Towards Visually Stabilized Swarms of Micro Aerial Vehicles

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***Abstract*— In this paper, an on-board system for relative visual localization of MAVs in large swarms of compact shapes is proposed. The proposed system is based on an image processing algorithm for circular black and white pattern detection. Our goal is to develop a robotic swarm platform completely independent on the surrounding environment that would be suitable for cluttered GPS-denied environments (both indoor and outdoor).**

We present an extension of the system in the sense of enlargement of its operational space by using multiple coupled cameras and possibility of easy and fast adaptation of their configuration to enable emulation of sensing capabilities of different species in nature. These improvements make it possible to detect and track multiple neighboring MAVs independently on the relative pose angle and to study swarming principles observed in nature by changing the sensing properties of individuals.

I. INTRODUCTION

Artificial swarms intend to imitate the swarm behaviors observed in nature in order to create a flexible self-organising and adaptive robotic system. There is no central control system and so the behavior of the swarm as a whole emerges from the behavior of the individuals. For example the Reynolds BOID model could be considered as a basic swarming behavior. The individuals in the swarm are usually identical and so easily replaceable in case of malfunction. This also makes the swarm very scalable.

The applications of such an artificial swarm can be collective environment exploration and monitoring, inspection in hardly accessible areas, dynamic target localization and tracking, 3D modeling, and surveillance (see our previous works [1], [2], [3] solving these tasks).

Most of these applications require to deploy a swarm in an environment with no pre-installed infrastructure for precise localization of robots. Although GPS is nowadays widely used for rough localization of MAVs in outdoor environment, its precision is insufficient for close cooperation of multiple MAVs in a swarm. Furthermore, it is not possible to use GPS localization in indoor environments.

For the deployment of a swarm of closely cooperating MAVs there is a need for a system providing precise relative localization of neighbours in the group. In this paper, we propose an on-board system for visual relative localization of MAVs in large swarms of compact shapes. Our goal is to develop a robotic swarm platform completely independent on the surrounding environment that would be suitable for cluttered GPS-denied environments (both indoor and outdoor). The sensing and control system relies purely on the on-board sensors and CPU power.

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II. RELATIVE LOCALIZATION SYSTEM

The MAVs working in close cooperation need to be able to detect neighboring individuals and to determine their precise relative location in order to perform coordinated tasks just as natural swarms (e.g. when escaping from a predator). This information enables the individuals to stay close to each other in a compact swarm as well as to avoid mutual collisions.

The proposed vision-based relative localization system is based on an image processing algorithm for circular black and white pattern detection (which was presented by our team in [4] and later extended for global localization in 3D in [5]). This method is robust with regards to changing light conditions and it can track objects with millimeter precision. It has been successfully used for verification of numerous works dealing with multi-MAV systems [6], [7], [8], [9], [10], [11], [12].

In this paper, we present an extension of the system from [13] in the sense of enlargement of its operational space by using multiple coupled cameras and possibility of easy and fast adaptation of their configuration to enable emulation of sensing capabilities of different species in nature. These improvements make it possible to detect and track multiple neighboring MAVs independently on the relative pose angle and to study swarming principles observed in nature by changing the sensing properties of individuals. The system will enable experiments, which cannot be conducted by biologist in nature, since it is impossible to gradually change sense organs of all animals in the swarm.

Fig. 1. Two mutually stabilized MAVs based on relative visual localization.

III. PATTERN RECOGNITION

The pattern recognition algorithm employed in the proposed system uses a circular segment detector. The detection procedure is based on on-demand thresholding and flood fill techniques to meet low computational requirements.

The pattern detection starts by searching for a black segment. If such a segment is detected the search for an inner white disc segment is initiated at the expected pattern center. After the pattern is detected, its image coordinates and dimensions are identified. Then, the image coordinates and dimensions are used to determine the 3D position coordinates with respect to the camera by the camera re-projection techniques.

IV. SENSOR MODULE

The HW realization of the sensor module (Fig. 2) consists of 4 Mobius cameras with 110-degree angle of view resulting onto overall 360-degree angle of view and a CPU board Jetson TK1 for image processing. The module can communicate with other systems (e.g. MAV motion controller) over Ethernet or UART.

