Ad-hoc heterogeneous (MAV-UGV) formations stabilized under a top-view relative localization

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***Abstract*— A stabilization and navigation technique for ad-hoc formations of autonomous ground and aerial robots is investigated in this paper. The algorithm, which enables a composing of heterogeneous teams via consequence splitting and decoupling, is aimed at deployment of micro-scale robots in environments without any precise global localization system. The proposed approach is designed for utilization of an on-board visual navigation and a top-view relative localization of team members. The leader-follower formation driving method is based on a novel avoidance function, in which the entire 3D formation is represented by a convex hull projected along a desired path to be followed by the groups. This representation of the formation shape is crucial to ensure that the direct visibility between the team members in environments with obstacles is kept, which is the key requirement of the top-view relative localization. A Receding Horizon Control (RHC) concept is employed to integrate this avoidance function. The RHC scheme enables fluent splitting and decoupling of formations and responding to dynamic environment and team members' failures. All these abilities are verified in simulations and experiments, which prove the possibility of formation driving based on the visual navigation and top-view relative localization.**

I. Introduction

Micro Aerial Vehicles (MAVs) may provide numerous new possibilities in applications that are strictly addressed to Unmanned Ground Vehicles (UGVs) recently. MAVs can be employed in locations that are hardly reachable by UGVs. They enable measurement and mapping in 3D environment. In reconnaissance and surveillance missions, they provide a top-view, which is important for a global overview of the scene. Besides, the top-view from MAVs could be efficient for a relative localization of team members in multi-robot applications. The aim of this paper is to investigate possibilities of utilization of such a visual top-view localization for stabilization of heterogeneous MAV-UGV formations. This approach may act as an enabling technique for deployment of fleets of micro unmanned vehicles outside laboratories equipped with a global localization system, which is usually used for stabilization of robotic groups in a compact formation.

The work presented in this paper is motivated by a scenario of multi-robot surveillance. In the illustrative mission, an autonomous formation of mobile robots with surveillance cameras has to repeatedly follow a predefined path in a wide phalanx to cover a large operating space. The desired path can be splitted into several branches to inspect smaller areas simultaneously by sub-formations created ad-hoc from the larger group. The heterogeneous MAV-UGV formations then can provide surveillance in large areas by spreading into a wide searching phalanx, where MAVs and UGVs give view from a different perspective and can visit locations of different types. In large areas under surveillance, there usually cannot be pre-installed a precise global localization infrastructure and public available systems (as GPS) lack sufficient precision for stabilization of compact formations. Therefore, we propose the formation driving technique, which is designed for the top-view visual relative localization and for a simple vision based navigation. Both these methods rely only on on-board sensory and computational resources of micro-scale robots. The relative localization uses simple light-weight cameras mounted on all MAVs and identification patterns placed on UGVs and MAVs, where the distance between the vehicles is available due to the known size of the patterns. Details on the visual based relative localization together with description of its precision and reliability is provided in [1]. The navigation approach (referred to as GeNav) uses image features detected by a monocular camera carried by a robot of the formation. It enables to robustly navigate the group along a pre-learnt path consisting of a set of straight segments (a proof of stability of this method, where the necessity of piecewise straight path is shown, can be found in [2]).

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II. State-of-the-art and progress beyond

In up-to-date literature, one can find works aimed at both aspects investigated in this paper, the formation stabilization [3], [4] and the path following by a formation [5], [6], [7]. The mentioned approaches rely on utilization of robots under a precise external global localization system (e.g. VICON system in [4], [6]) or only theoretical solutions verified by simulations are provided [3], [5], [7]. Our work goes beyond these approaches by strict utilization of on-board systems for robots' localization and navigation, which are inherently included in the essence of the formation driving approach. We rely on the Receding Horizon Control (RHC) to be able to involve the requirements of available robust localization and navigation techniques into the formation driving. In particular, constraints imposed by the inter vehicle relations (shape of the formation feasible for the top-view relative localization) and by the GeNav technique employed for the navigation of the entire group along straight line segments of the desired path are included. This paper extends our previous publication [8] with the description and verification of the algorithm that provides the ability of the formations merging and splitting to be able to inspect smaller areas simultaneously.

