVs workspace need to be considered in the swarming mechanism. Being inspired by flocks in nature, the MAVs that detect an obstacle in their proximity (usually the outer particles of the swarm in the direction of the obstacle) immediately start their avoiding manoeuvre to keep the obstacle in the safe distance. Such sudden change of positions of these MAVs deviates the system from the equilibrium given by eq. (2), and thus the avoidance signal is propagated through the group without any explicit communication between the swarm members. Moreover, if the obstacle is detected in a close proximity of the swarm, the initial avoidance manoeuvre of the MAVs that detect the obstacle results in fast change of their heading, which can be detected by the vision system of their neighbours. The shape of the entire swarm can be then reshaped very fast through interactions between particles of the group. This evokes the required evasive action in the decentralised way. Influence of obstacles is incorporated into the control rules of each MAV by force

$$\mathbf{F}_{obs_i} = \sum_{o\in\mathcal{O}} \delta e_{oi}\frac{\mathbf{H}_{oi}}{\|\mathbf{H}_{oi}\|}, \quad (3)$$

[1]Values $K_d = 1.5$ and $D_d = 2$ are used in all experiments in this paper.

[2]In all experiments presented in this paper, constant values $a = 5$, $b = 4$, $c = 0.6$ are used based on the model of reliability of the relative localization presented in [34].

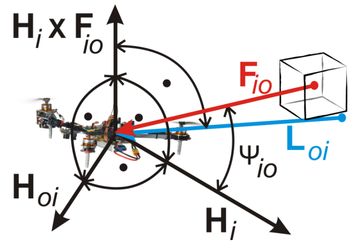

Fig. 3. Explanation of forces integrated into the swarm stabilization rules for obstacle avoidance.

in which contribution of each obstacle o in the set of detected obstacles $\mathcal{O}$ is collected. The value of the distance function $e_{oi} = b_o e^{a_o\|\mathbf{L}_{oi}\|}$ exponentially decreases with distance $\|\mathbf{L}_{oi}\|$ between the obstacle o and the $i-th$ swarm particle[3]. The direction dependency function $\delta = (1 + \cos(\Psi_{io}))$ enables to integrate the information on fast response of a neighbour to suddenly appearing obstacles. This is crucial ability for achievement of inter-vehicle avoidance during avoiding obstacles in MAV swarms with fast dynamics. In the direction dependency function, the repulsion is generated according to the relative angle Ψ_{io} between the vector $\mathbf{L}_{oi}$, which connects the positions of the MAV and the obstacle, and the vector in direction of movement of the MAV.

Finally, vector $\mathbf{H}_{oi} = (\mathbf{H}_i \times \mathbf{F}_{io}) \times \mathbf{H}_i$ is perpendicular to the vector $\mathbf{H}_i$, which is placed in direction of movement of the i-th MAV. Vector $\mathbf{H}_{oi}$ is oriented in direction from the obstacle as shown in Fig. 3. The force $\mathbf{F}_{io} = K_o\mathbf{L}_{oi} + D_o(\mathrm{d}\mathbf{L}_{oi}/\mathrm{d}t)$ incorporates a prediction of the obstacle movement into the avoidance function (through the derivative of $\mathbf{L}_{oi}$) to keep the MAV in a safe distance to obstacles. Again, the constants K_o and D_o influence speed of the respond to changes in the proximity of robots[4].

The last rule included in the swarming behaviour is important for navigation of the MAV group along a given path through the environment. In this paper, we propose an approach of a receding target, which is followed by the MAVs. The target is a virtual moving point, which position is defined ahead the swarm. Distance D_T between the center of gravity of the group and the virtual point is always kept constant in this approach. The value of D_T should be bigger than expected radius of the swarm, which depends on the number of swarm particles, desired distance between MAVs, and allowed elasticity of the group shape (the shape of the swarm is elliptical in direction of its movement if passing through narrow corridors). If radius of the swarm exceeds the value of D_T, some MAVs get ahead the target, which results in their decelerating. On the contrary, too big value of D_T can cause deviation of the group from the desired path in case of a short turn (or breakage) of the path.