The resolution of processed frames is 4x 640x480 and the frame rate of cameras is 30 FPS. The processing is synchronized by the SW so that the frames from all 4 cameras are processed simultaneously at each cycle. Furthermore, the system is designed in a way that it is able to cope with camera connection/disconection at runtime (e.g. camera fail and replacement). Each camera is uniquely identified by the port it is connected to and has its own configuration.

The pattern recognition SW detects circular markers (hereinafter called "blob") of predefined inner and outer diameters in the image. And so it is able to determine the 3 coordinates of the position of the blob relative to the camera. Once the blob is detected by a camera of the system, its coordinates relative to this individual camera (referred to as camera coordinate system) must be transformed to a common coordinate system (referred to as module coordinate system). The module coordinate system may be chosen arbitrarily, but for simplicity we choose the module coordinate system the same as the coordinate system of the front camera.

V. AUTONOMOUS CALIBRATION

In order to determine the proper transformation between the camera coordinate system and the module coordinate system, we use the fact that the fields of views of the individual cameras overlap. When the blob is moved around the module in such a way that it's trajectory is partly going through the overlapped area between each couple of neighboring cameras, it is possible to autonomously compute the transformations based on the measured data from the overlapped areas.

At first, we select the module coordinate system relatively to the coordinate system of one of the cameras such that

$$X_M = R_{C1\to M} \cdot X_{C1} + O_{C1\to M}, \tag{1}$$

where X_M and X_{C1} are the coordinates of the blob in the module coordinate system and in the camera coordinate system respectively and $(R_{C1\to M}, O_{C1\to M})$ is the transformation (rotation and offset) from the camera coordinate system to the module coordinate system.

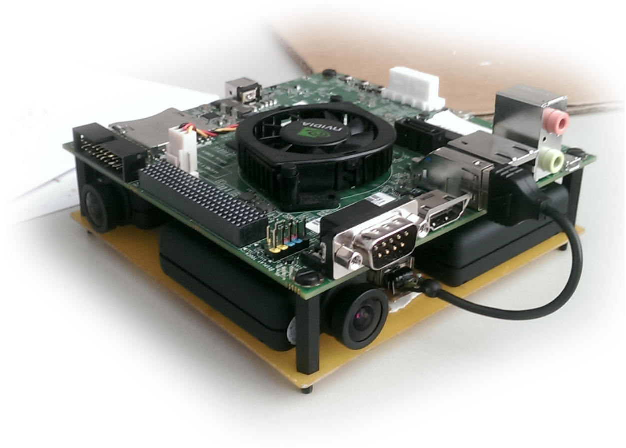

Fig. 2. The relative visual localization sensor module.

From the data measured in the overlapped area between two neighboring cameras (let's say camera coordinate systems $C1$ and $C2$), we are able to obtain the transformation $(R_{C2\to C1}, O_{C2\to C1})$ by using the least square method to match the path of the blob in coordinate system $C2$ with the path in $C1$.

Then, it is possible to compute the transformation $(R_{C2\to M}, O_{C2\to M})$ as

$$\begin{aligned} X_M &= R_{C1\to M}(R_{C2\to C1} \cdot X_{C2} + O_{C2\to C1}) + O_{C1\to M} \\ &= R_{C2\to M} \cdot X_{C2} + O_{C2\to M}. \end{aligned} \tag{2}$$

Similarly we are able to obtain the transformation from all camera coordinate systems.

This calibration procedure allows us to change the configuration of the cameras in a semi-autonomous or even fully-autonomous fashion, if the system would be equipped by servos for cameras rotation. After a new setting of cameras is achieved (manually or by the servos), the system can be re-calibrated by moving the pattern around the sensory device, which can be realized by a 360-degree rotation of the MAV carrying the sensor in front of a pattern mounted on a neighbour. The calibration procedure is enough robust even to changing relative position between the turning MAV and its neighbour, which can be caused by flight oscillations.

VI. MARKER CLUSTERING

In order to utilize the full 360-degree angle of view of the sensor module, we also need swarm individual markers visible from any direction. For this purpose we use markers consisting of 3 planar blob markers (Fig. 3) as we presume the swarm individuals to fly roughly in the same altitude plane.

However this leads to the fact that the sensor module may detect 2 patterns belonging to one MAV. Also the overlapping of camera fields of view leads to the side effect that the patterns are detected twice in the overlapping areas. To suppress this undesired behavior an output filter is implemented in the sensor module which groups the detected patterns into target clusters of certain diameter. One target cluster is expected to correlate to one MAV as the MAVs physically need to have certain keep-out distances. The sensor module then passes only coordinates of the target clusters (average of the coordinates of the patterns in the cluster) to the superior system (in our case the MAV motion controller).