RHC is usually employed in the formation driving approaches due to its ability to respond to changes in dynamic environment [7], [5], [6]. In [5] and [6] it was shown, that the computational power of microprocessors available on-board of unmanned helicopters enables to employ RHC techniques also for the formation control of such a high dynamic system, similarly as it is proposed here. Again, we go beyond these papers mainly in the aspect of the formation stabilization with included requirements of the top-view relative localization, which could be an enabling technique for deployment of heterogeneous MAVs-UGVs teams outside the laboratories without any global localization. We present a novel dynamic obstacle avoidance function with a simple and effective representation of the 3D formation as a convex hull. Besides, our formation driving method is designed for the purpose of simple yet stable visual navigation [2], which is well suited for the surveillance missions being our target applications. Finally, our method is well suited for creating of ad-hoc formations via merging and splitting under the RHC stabilization.

III. Preliminary notes

The problem of following desired paths by n_F compact UGV-MAV formations of given shapes is tackled in this paper. Let us assume that the environment contains n_0 of compact static (in a known map) or dynamic and unknown (detected by on-board sensors) obstacles. For the global localization of each group, we assume that a robot of the group, called GeNav leader, is equipped with the navigation system based on the features detection. The GeNav system is suited for guidance of robots along a path that consists of set of straight segments. Beside the GeNav leader, each formation consists of MAV followers (quadrotors) and may consist also of UGV followers (robots without any localisation system available on-board). MAVs are equipped with a bottom camera and the system for visual relative localization between the camera and centres of identification patterns carried by all UGVs and MAVs (except MAV flying in the highest altitude).

For the formation driving description, let $\psi_j(t) = \{x_j(t), y_j(t), z_j(t), \varphi_j(t)\}$, where $j \in \{GL, VL, 1, \ldots, n_r\}$, denote configurations of the GeNav leader GL, a virtual leader VL, and n_r followers of each formation at time t. GL is positioned in front of each formation and it is used as a reference point for the coordinate system using the top-view relative localization. VL is initially placed in the same position and orientation as the GeNav leader and it acts as a reference point for the proposed formation driving technique. Using the presented trajectory following approach (Section IV-B), it keeps the same position as GL except the deviation caused by obstacles that could brake the top-view localization or to cause collisions. Besides, VL is crucial for merging of sub-formations into a compact formation, where the relative error in position has to be diminished.

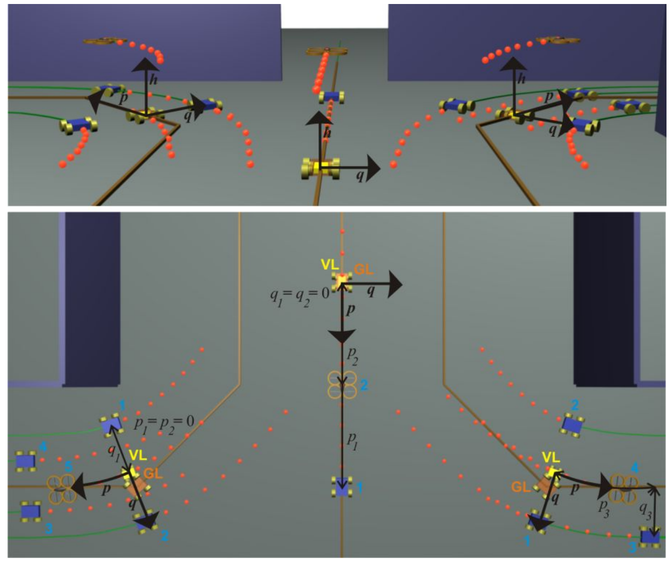

Fig. 1. Curvilinear coordinates of three formations going into the merging point.

The Cartesian coordinates $x_j(t)$, $y_j(t)$ and $z_j(t)$ define positions $\bar{p}_j(t)$ of all robots (leaders and followers) and $\varphi_j(t)$ denotes their heading. Both platforms, MAVs and UGVs, (except the robots assigned as the GeNav leaders) are denoted as followers in this notation. For the MAVs, the heading $\varphi_j(t)$ becomes directly the yaw. Roll together with pitch do not need to be included in the kinematic model employed in RHC, but they depend on the type of utilized MAVs as we have shown for a quadrotor in [9].

