IMU- and GNSS-Assisted Single-User Control of a MAV-Swarm for Multiple Perspective Observation of Outdoor Activities

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KEYWORDS

autonomous micro aerial vehicle, swarm orientation, observation of outdoor activities, degrees of freedom, human-multirobot interaction

ABSTRACT

In this paper we present our approach to enable a single user to control a swarm of multiple unmanned micro aerial vehicles (MAVs) without significant cognitive effort. Since even moderately sized swarms exhibit several dozens of degrees of freedom, most of the control effort has to be off-loaded from the human to an autonomous swarm controller unit.

The set of MAVs equipped with an on-board camera allows the simultaneous observation of a target from multiple perspectives. Since the MAVs can hover at a position but are also very agile, the perspective on the target can be maintained for fixed or mobile targets. A typical application is documentation or analysis of sportive outdoor activities, such as biking, skiing or climbing.

We describe how the swarm controller unit determines and maintains the formation that satisfies all the perspectives specified by the user by using position and attitude information obtained from onboard inertial measurement units (IMUs) and GPS-receivers placed on the MAVs and the target. A device carried by the observed person acts as user interface and provides the target position using its built-in GPS sensor.

The formation of the swarm can be defined with respect to different reference orientations. We describe three such reference orientations: geographic orientation, device orientation and device movement.

We have validated our concept by carrying out two outdoor experiments. The first experiment included a single quadrotor, whose flight parameters were changed by user input during the experiment ("changing perspective"). In the second experiments the observed person additionally walked along a certain path, and a formation of four quadrotors was following and observing the person, ("changing perspective and moving user").

INTRODUCTION

A substantial body of work addresses swarms of autonomous platforms as instances of multi-agent systems that cooperatively perform tasks, such as sensing various aspects of an extended environment. Many approaches exist that strive to derive control strategies for completely autonomous operation of such swarms.

Schwager et al. describe a decentralized control strategy for positioning and orienting multiple robotic cameras to collectively monitor an environment in [1]. A behavior-based decentralized control strategy for unmanned aerial vehicle (UAV) swarming by using artificial potential functions and sliding mode control technique has been proposed by Han et al. in [2]. Lotspeich investigated the use of an adaptive swarming algorithm that utilizes local state information to influence the overall behavior of each individual agent in the swarm based upon the agent's current position in [3]. Autonomous pattern formation and reconfigurability aspects in the distributed control of a swarm of unmanned aerial vehicles have been investigated by Bennet et al. in [4].

While we are utilizing a swarm of autonomous platforms, to achieve the benefits of the parallelized operation of multiple sensors, we are not striving for autonomy in determining the formation of the swarm in the work presented here. Instead, we are aiming at enabling a human operator to control a swarm that usually would exhibit too many degrees of freedom for manual control by a single user.

In this paper we present our approach to enable a single user to control a swarm of unmanned micro aerial vehicles (MAVs). These platforms are realized as so called quadrotors. Each individual quadrotor can be operated in an autonomous mode, i.e. controlled by an onboard computer, or in a semi-autonomous mode, controlled partially by a human operator. If each MAV is equipped with an on-board camera, the multitude of MAVs in the swarm allows the simultaneous observation of a target from multiple perspectives.

Since the quadrotors can hover but are also very maneuverable when moving, the perspective on the target can be maintained for fixed or mobile targets. A typical application is documentation or analysis of sportive outdoor activities, such as biking, skiing or climbing. The availability of multiple perspectives over an extended range of the athlete's movement would allow the recording of sports videos and unprecedented biomechanical observations of an athlete to analyze and improve the sequence of movements.

Since even moderately sized swarms exhibit several dozens of degrees of freedom, most of the control effort has to be off-loaded from the human to a swarm controller unit. This controller has to determine and maintain the formation that satisfies all the perspectives specified by the user. To achieve this goal, our controller uses position and attitude information obtained from onboard inertial measurement units (IMUs), magnetometers and GNSS-receivers placed on the MAVs and the target.