The deviation of the swarm from the desired path can be minimized by two improvements of the method. In the first approach, the position of the target is placed on the tangent

[3]Values of parameters $a_o = -3$ and $b_o = 100$ are used in experiments in this paper.

[4]Values $K_o = 1.5$ and $D_o = 2$ are used in experiments in this paper.

line to the path at nearest point P on the path to the centre of gravity of the swarm (see Fig. 15 for demonstration of this approach). Again, the receding target is always in distance D_T from the point P.

In the second approach, each swarm particle follows its own virtual receding target. This individual target is placed on the line that passes through the centre C_i of the particular MAV and that is perpendicular to the tangent line to the path at nearest point to C_i. The distance between the individual target and centre C_i can be significantly shorter than the value of constant D_T in the first approach, since the problem of MAVs flying ahead of the target cannot occur (each MAV has its own target).

The advantage of the first approach lies in the lower probability of undesirable splitting the swarm into independent sub-groups, since all MAVs follow the same target, which acts as a global instrument of aggregation. In the second approach, aggregation is achieved only through the force in eq. (2) that attracts each MAV to its neighbours. The most significant disadvantage of the approach with the collective target is the necessity to estimate the centre of gravity of the whole swarm. Exact calculation of the centre of gravity is impossible due to the absence of communication between swarm particles and missing knowledge of the global positions of swarm members. The estimation of the centre of gravity can be only realized using the onboard vision system, i.e. based on mutual positions of neighbours, information on density of swarm members in different directions, etc. The first approach is applied in all numerical experiments presented in this paper, while the second approach is used in real experiments.

In both approaches, each MAV is attracted to the receding target (either global or individual) by a force in direction of the relative position vector $\mathbf{L}_{ig}$ from the i-th MAV to the goal as follows:

$$\mathbf{F}_{goal_i} = K_g \frac{\mathbf{L}_{ig}}{\|\mathbf{L}_{ig}\|} + D_g \frac{\mathrm{d}\mathbf{L}_{ig}}{\mathrm{d}t}. \tag{4}$$

In comparison with eq. (1), where the magnitude of the force varies based on the relative distance to the neighbours, magnitude of this force is normalized to ensure that its effect will be the same for all MAVs independently of their positions within the group. The constants of the spring-damper model, K_g and D_g, determine influence of the target movement on the swarm behaviour[5].

Such approach of path following protects the swarm against dead-lock or undesirable oscillations around local extremes in complex environments with obstacles, which may happen if the swarm is attracted directly into the final desired location. In our case, the problem of avoiding local extremes is solved already on the path planning level. The proposed approach is enough robust for utilization any path planning technique that considers size of the robot (the expected size of the swarm in our case). In addition, the proposed swarm stabilization method allows to follow a path that leads through a narrower corridor than is the actual size of the swarm. In these corridors, the shape of the swarm is autonomously shrunk by the effect of forces from eq. (3) imposed by the obstacles (walls of the corridor). This is beneficial in situations in which a path in sufficient distance to all obstacles does not exist or in which a passage through a narrow corridor is an efficient short-cut. See Fig. 14 for simulation of swarm movement through such narrow corridor.

[5]Values $K_g = 1.1$ and $D_g = 2$ are used in experiments in this paper.

IV. Quadrocopter model and control

The swarm stabilization and control approach presented in the previous section III provides a total virtual force $\mathbf{F}_{swarm_i} = \mathbf{F}_{ind_i} + \mathbf{F}_{goal_i} + \mathbf{F}_{obs_i}$ that should act on the i-th MAV. In this section, a low level controller that enables to realise action of this virtual force and to steer the vehicle accordingly will be described together with description of particular sensors that have to be employed for MAV control.