The kinematics for any robot j in 3D is described by the simple nonholonomic kinematic model: $\dot{x}_j(t) = v_j(t)\cos\varphi_j(t)$, $\dot{y}_j(t) = v_j(t)\sin\varphi_j(t)$, $\dot{z}_j(t) = w_j$ and $\dot{\varphi}_j(t) = K_j(t)v_j(t)$, where feed-forward velocity $v_j(t)$, curvature $K_j(t)$ and ascent velocity $w_j(t)$ represent control inputs denoted as $\bar{u}_j(t) = \{v_j(t), K_j(t), w_j(t)\}$. We assume that UGVs operate in a flat surface and that $z_j(\cdot) = 0$ and $w_j(\cdot) = 0$ for each of the UGVs. In case of MAVs, $v_j(\cdot)$, $K_j(\cdot)$ and $w_j(\cdot)$ values are inputs for the low level controller, as shown in [9].

Let us now define a time interval $[t_0, t_{end}]$ that consists of a sequence of elements of increasing times $\{t_0, t_1, \ldots, t_{end-1}, t_{end}\}$, such that $t_0 < t_1 < \ldots < t_{end-1} < t_{end}$. We will refer to t_k using its index k in this paper. The inputs of the receding horizon control are held constant over each time interval $[t_k, t_{k+1})$, where $k \in \{0, \ldots, end\}$. We will call the points at which the control inputs change as *transition points* and we will refer to them with index k. Δt will be a sampling time, which is uniform in the whole interval $[t_0, t_{end}]$. The control inputs $v_j(k+1)$, $K_j(k+1)$ and $w_j(k+1)$ are constant between transition points with index k and $k+1$.

We propose to maintain the shape of each heterogeneous formation using the leader-follower technique with the notation visualized in Fig.1. In this method, both types of followers, MAVs and UGVs, follow the trajectory of the virtual leader in distances defined in $\{p, q, h\}$ curvilinear coordinate system. The position of each follower i is uniquely determined by states $\psi_{VL}(t_{p_i})$ in *travelled distance* p_i from the actual position of the virtual leader along the virtual leader's trajectory, by *offset distance* q_i from the trajectory in perpendicular direction and by elevation h_i above the trajectory. t_{p_i} is the time when the virtual leader was at the *travelled distance* p_i behind its actual position.

IV. Description of the formation driving method

A. Overview of the formation driving method

The stabilization of each MAV-UGV formation is realized separately in a decentralized manner, where only the desired paths and shapes for each formation are distributed within the teams by a *coordination unite*. The formation control algorithm is divided into three main blocks (see Fig. 2). The first block, *GL* leader, is responsible for navigation of the entire formation in the environment. It provides control inputs for the GeNav leader based on image features gained by its on-board camera. The GeNav method enables to navigate a robot or a group of robots along a pre-learnt path consisting of straight segments.

Beside the GeNav leader steering, the output of the *GL* module is a prediction of GeNav leader's states. The predicted trajectory consists of n states derived with constant sampling time Δt and it acts as an input of the *VL* block. This part is important for avoidance of obstacles and it enables to follow the GeNav leader in connections of the line segments of the desired path. In the *VL* part, the *Trajectory Following* block provides control inputs for the virtual leader, which respects the requirements of the top-view relative localization through the model of the formation. In the straight segments of the desired path, the trajectory found by the *Trajectory Following* block follows the desired trajectory with a minimal deviation. A significant deviation arises mainly due to appearing obstacles or near to line segment connections. Besides, it is important to diminish the position error in case of the sub-formations merging. Details on the trajectory following mechanism with emphasis on incorporation of the 3D heterogeneous formation stabilized under the top-view localization are presented in Section IV-B.

The trajectory obtained in the *Trajectory Following* block is described by a sequence of configurations of the virtual leader $\psi_{VL}(k)$, where $k \in \{1, \ldots, N\}$, and by constant control inputs applied in between the transition points. According the RHC concept, only a portion of the computed control actions is applied on the interval $\langle t_0, t_0 + n\Delta t\rangle$, known as the receding step. This process is then repeated on the interval $\langle t_0 + n\Delta t, t_0 + N\Delta t + n\Delta t\rangle$ as the finite horizon moves by *time steps* $n\Delta t$, yielding a state feedback control scheme strategy. The unused part of the trajectory can be employed for re-initialization of the planning process in each planning step, since the plan of the formation between two consequent steps is usually changed only slightly. To summarize this, n is number of transition points in the part of the planning horizon, which is realized by robots in each planning step and N is the total number of transition points in the planning horizon.