The operator's task is reduced to that of defining the desired perspectives for each camera and thereby implicitly each MAV, by setting the distance to the target's position and the azimuth angle with respect to a reference angle. Based on the position information and the perspectives defined by the operator, the controller unit is able to determine and control the position and attitude of each quadrotor.

In our experimental setup the user interface is implemented on a small handheld device (an Android Smartphone), which also provides the target position using its built-in GPS receiver. Since the desired position of every MAV is also a function of the target position and potentially attitude, the desired positions are recomputed every time the target changes its position or the intended perspective is modified. If the desired position or attitude of a MAV changes, the coordinates and yaw are transmitted to the MAV, which then transitions autonomously to the new position and yaw.

Figure 1 Hummingbird AutoPilot with video link and camera

The autonomous platforms we employed in our experiments are quadrotors (in our case of the type "Hummingbird AutoPilot" built by Ascending Technologies [7] (see Figure 1)), which belong to the category of micro aerial vehicles (MAV), which in general range from large insect size to medium bird size. The Hummingbird is equipped with several sensors: GPS, a three-axis accelerometer, three gyroscopes for yaw, pitch and roll, a pressure sensor for height measurements and a three-axis magnetometer.

By further equipping the MAVs with onboard cameras and arranging N of these entities around a person, he or she can be observed from multiple perspectives at the same time. In our experiment the camera is rigidly mounted on the quadrotor frame and has no extra actuators (like servomotors for panning, tilting or zooming). Hence, the height and yaw (rotation around the vertical axis) of the MAV need to be adjusted to keep track of the observed person or object.

CONCEPT OF SINGLE USER CONTROL

Manually controlling a single MAV with a remote control usually requires some training and practice. If stable pointing of an on-board camera towards a moving target is an additional requirement, the capabilities of most single human operators are exceeded. Our approach aims at enabling a single person to control an entire swarm of MAVs and keep their cameras pointed without significant cognitive effort.

Depending on the application, N (the number of elements per swarm) may range from a few up to hundreds or more. If every single element in the swarm needs to be controlled by a human operator the effort to control the swarm grows linearly with N. In order to achieve economic operation of swarms, it is desirable that many swarm elements can be controlled by a single operator. However, human perception capabilities are very limited [5], and therefore the ability to survey the input of several platforms with several degrees of freedom is not given.

Degrees of Freedom

An arbitrary object moving in free space has 6 Degrees of Freedom (DoF). These are translation in three directions and rotation around three axes.

For our further discussion we will make use of the quadrotor platforms utilized in our experiment as an example. By definition a quadrotor is under-actuated, since it has only 4 actuators, but 6 Degrees of Freedom. Translations in longitudinal or lateral direction are always coupled with a change of roll or pitch and vice versa. Usually roll, pitch, as well as change in yaw and altitude are controlled by a pilot with a remote control. To simplify the task, an onboard control unit maps these four inputs to ratios of thrust generated by a quadrotor's four propellers. The control of a quadrotor is further simplified as the on board control unit uses the IMU and magnetometer data to stabilize the quadrotor's attitude. To compensate for external influences like wind, a pressure sensor and GPS receiver can be utilized to provide altitude and horizontal position stability.

A formation of four such robots has 24 DoFs. Due to the aforementioned under-actuation of quadrotors these are reduced by 8 in our case. Still, the user would have to actively control the remaining 16 DoFs. Our approach is to further reduce the cognitive load on the user by reducing the necessary input to a few parameters that define the user's intent, i.e. the observation perspectives in our case. From these parameters the relative position and attitude for each MAV is calculated (see section 5).

The number of elements a human operator can control depends on which kind of inputs have to be perceived and which kind of parameters have to be controlled. For instance an underwater robot with 6 DoFs is relatively easy to control, but already needs some training.

If the same total number of DoF has to be controlled for several individual robots, like controlling the height of multiple underwater robots the operator will run into more difficulties. Still manageable would be to control an equal height of all platforms, but if each platform has to be kept at a different independent height, maintaining control becomes more and more difficult for the user.