In the control system, the following dynamical model is used:

$$\begin{aligned}
\ddot{x}^W &= \frac{U}{m}\left(\sin\psi^I \cos\phi^W - \sin\theta^I \sin\phi^W\right), \\
\ddot{y}^W &= \frac{U}{m}\left(\sin\theta^I \cos\phi^W + \sin\psi^I \sin\phi^W\right), \\
\ddot{z}^W &= \frac{U}{m}\cos\theta^I \cos\psi^I - g,
\end{aligned} \tag{5}$$

where $\phi^{\cdot}$ is the *yaw* angle, $\theta^{\cdot}$ is the *pitch* angle, $\psi^{\cdot}$ is the *roll* angle, U is the collective thrust, m is the mass of the MAV and g is the gravitational acceleration. Three frames of reference (Fig. 4) are considered for description of the MAV control mechanism. The world frame (W) that is fixed in the workspace, the body frame (B) that coincides with particular MAV, and the IMU frame (I) in which the *yaw* and *pitch* angles are measured.

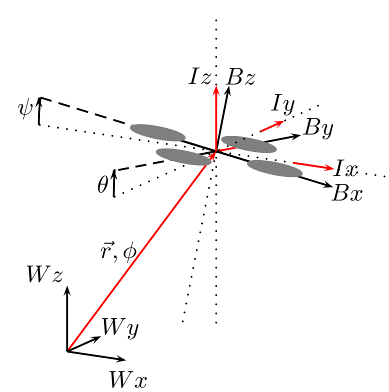

Fig. 4. The reference frames used in description of MAV control scheme. W-world frame; B-body frame; I-IMU frame

In the flocking method presented in section III, air resistance and air-flow affects from propellers neighbouring vehicles are neglected and it is assumed that a force for compensation of gravitation is added together with the force derived for each vehicle in each planning step of flocking.

Therefore, we can simply obtain the desired velocity of MAVs in each sampling interval by applying Newton's second law, based on its current velocity and the actual force $\mathbf{F}_{swarm_i}$.

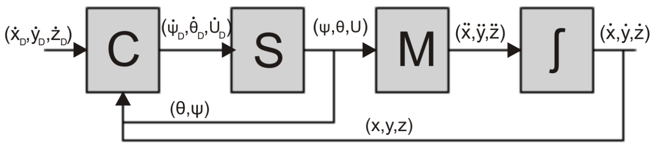

Fig. 5. Velocity controller for realization of outputs from the swarm rules. The system consists of the controller (block C), the stabilization unit (S), and the model (M) from eq. (5).

The velocity controller to achieve the desired velocity of each MAV is shown in Fig. 5, and the overall system for MAV stabilization and control is depicted in Fig. 6. The control scheme is suited for the MikroKopter quadcopter platform with the PX4Flow smart camera sensor[6], which is used for experimental evaluation of the method in this paper. The commercially available MikroKopter set includes a proprietary attitude stabilization board (Flight-CRTL) using an onboard Inertial Measurement Unit (IMU) for control feedback. The velocity controller is built upon this lowest level. The HW solution is based on a custom board with the ATmega μ-controller.

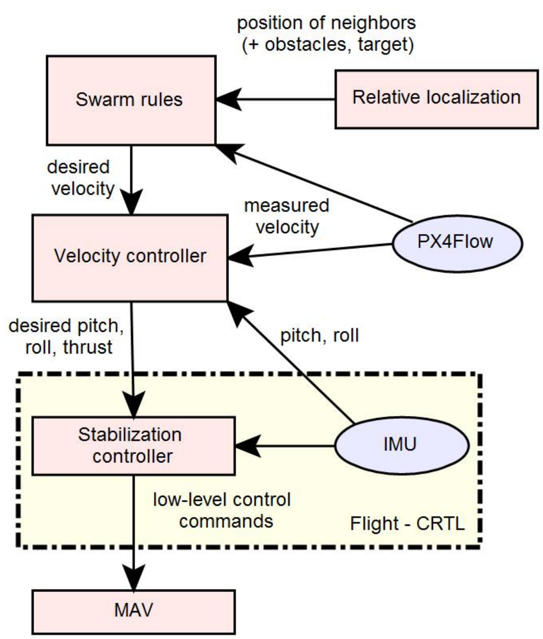

Fig. 6. Scheme of the MAV stabilization and control system and data flow.