In the proposed formation driving system, the trajectory obtained in the *Trajectory Following* block is used as an input for the *Formation Driving* module, where the transition points of the trajectory are shifted for each of the follower i by the vector $V(t_{p_i})$. The core of the third main block, which is multiplied for MAVs and UGVs followers, is also the *Trajectory Following* module. This part is responsible for avoiding impending collisions with obstacles or team members and it corrects deviations from the desired trajectory provided by the virtual leader.

The physical communication via WiFi is required only between the *GL* leader and particular followers. It is assumed that the *GL* and *VL* modules as well as the *Coordination Unite* are realized on the same vehicle. Also the data from the relative localisation processes are stored there. Therefore, the communication between the *GL* leader and followers is limited to sending the desired trajectory and actual data from the visual relative localization.

Finally, let us remark that the trajectories of *VL* leader and followers are given in the local frame of the *GL* leader, since all members of the formation know its relative position provided by the top-view localization.

The ability of the system to ensure 3D formation stabilization under the top-view visual relative localization in environments with dynamic obstacles requires to integrate an obstacle avoidance function into the trajectory following methods (introduced in the previous subsection). The proposed avoidance function is based on a representation of the entire formation, which incorporates the requirement on the direct visibility between the robots into the formation stabilization process.

In the method, the 3D formation is represented by a convex hull of positions of followers projected into a plane $\mathcal{P}_{VL}$, which is orthogonal to the trajectory of the virtual leader in its actual position. The convex hull of the set of projected points is an appropriate representation of the 3D formation under the top-view relative localization by two reasons: 1) Each follower i intersects the plane $\mathcal{P}_{VL}$ at the projected point in future. 2) The convex hull of such a set of points denotes borders of the area, which should stay obstacle free. This ensures that the direct visibility between MAVs and UGVs, which is crucial for the presented top-view visual localization, is satisfied.

Moreover for the obstacle avoidance function presented in Section IV-B, the convex hull needs to be dilated by a detection boundary radius r_s to keep obstacles in a desired distance from followers. Only obstacles that are closer to the convex hull than r_s are considered in the avoidance function. In the trajectory following process applied for the followers' control, the dilated convex hull is reduced to a circle with radius equal to r_s to represent a single robot.

B. RHC trajectory following

The aim of the formation stabilization mechanism with the obstacle avoidance function is to find a control sequence that

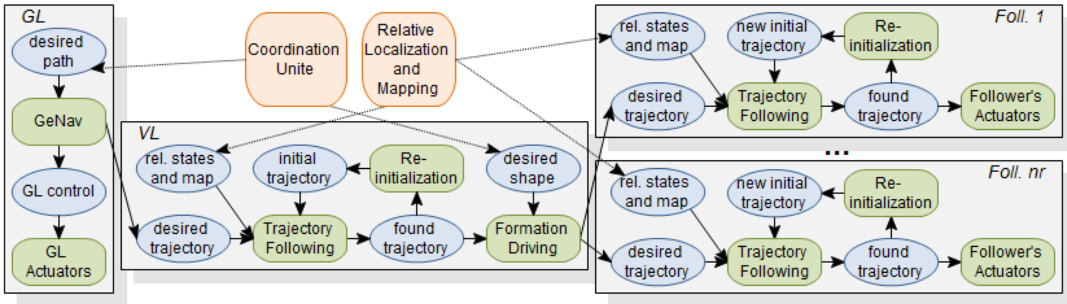

Fig. 2. Relation between modules of the formation stabilization system.

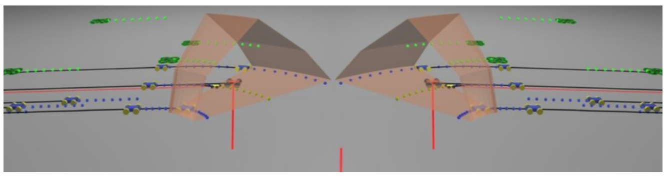

Fig. 3. The dilated convex hull projected along the planned trajectory of virtual leaders leading formations into a merging point.

steers the virtual leader along the desired path followed by the GeNav leader and consequently to find control sequences that stabilize the followers behind the virtual leader in desired relative positions. The intention of the method is to keep the virtual leader as close as possible to the GeNav leader and followers as close as possible to their desired position behind the virtual leader, while the requirements given by the non-collision formation driving and the top-view relative localization are satisfied.