User Interface

In our experiment we concentrated on interfaces and usability for a single user control of multiple MAVs. To control the formation of MAVs a single user interface needs to provide an intuitive usability for specifying the desired MAV formation. Ideally, the user interface does not require specialized hardware. In our experiments we show that a common-of-the-shelf Smartphone suffices as user device.

To prove this concept we implemented a user interface which allows the operator to specify 2 DoF for each quadrotor. Any quadrotor can be placed around the controlling user by setting the desired distance and angle using sliders in the user interface (see Figure 2). As a result the total number of degrees of freedom is reduced to 8 for 4 quadrotors.

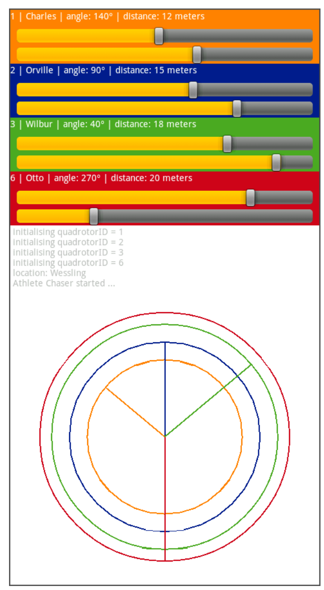

Figure 2 User interface for setting parameters for the formation of MAV's

The user is further relieved from the real-time control loop, as the formation follows autonomously the movements of the observed person. This is achieved by taking his or her position and the perspective parameters specified in the user interface into account and computing the necessary positions of all elements in the formation. Only if the desired perspective changes, i.e. the desired observation angle or distance changes, the user needs to operate the interface.

Formation orientation

The formation of the swarm, implicitly given by distances and angles of the single platforms, can be defined with respect to different reference orientations. We describe three different reference orientations: geographic orientation, device orientation and device movement.

The geographic orientation is the reference for the yaw angle of the MAV when waypoint navigation is used. In this case all yaw angles sent to the robot are defined with respect to this reference orientation by using the onboard magnetometer to sense the earth's magnetic field. It is straightforward to utilize this global angular reference for formation orientation. This angular reference is independent of any sensor orientation situated on the observed object or person.

An example for a movement of the observed device and the resulting movement of the formation using the geographic reference angle can be seen in Figure 3. While the device is changing its position and orientation, the formation follows the position change but keeps its orientation with respect to the geographic orientation.

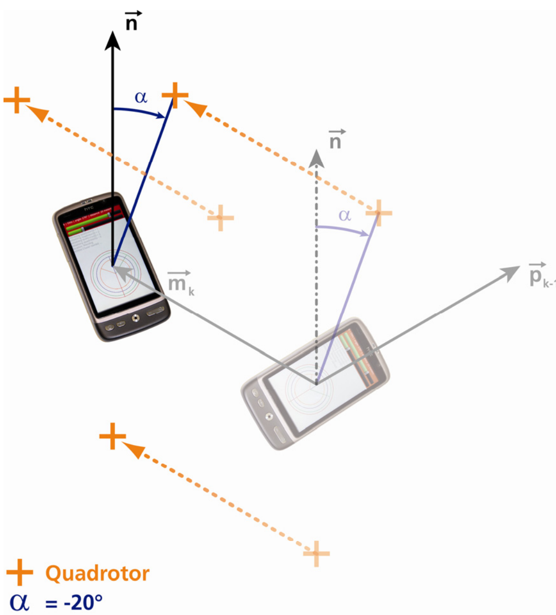

Figure 3 Formation orientation defined with respect to geographic north

Although we employed this scheme to define the formation orientation in our experiments, we describe two further useful reference orientations.

The second scheme is based on the device orientation for adjusting the formation of MAVs around the observed object. If the device is rotated, the entire formation will rotate accordingly. Figure 4 illustrates the recalculation of the position and the rotation of the z-axis of each quadrotor. The rotation of the formation follows the observed device based on the pointing derived from the magnetometer in the handheld device as reference angle.