In the position controller, data received from the PX4Flow sensor together with the output from IMU, serve as the control feedback as depicted in Fig. 5. The PX4Flow sensor provides information on the altitude z^W and velocity $(\dot{x}^W;\ \dot{y}^W)$ relative to the surrounding environment. The IMU provides angles θ^I and ψ^I. Three PID controllers are integrated together for control of MAV movement in I_x, I_y, and I_z coordinates. Identical controllers are used for control of forward and lateral movement due to the system decoupling. The position controller computes the desired control outputs ϕ^I_D, ψ^I_D, and U^I_D, which are used as the input in the stabilization controller in the Flight-CRTL module.

[6]http://pixhawk.org/modules/px4flow

As described in section III, the proposed flocking approach relies upon local information on proximity of MAV for which the control force is computed. In the presented experiments, the guess of current positions of neighbours in the swarm is given by the system of visual relative localization. The onboard camera modules provide relative coordinates, x^I_n, y^I_n, z^I_n, to the circular pattern attached on the particular neighbour. In addition to this information, which is crucial for swarm stabilization and inter-vehicle avoidance, current velocity $(\dot{x}^W, \dot{y}^W)$ of the MAV is provided by the PX4Flow sensor, which is necessary for realization of the force acting on the MAV.

In the experiments, the relative position of the target is estimated based on a guess of the current MAV position in the environment, which is provided by integration of the velocity from the PX4Flow sensor (odometry), and by the current position of the target. Precision of such an approach is sufficient for experiments with duration in order of minutes. For long-term experiments, another sensor for global localization or for direct detection of the target would be required. For example, precision of GPS is insufficient for the group stabilization and inter-vehicle collision avoidance (required distance between MAVs may be smaller than precision of GPS and also reliability of GPS is insufficient), but for a rough estimation of the position of the group relatively to the target, GPS is sufficient. Finally, an obstacle detection sensor needs to be employed for deployment of the system in workspace with obstacles. Our work is not focussed on obstacle detection and/or map building, and the obstacle avoidance ability of this approach is shown only in simulations.

V. Analyses of swarming behaviour and experimental verification of the method

A. *Analyses of influence of the relative localization constraints on the swarm stabilization*

The aim of the simulations in this section is to verify performance of the swarm stabilization method with different number N of neighbours that have to be stabilized with each MAV by the relative localization. It means that each MAV should always keep at least N MAVs within the range of the relative localization ($fd = 5$ map units) during the experiment. If an MAV has just N neighbours within the range fd and one of these neighbours approaches to the distance fd from the MAV, the attractive force to the particular swarm member is amplified in these simulations.

The initial position of MAVs and obstacles is identical for all simulations (see Fig. 7). The obstacles are represented as vertical columns in the experimental setup, and the MAVs are placed in such a way that the shortest distance between neighbouring particles is $D = 2$ map units (mu).

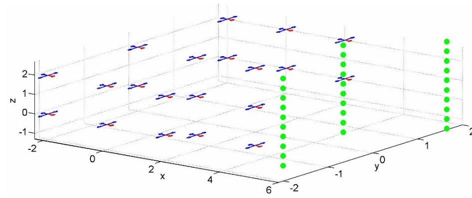

Fig. 7. Initial setup of all experiments presented in this section.

The number of required neighbours N is set to zero in the first simulation (see snapshot in Fig. 8 and the graph of the shortest distances between MAVs in Fig. 9). Therefore, the strong attractive force, which is integrated into the swarming rules for keeping the localization linkage, is never applied in this experiment. During the simulation, several MAVs are separated from the swarm due to repulsive forces from the obstacles (their relative distance to the nearest neighbour exceeds the threshold $fd = 5$ mu).