To define the trajectory planning problem in a compact form, we need to gather states $\psi_j(k)$, where $k \in \{1, \dots, N\}$ and $j \in \{VL, 1, \dots, n_r\}$, into vectors $\Psi_j \in \mathbb{R}^{4N}$ and the control inputs $\bar{u}_j(k)$ into vectors $\mathcal{U}_j \in \mathbb{R}^{3N}$ for each of the formation. All variables describing the trajectory of the virtual leader or a follower can be collected in a single optimization vector: $\Omega_j = [\Psi_j, \mathcal{U}_j] \in \mathbb{R}^{7N}$. Then, the trajectory planning can be transformed to minimization of a cost function $J_j(\Omega_j)$, $j \in \{VL, 1, \dots, n_r\}$, subject to sets of equality constraints $h_j(k) = 0$, $\forall k \in \{0, \dots, N-1\}$, and inequality constraints $g_j(k) \leq 0$, $\forall k \in \{1, \dots, N\}$. The cost function consists of three parts as described in details in [8].

Solutions with states deviated from the desired states $\bar{p}_{d,j}(k)$, where $k \in \{1, \dots, N\}$, are penalised in the first part. The desired states are obtained by the prediction of the movement of the GeNav leader in the virtual leader's trajectory tracking. In the followers' trajectory planning, the desired states are derived from the result of the virtual leader's trajectory tracking using the formation driving concept for each of the followers.

The second term of $J_j(\Omega_j)$ contributes to the final cost when an obstacle is inside the projection of the dilated convex hull along the planned trajectory. The convex hull represents the entire formation in case of the virtual leader's trajectory planning or a single robot in case of the followers' trajectory planning. Examples of the projected convex hull are shown in Fig. 3. The value of the second term of $J_j(\Omega_j)$ will be increasing as the obstacle is approaching to the centre of the convex hull.

The third part of the cost function $J_j(\Omega_j)$ is crucial for the failure tolerance of the system. This term is a sum of avoidance functions in which the other members of the team are considered also as dynamic obstacles if they are leaving their desired position within the formation.

The equality constraints $h(k)$ represent the discretized kinematic model for all $k \in \{0, \dots, N-1\}$, which ensures that the obtained trajectory stays feasible for the utilized robots. The sets of inequality constraints $g(k)$ characterize bounds on control inputs $\bar{u}_j(k)$ for all $k \in \{1, \dots, N\}$. The control inputs are limited by vehicle mechanical capabilities (i.e., chassis and engine) as $v_{min,i} \leq v_i(k) \leq v_{max,i}$, $|K_i(k)| \leq K_{max,i}$ for all followers. For MAVs also constraints $w_{min,j} \leq w_j(k) \leq w_{max,j}$ have to be satisfied. These limits are extended for the virtual leader planning, since the trajectory of the virtual leader must be feasible for all followers in their desired positions. For the virtual leader, the admissible control set can be determined using the leader-follower approach as $\max_{i=1,\dots,n_r} \left(\frac{-K_{max,i}}{1-q_i K_{max,i}} \right) \leq K_{VL}(k) \leq \min_{i=1,\dots,n_r} \left(\frac{K_{max,i}}{1+q_i K_{max,i}} \right)$ and $\max_{i=1,\dots,n_r} \left(\frac{v_{min,i}}{1+q_i K_L(t)} \right) \leq v_{VL}(k) \leq \min_{i=1,\dots,n_r} \left(\frac{v_{max,i}}{1+q_i K_L(t)} \right)$. These restrictions must be applied to respect different values of curvature and speed of robots in different positions within the guided formation. Intuitively, e.g. the robot following the inner track during a turning movement goes slower but with a bigger curvature than the robot further from the center of the turning.

C. Splitting and merging

The formation splitting and merging process is realized fully autonomously using the RHC stabilization method presented in this paper. Firstly, let us analyse in which place before the crossroad of desired paths to split the formation. Two opposite requirements have to be satisfied. 1) The point of splitting needs to be postponed to as late as possible, since the robots connected to a single team better avoid collisions within the formation and with obstacles. Then, the coordination of robots may be ensured by the proposed formation driving approach. 2) The formation have to be splitted under the control of independent virtual leaders once the planning horizon reaches the crossroad. From this point, the planning horizons have to follow different directions of the desired roads. Therefore, the splitting point is placed in distance l_{spl} ahead of the center of the crossroad. l_{spl} is an upper bound of the length of the planning horizon: $l_{spl} = N\Delta t \max_{\tau\in\langle t;t+N\Delta t\rangle}(v_{max,L}(\tau))$. In the switching process, the virtual leader agent leading the old formation is killed and new virtual leaders for each arising formations are created. Dedicated robots (former followers) equipped as GeNav leaders switch on the GeNav navigation algorithm and the old GeNav leader becomes a follower if it is not employed to lead one of the new formations.