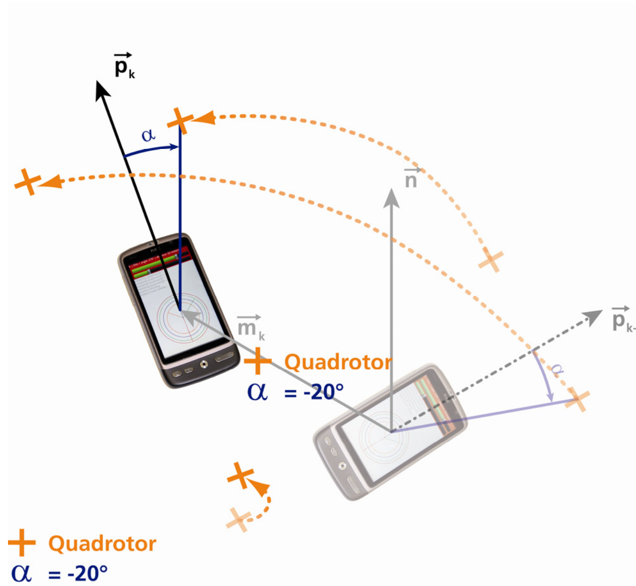

Figure 4 Formation orientation defined with respect to device pointing

The formation can also be oriented based on the movement of the observed device. In this case the formation controller unit uses the movement vector to compute the position and orientation of each quadrotor around the device (see Figure 5). The fictitious movement vector m_{k-1} defines the reference angle for the formation at time of k-1.

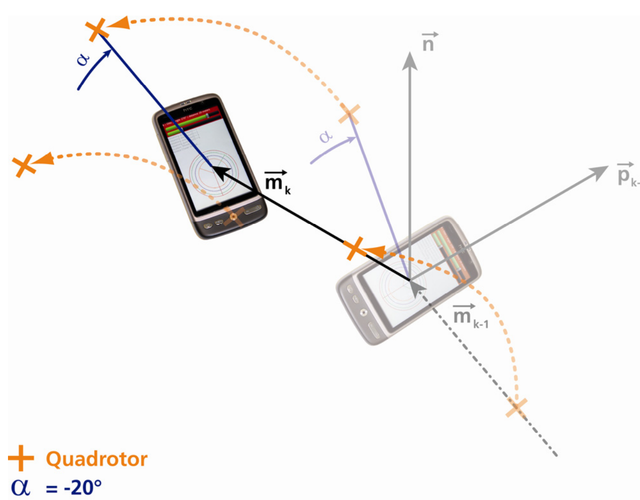

Figure 5 Formation orientation defined with respect to device movement

While conducting the outdoor experiments the interface operators had difficulties conceiving if the formation was oriented based on the device pointing, device movement or geographic north. As the orientation of the formation was not intuitively recognized by the user, additional information has been provided to them on how the formation is arranged based on geographic north around the observed target.

Coordinate Systems

The quadrotor positions are measured by onboard GPS receivers and converted from geodetic coordinates into a local Cartesian coordinate system. The relative position for each quadrotor is then calculated using straight-forward trigonometry. The multitude of possible positions of the quadrotor results in a cone, standing on its top (see Figure 6). The angle of the cone's flank is given by the camera angle ß, which remains constant during the experiment. The position on the cone's surface is calculated based on the two input parameters, angle α and distance r.