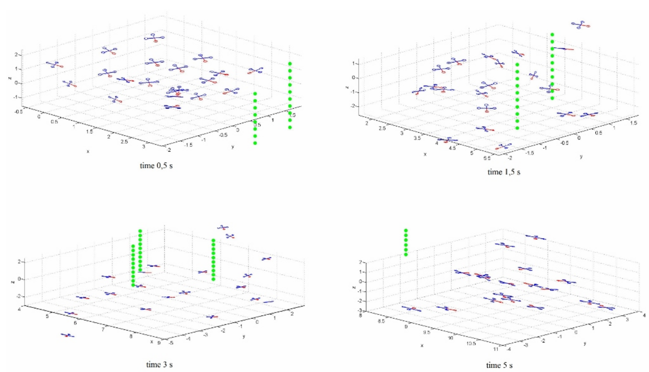

Fig. 8. Snapshots from the simulation with number of neighbours $N = 0$.

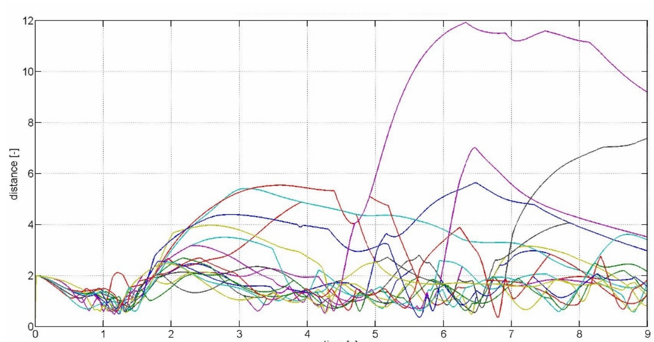

Fig. 9. Relative distances to the nearest neighbour for each MAV of the swarm in the simulation shown in Fig. 8.

The number of neighbours is set as $N = 1$ in the second simulation (see snapshots in Fig. 10 and the graph of the shortest distances to the nearest neighbour for each MAV in Fig. 11). If the nearest neighbour of an MAV approaches to the relative distance $fd = 5$ mu, the attractive force pushes this MAV to the direction of this neighbour, which also helps to keep integrity of the MAV swarm (compare graphs 8 and 10). No MAV becomes more distant from its nearest neighbour than the given threshold 5 mu during the experiment, which ensures required reliability of the visual relative localization.

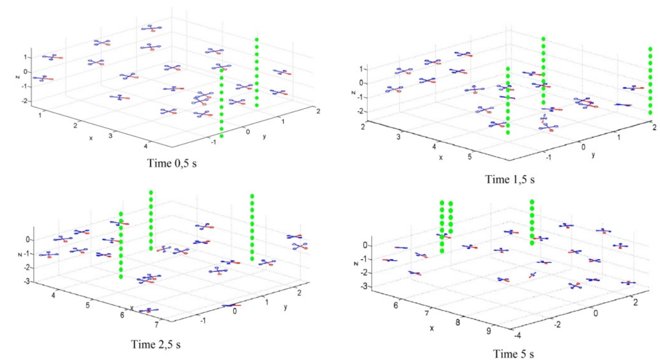

Fig. 10. Snapshots from the simulation with number of neighbours $N = 1$.

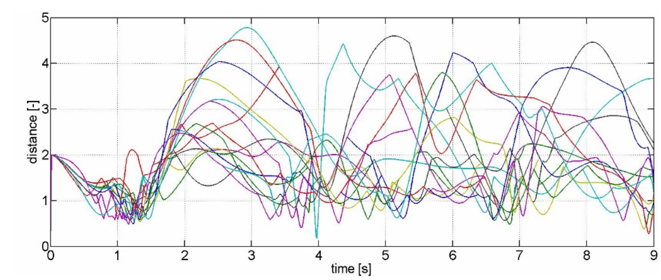

Fig. 11. Relative distances to the nearest neighbour for each MAV of the swarm in the simulation shown in Fig. 10.