The place of the formation merging is also restricted by two antagonistic requirements: 1) again the sub-groups should be merged as soon as possible to enable the cooperative movement and 2) the virtual leaders of sub-formations have to follow parallel desired paths. Therefore, the formations are merged if the positions of virtual leaders of all formations are behind the crossroad of their desired paths. The merging process is begun once all the sub-formations are waiting in the merging position. Reversely to the splitting, the redundant GeNav leaders become followers, the old virtual leaders processes are killed and a new virtual leader is created for leading the arising formation. The formations are linked through the visual relative localization, which means that the coordinate systems of the separate groups are unified via new links between MAV cameras and identification patterns on an MAV or UGV robot. Possible deviations in positions of particular groups that are caused by positioning error of the visual navigation are compensated in the next few steps of the periodical RHC replanning.

V. VERIFICATION EXPERIMENTS

Results presented in this section have been obtained using the proposed algorithm with parameters: $n = 2$, $N = 8$ and $\Delta t = 0.25s$. We have employed the Sequential Quadratic Programming (SQP) method [10] for solving the optimization problems used in the virtual leader trajectory tracking and for the stabilization and obstacle avoidance of followers. This solver provided the best performance from the tested available algorithms. Nevertheless, one can use any optimization method, which is capable to solve such an optimization problem.

The performance of the proposed approach in a complex mission with static and dynamic obstacles is shown in the video available on-line at [11] and reported in [8]. In the experiment, the formation driving technique is employed in a scenario with a heterogeneous team of 4 MAV followers and 8 UGV followers led by 1 UGV GeNav leader and 1 virtual leader. The formation is periodically moving through three rooms connected by a corridor. Three MAVs are positioned in a lower altitude to be able to relatively localize the ground robots and the fourth MAV is flying above to provide relative positions of the lower MAVs. The objective of the mission is to follow a given path and to keep a desired shape of the

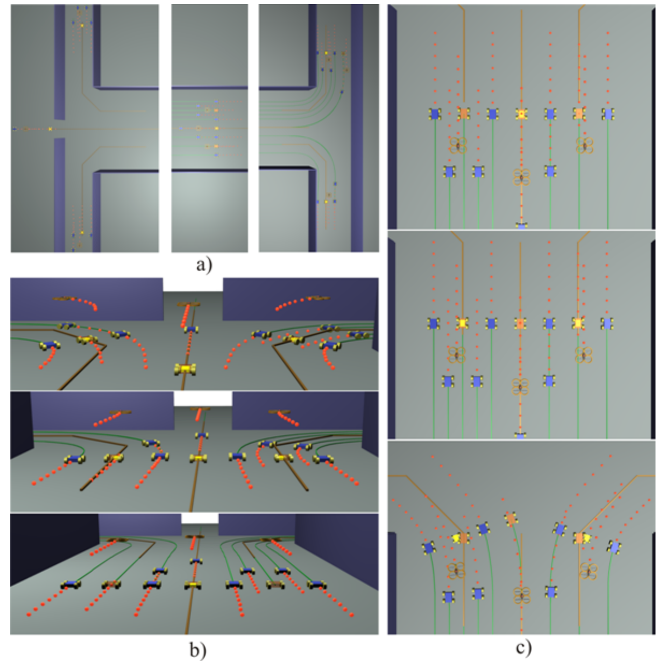

Fig. 4. Formation splitting and merging. a) Overview of the scene with depicted 3 single, 1 merged and 2 splitted formations. b) The merging process. c) The splitting process.

formation (the shape can be autonomously changed only due to an obstacle avoidance).