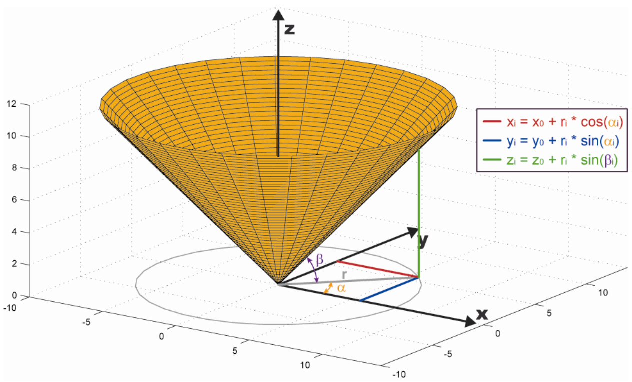

Figure 6 Possible positions of a quadrotor

The yaw angle is calculated so that the onboard camera is always facing towards the observed object. The position is then converted from its Cartesian coordinate system back into geodetic coordinates and, together with the yaw, transmitted as waypoint to the quadrotor.

EXPERIMENTAL SETUP

We conducted our experiments in an outdoor sports area in Wessling, Germany (48.0695°N, 11.2406°E). It provided enough space without obstacles and good GPS signal reception. As the platform running the user interface we used an HTC Desire Smartphone (see Figure 7) with the Android 2.2 operating system. This device is equipped with a GPS sensor, magnetometer and an IEEE 802.11 WiFi interface [8].

Figure 7 HTC with user interface

During the experiments, we used four quadrotors of the same type. For an easy identification we named them *Charles*, *Orville*, *Wilbur* and *Otto*. One of the quadrotors (*Orville*) has been equipped with a camera and an analog video link for real-time wireless transmission of video images to the ground.

In addition and adjacent to the already described sensors, each quadrotor was equipped with an IEEE 802.15.4 ZigBee module to receive control commands. These control commands were sent by a central command server, which itself received commands from the Smartphone carried by the observed person. Smartphone and control server were connected using IEEE 802.11 WiFi (see Figure 8).

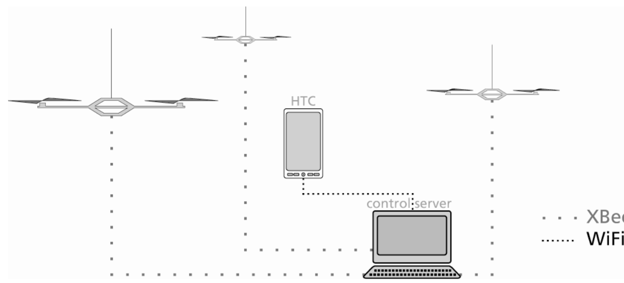

Figure 8 Experimental Setup - Network

The position for every quadrotor was calculated on the Smartphone, based on its own position and the input parameters from the user interface. All positions were then sent to the control server, where they were encoded into waypoint commands and relayed to the corresponding quadrotors.

The control server had the additional functionality to provide a real-time overview (see Figure 9) of the actual positions (the grey icons) and desired positions (the orange icons) based on the NASA World Wind globe visualization software [9]. This software tool was not only used in the field, but also for visualization of our lab simulations.

Figure 9 Screenshot World Wind on control server

Two main experiments have been carried out. The first experiment included a single quadrotor, whose parameters were changed by user input during the experiment ("changing perspective"). In the second experiments the observed person additionally walked along a predefined path (a square marked with traffic cones), and a formation of four quadrotors was following the person, according to the chosen parameters ("changing perspective and moving user"). The reference angle for the formation orientation is geographic east and positive angles are defined counterclockwise (see Figure 10).

Changing perspective

The initial setup for this experiment was a single quadrotor with 0° rotation angle. It was located directly in the east of the observed person, and at a distance of 15 meters (see Figure 10).

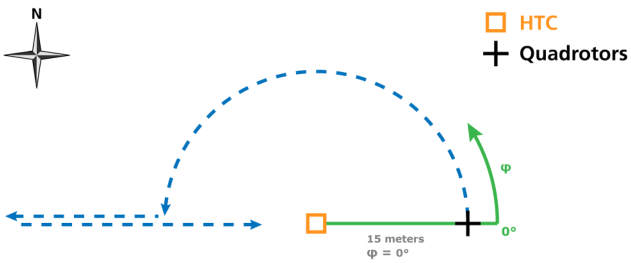

Figure 10 Experimental Setup - Changing perspective

The user increased the rotation angle of the quadrotor's position slowly to 180°, and the camera perspective followed the movement due to the synchronously updated yaw of the quadrotor, so that the observed person was permanently in the center of the camera view. Subsequently, the distance between quadrotor and observed person was changed to approximately 25 meters and back to 5 meters.