In the third simulation, two neighbours are required in the localization distance 5 mu for each MAV ($N = 2$). The graph of the shortest distances to the second nearest neighbour is shown in Fig. 12. The requirement on connectivity with at least two neighbours for each MAV is satisfied during the experiment. Such stronger requirement again increases integrity of the swarm and also robustness of swarm stability. In case of temporary drop-out of the onboard relative localization with one of the neighbours, the MAV can be connected with rest of the team through the second vehicle in its sensory range.

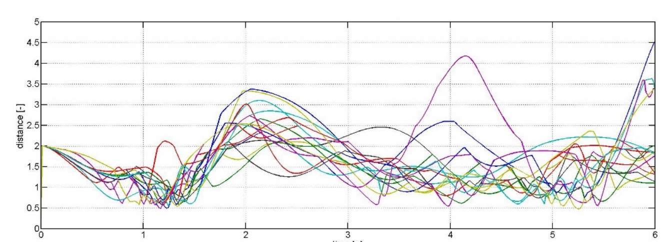

Fig. 12. Relative distances to the second nearest neighbour for each MAV of the swarm in the simulation with number of neighbours $N = 2$.

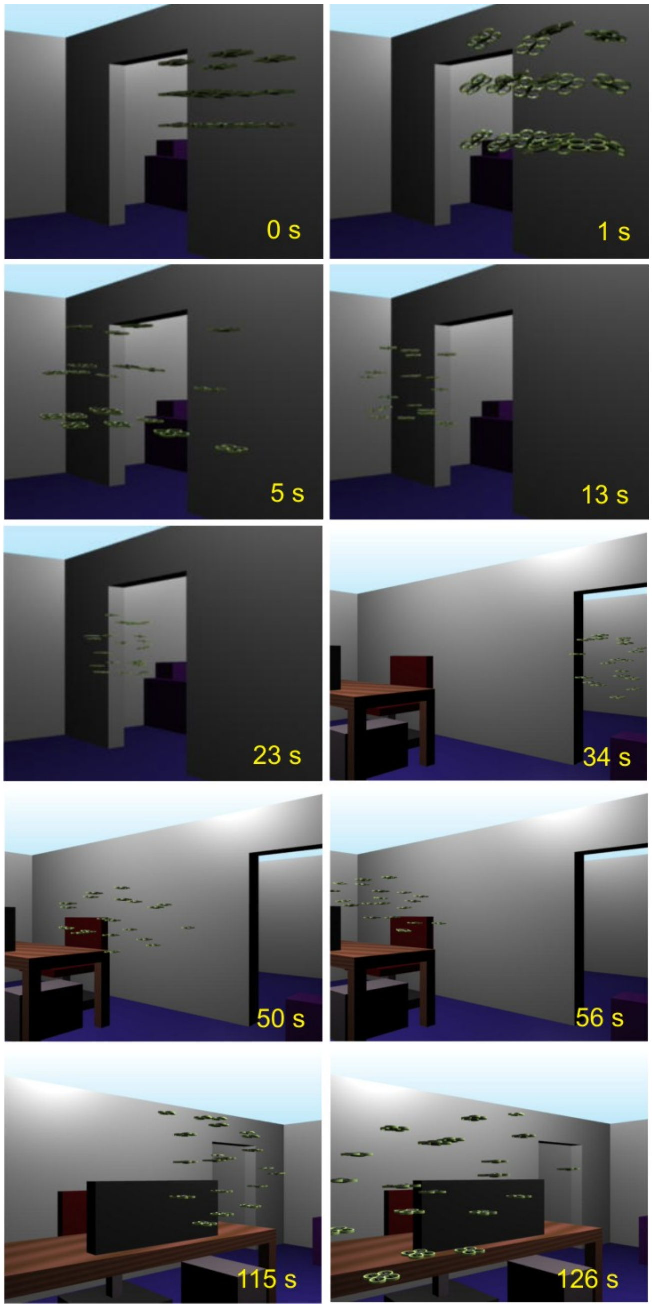

Fig. 13. Snapshots of the swarm movement along obtained 3D Voronoi diagram path in an office environment. Complete movie of the simulation is available on [36].