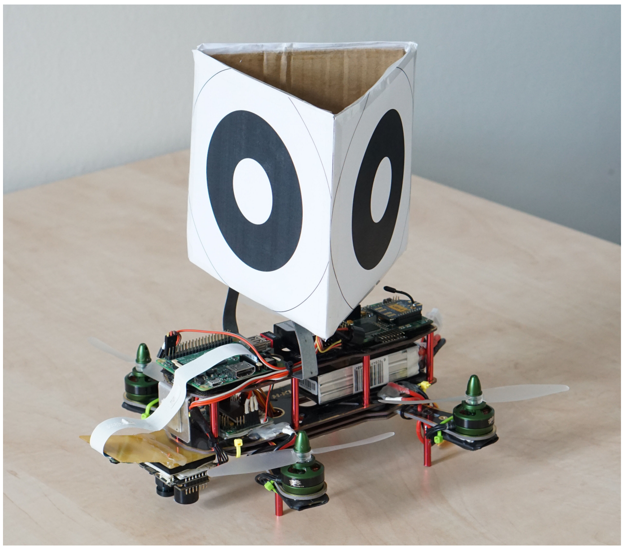

Fig. 3. A swarm individual with omni-directional localization marker attached.

VII. RESULTS

An example demonstrating the process of transformation during the autonomous calibration can be seen in Fig. 4, which shows the trajectory of a blob marker observed from two different cameras. The autonomous calibration script computes transformation of the trajectory of the object (blob marker) observed by the second camera to match the coordinate system of the first camera. The standard deviation between the trajectory observed from the first camera and the transformed trajectory from the second camera is 0.015 m.

Example of a result of autonomous calibration with 3 cameras rotated by 90-degrees is shown in Fig 5 where the blob marker was subsequently detected by individual cameras as it was moved around the sensor module. The autocalibration had been performed based on the overlapping segments displayed in the figure.

The maximal distances of pattern detection reached with the proposed camera module are listed in Table I. From comparison with Table V from [4], it can be seen that the localization system with the Mobius cameras provides the ability to detect smaller patterns in the same maximal distance than the previous system with Caspa cameras connected into Gumstix Overo processor.

TABLE I
MAXIMAL MEASURABLE DISTANCE

Camera Resolution	Pattern Size	Maximal Distance
640 x 680	140/84 mm	6.96 m
640 x 680	55/23 mm	2.54 m

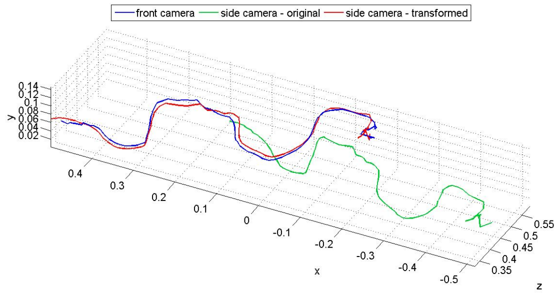

Fig. 4. Autonomous coordinate system transformation.

VIII. CONCLUSIONS

In our previous work, the relative visual localization system has been used with a single cameras with limited field of view which resulted into fairly limiting constrains for the relative pose of the individuals in the swarm. The sensor module proposed in this paper does not have this limitation and enables to implement free-form swarm behaviors in real-work conditions. Moreover, the system enables to emulate sensing capabilities of different species that perform swarming behavior in nature and even change these capabilities (possibly in-flight) and so study influence of their perception on the swarming behavior and swarm stability, which cannot be achieved by experiments with living creatures.

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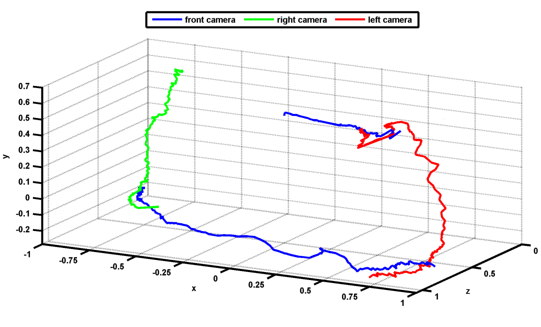

Fig. 5. Blob marker detection by 3 autocalibrated cameras.

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