Figure 11 shows the sports field with the user interface operator (orange box) and one quadrotor up in air. The control server is situated behind the goal (on the left).

Figure 11 Changing perspective with live image from quadrotor camera

During the first experiment, we attached a video camera to the quadrotor and transmitted its signal via analog radio to ground, where it was captured. An image of the camera output while rotating the quadrotor can be seen in Figure 11 in the upper left corner.

Changing perspective and moving user

The second experiment was conducted using four quadrotors. Each quadrotor was positioned with an initial distance and angle (see Figure 12) with respect to the observed user (orange box).

Charles: 12 meters and 140°
Orville: 15 meters and 90°
Wilbur: 18 meters and 40°
Otto: 20 meters and 270°

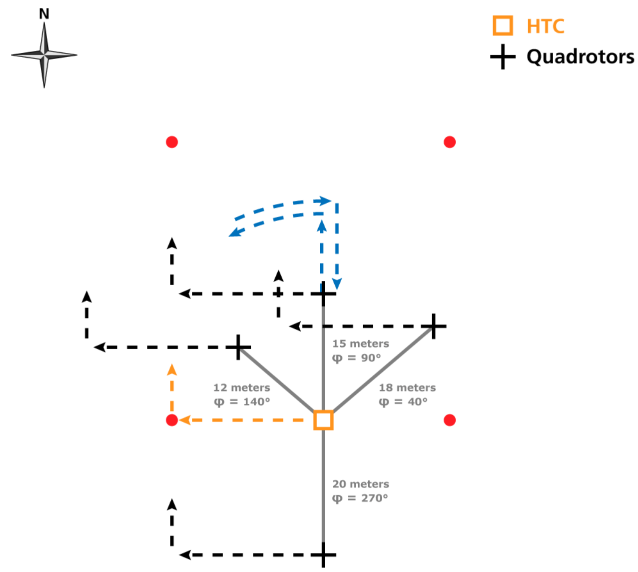

Figure 12 Experimental Setup - Changing perspective / moving user

At the beginning, the user changed the distance and angle (blue arrows) of one quadrotor (*Orville*, located in the north of the observed person). After that, the observed person walked along a predefined path around a square formed by four red traffic cones. All four quadrotors were following the person in a stable formation, given by each individual distance and angle.

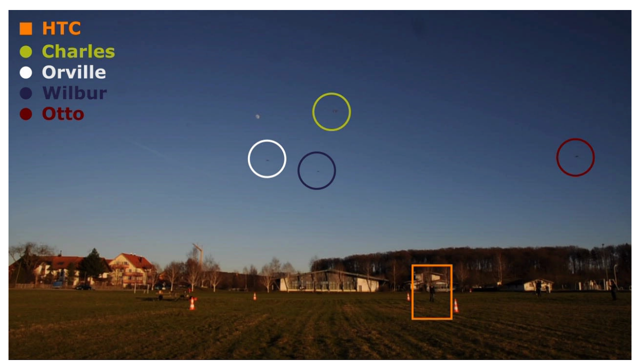

Figure 13 Changing perspective and moving user with 4 quadrotors

In Figure 13 a picture of the conducted "Changing perspective and moving user" experiment can be seen. The user (orange box) is changing the distance of the quadrotor *Orville* (white circle) back to a distance of approximately 15 meters, while the other MAVs *Charles* (yellow circle), *Wilbur* (blue circle) and *Otto* (red circle) are hovering at their designated initial position.

The described experiments have been recorded as video. Figure 11 and Figure 13 are screenshots of the resulting video footage. The movies and recorded data are available under [10].