B. Simulations of swarm movement along predefined paths in complex environments

In the first simulation scenario, a swarm of 20 MAVs follows the shortest path in the 3D Voronoi diagram in an office-like environment (see Fig. 13). In the simulation, the influence of air-flow from the propellers of the neighboring MAVs is not considered (neither in the simulation engine, nor in the swarming rules), and therefore the swarm particles may fly one above the other (this was not allowed in the simulations in previous section, where the MAVs are considered as vertical cylinders in the flocking approach).

At the beginning of the simulation in Fig. 13, the swarm is initialized in a compact formation with relative distances between swarm members that are shorter than the equilibrium achieved after stabilization of the group based on the proposed method (see the first snapshot of the simulation). The simulation shows very fast response of the swarming algorithm. After one second (the second snapshot), all MAVs are in safety relative distances to their neighbours.

The swarm is stabilized (required distances between MAVs in the swarm were achieved) after 5s, as depicted in the third snapshot. The snapshot captured at time 13s shows the swarm passing by a connection of two straight segments of the 3D Voronoi diagram. The movement of the swarm through this sharp corner is fluent since the desired target is moving in a sufficient distance in front of the group (see the video record of the simulation in [36]). In snapshots taken at 23s and 34s, the swarm flies through narrow doors. The obstacles enforce the swarm to autonomously contract its shape while passing through the door. After reaching the second room, the MAV swarm is forced to avoid a table by changing its attitude (snapshots taken at 50s and 56s). Finally at time 115s-126s, the swarm avoids in sufficient safety distance an obstacle located on the table.

In the second experiment in Fig. 14, the ability of swarm stabilization and mutual collision avoidance in narrow corridors are tested and evaluated. It was observed that the positions of the MAVs are changed from spherical to oval shape of the swarm if approaching to the corridor. The new shape is achieved as a new equilibrium of the swarm stabilization problem. The dilatation of the swarm is caused by the insufficient space that is required for the swarm keeping safe mutual distances between MAVs and distances between MAVs and obstacles in spherical shape. The new achieved constellation may be considered as a compromise between the effort to keep MAVs in the desired mutual distances from their neighbours, to keep MAVs in the safe distance to obstacles, and to follow the dynamic target along the path.

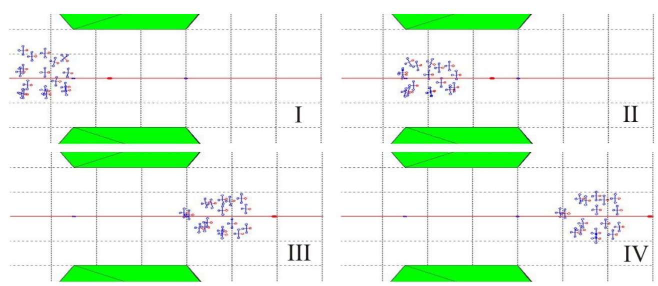

Fig. 14. Snapshots of the swarm movement through a narrow corridor. Complete movie of the simulation is available on [36].

An additional pair of obstacles was added into the map to show the process of following the virtual target (see the simulation in Fig. 15). The swarm follows a straight line segment in the first three snapshots. Once the centre of gravity of the swarm reaches the end of the first segment (snapshot III in Fig. 15), the position of the virtual target is suddenly changed to enable the swarm to follow the second line segment (snapshot IV). Once the third line segment is reached, the position of the virtual target again suddenly drops into the direction of this segment.