During the experiment, performance of the formation driving resulting from the presented concept is shown. The formation is temporarily shrunk to pass a narrow passage. Then, it is avoiding overhead obstacles that are sufficiently high to be passed under by all robots except the MAV flying in the highest altitude. The GeNav leader can be navigated without any influence of the obstacle, but the rest of the formation has to move away from the desired path to keep the constraints given by the relative localization, which results in the deviation of the virtual leader from position of the GeNav leader. This enables to avoid the obstacle in a way that the obstacle is always situated outside the dilated convex hull of the formation. Besides, the turning in connections of path segments of the desired path is demonstrated. The virtual leader and the followers are always waiting for the GeNav leader, which is turning on the spot. The formation is deviated from the path to be able to smoothly continue without any complicated manoeuvring. A failure tolerance (steering of a follower is blocked) of the system is presented with highlighted responses of other robots to predictions of possible collisions. Finally, manoeuvres for avoiding unknown and dynamic obstacles are presented. The first obstacle is avoided using the virtual leader's obstacle avoidance function at the price of temporarily leaving the desired path. The second dynamic obstacle cannot be avoided by the virtual leader's re-planning, since it was detected too late by followers. Therefore, the shape of the formation has to be temporarily changed (by the follower's re-planning) to keep the obstacle outside the dilated convex hull.

In the second simulation, the ability of the formation merging from smaller separate teams (Fig. 4 b)) and the consequence splitting back into independent units (Fig. 4 c)) is shown. In the first snapshot in Fig. 4 b), the smaller formation consisting of GeNav leader and 2 followers (MAV and UGV) is waiting in the merging point for the two formations. The first one consists of the GeNav leader, 1 MAV follower and 3 UGV followers. The second one consists of GeNav leader, 1 MAV follower and 3 UGV followers. Once the merging point is reached, the three virtual leaders leading the separate formations are switched off and a new virtual agent is created in the position of the middle robot equipped as the GeNav leader. The two remaining GeNav leaders in the former outer formations become followers and the whole group continues led by one shared GeNav leader and one virtual leader into the splitting point at the end of the wide corridor. In this point, the formation is divided into two new sub-formations, each led by own virtual and GeNav leaders. The GeNav leader employed for navigation of the large formation becomes a follower.

The ability of the obstacle avoidance by temporary shrinking of the formation is shown also in the hardware experiment in Fig. 5. The Cameleon robot from ECA company has been employed as the leader of the formation carrying the localization tags for the system of visual relative localisation on-board of MAVs. Two MikroKopter quad-rotors have been used to the formation stabilization and the UGV following. In Fig. 5 beside the pictures from the experiment, one can see visualisation of plans of the robots found by the presented approach. An experiment of the formation movement in connections of path segments can be found in the report in [8] and in video record of the experiment in [11]. In the experiment, the Pioneer 3-AT robotic platform is employed as the GeNav leader and two MMP5 platforms and the Ar.Drone MAV act as followers. To be able to follow the proposed approach, the MAV is equipped with a bottom monocular camera and with a vision system [12] being able to identify location and size of color dresses of UGVs in the image. This information is used for the relative localization of all members of the formation. Beside the pictures of the formation movement, images used for the GeNav visual navigation and for the top-view relative localization are shown in [8].

VI. Conclusion

A novel approach for stabilization and navigation of 3D UGV-MAV formations with splitting and merging abilities was presented in this paper. The proposed formation driving approach is based on visual navigation and relative localization techniques using simple on-board sensors. The method aims to enable utilization of teams of closely cooperating micro-scale robots in environment without any pre-installed global localization system.

VII. Acknowledgements

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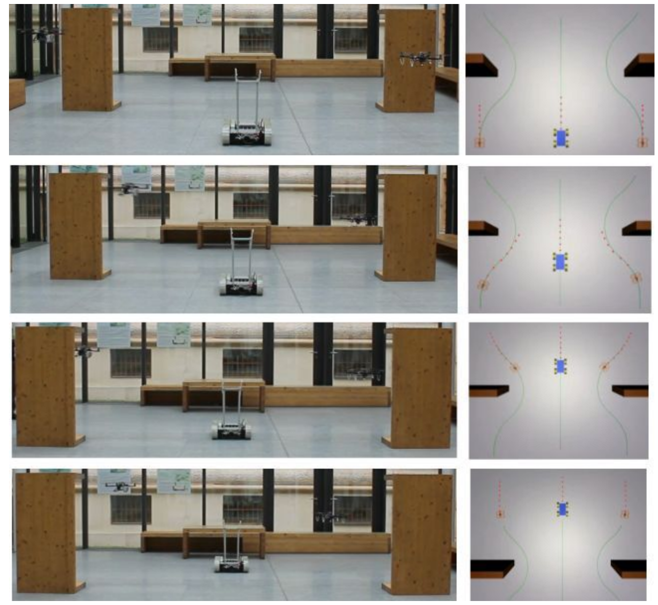

Fig. 5. Formation stabilization based on the visual relative localization.

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