RESULTS

We performed the experiments several times. The track for the first experiment, i.e., changing perspective, is shown in Figure 14. First, the angle is changed, resulting in a half circle around the HTC position in the middle. Afterwards, the distance is changed at a fixed angle, which can be seen on the left (the western) part of the figure. The measured radius of the flown circle is smaller than the original target radius. This is due to the slight lag the quadrotor exhibits when following the target path.

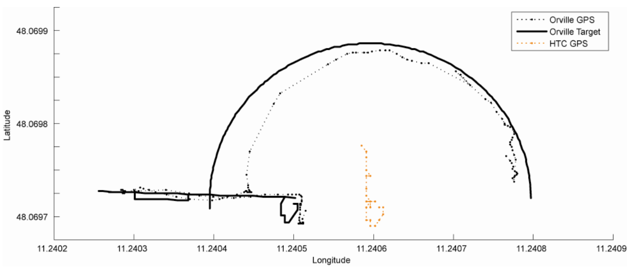

Figure 14 GPS track of changing perspective

The second experiment was conducted with four quadrotors, as been described before. The tracks of the quadrotors and the person carrying the HTC are shown in Figure 15. The arrangement was as follows: The observed person carrying the HTC is located in the middle (orange circles). The four quadrotors are arranged around it, *Orville* in the north (black), *Charles* in the northwest (green), *Wilbur* in the northeast (blue) and *Otto* in the south (red). The formation is following the HTC on its way around the cones, resulting in the squares.

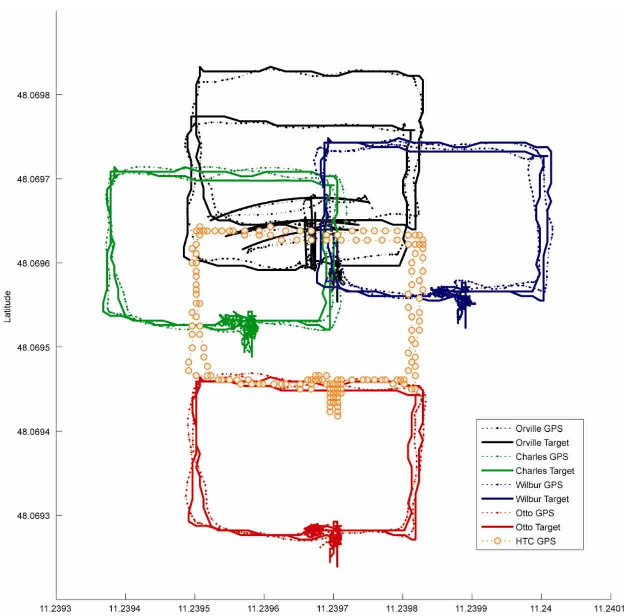

Figure 15 GPS tracks of changing perspectives and moving user

The changes in distance and angle can be seen in the path of the quadrotor *Orville* (see Figure 16). It includes 3 perspective changes and 2 movements around the square. The desired position, calculated with respect to the HTC position is indicated by the black line, whereas the measured position of the quadrotor is illustrated by a dashed grey line.

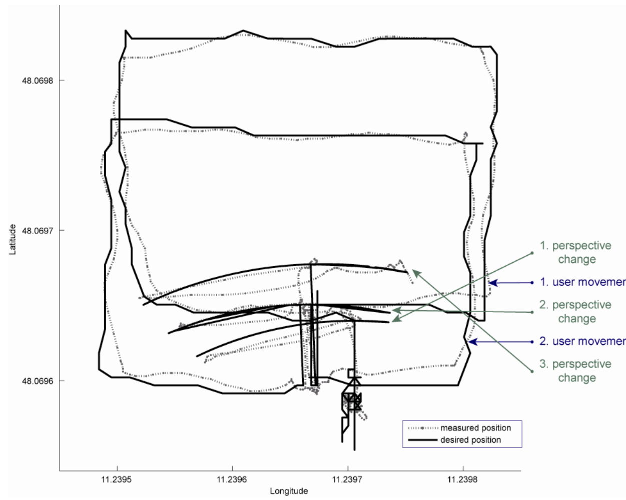

Figure 16 Detailed GPS-Track of quadrotor Orville (changing perspectives and moving user)

The position over time of *Orville* can be seen in Figure 17. The upper chart shows the change of the latitude geodetic coordinate, the lower chart the longitude change.