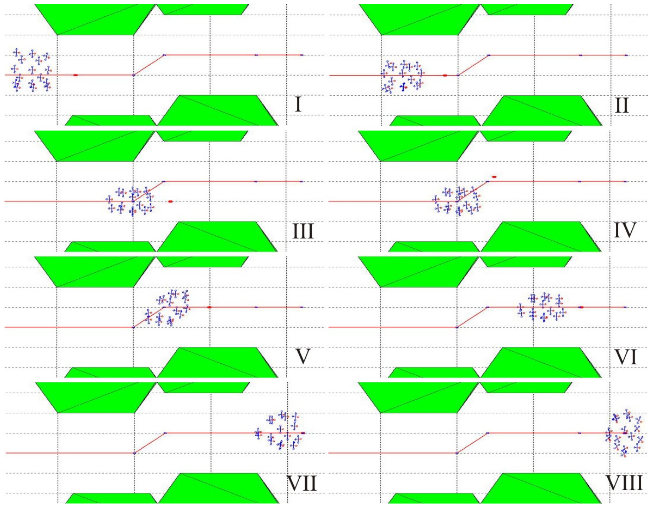

Fig. 15. Simulation of the swarm movement in a narrow corridor along a path composed from three line segments. Complete movie of the simulation is available on [36].

C. *Experiments with quad-rotor MAVs*

The possibility of stabilization of MAV group using the onboard relative localization system has been tested in numerous experiments with quadrotor helicopters in indoor and outdoor environment (see Fig. 16-17 for snapshots and `http://mrs.felk.cvut.cz/research/swarm-robotics` for actual movies of the system).

In experiments, MAVs follow a given path, where the position estimation of the group relatively to the path is obtained by integration of MAV velocity from the PX4Flow sensor. In short-term experiments, position error of this method does not influence performance of the system. Moreover, the error would be reduced by coupling of team members via the mutual localization in large swarms. For long-term experiments, an onboard system providing information on global position of the group in the environment would be necessary (see e.g. [37], [38] for proper methods designed within our team).

In the indoor experiment, the MAV in the middle of the group is stabilized using the data from the PX4Flow sensor, while the outer MAVs are stabilized in a desired relative position to the middle MAV using onboard relative localization in control feedback. Sensor data processing and control commands are all computed onboard of MAVs.

The outdoor experiment is conducted in outdoor environment to show robustness of the system in changing light and windy conditions. Moreover, the grass surface is a challenging environment for the PX4Flow sensor. Due to the grass blowing in the wind, an additional noise is added into the measurement, which increases the position error. In

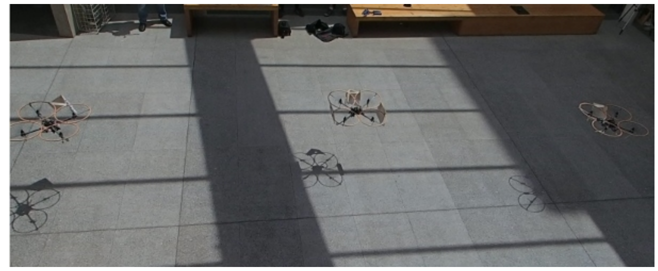

Fig. 16. Experiment with 3 MAVs relatively stabilized using onboard visual localization in indoor environment.

the experiment, MAVs repeatedly follow the path and then return to the initial position. Again, the MAVs strictly rely on onboard sensors, and no communication is required for group stabilization.

Fig. 17. Experiment with 2 MAVs following a preplanned path in outdoor environment. Video record of the experiment is available on [36].

VI. Conclusion

A bio-inspired swarm stabilization approach for control and navigation of large teams of MAVs along a given path was presented in this paper. The method respects restrictions of swarm robotics in terms of missing communication among vehicles, decentralized control rules, anonymity of swarm particles, and onboard sensors that provide information on local proximity of MAVs. The swarm behaviour proposed in this paper is designed for MAV platforms equipped with the onboard visual relative localization of neighbouring team members. This sensor is very similar to sense organs of animals that perform flocking behaviour in nature, and it provides possibility of flying in very compact groups, for which precision and reliability of commonly available localization systems (such as GPG) is insufficient.

VII. Acknowledgements

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