There is a delay between desired position and measured position of several seconds. The main cause of the delay between desired and measured quadrotor positions is the inertia of the quadrotor system, further increased by the parameters of the waypoint navigation controller which in its current implementation does not fully exploit the dynamic capabilities of the quadrotor.

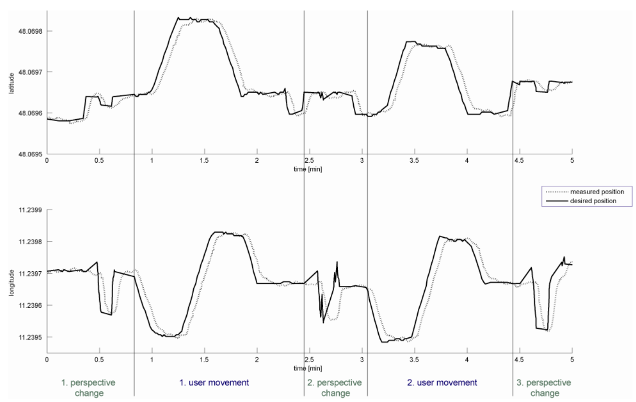

Figure 17 Movement over time of quadrotor Orville (changing perspectives and moving user)

Generally, GPS measurements proved to be sufficient for keeping several quadrotors in a relatively close formation. As no anti-collision procedures were used, we kept a minimum distance of three meters between the quadrotors to avoid potential crashes due to noisy GPS measurements.

CONCLUSIONS AND OUTLOOK

The system has been simulated and experimentally validated. An outdoor experiment was conducted in an area free of obstacles using GNSS for localization. For our requirements common off-the-shelf GPS receivers without differential or carrier phase functionality were sufficient for observing an object from multiple perspectives although we had some problems obtaining a GPS fix on one of the quadrotors.

The orientation of the formation was not intuitively recognized by the user. Both interface users had difficulties in assessing whether the formation was oriented based on the device pointing, device movement or geographic north and therefore needed an additional explanation. The usage of geographic north is deceptive and ambiguous for the user in an outdoor environment. Both users requested the device pointing as an adequate formation orientation. In our opinion this approach is only appropriate while holding the control device in front of the user. If the device is mounted on the shoulder or helmet of an athlete for acquiring medical data in the field, the formation orientation should be based on the movement vector. Therefore, further studies in usability engineering have to be conducted. Thorough investigations of user requirements have to be carried out, following an implementation of an improved user interface, which then needs to be compared and evaluated.

A problem we faced during the outdoor experiments was related to the change of the yaw to adjust the orientation of the onboard mounted camera. The dynamics of the yaw-change of a quadrotor are significantly higher than the dynamics of its position change, which results in an undesired shift of the object in the cameras image. To avoid this effect the position and yaw change require synchronization, such as using trajectories to constantly keep the observed object in the center of the image.

One application that we plan to realize in the future is the automatic observation of a pedestrian for security. A person walking through an unlighted park at night can call for support with his or her Smartphone. The quadrotors within range, which are additionally equipped with a small spotlight, start tracking the person. Through the presence of an observation camera and the additional illumination, we expect an increase of the inhibition level of possible offenders.

Swarms and formations with increasingly large numbers of elements become realizable. However, human cognitive capabilities cannot match this increase. As a result sensors, feedback loops and abstractions are required to bridge the resulting gap. Further studies of the relationship between state estimation, feedback loops, dynamic properties of elements and usability need to be conducted.

With this paper we aim to set a starting point to research into managing increasingly complex tasks of autonomous swarms with a single user interface.

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