

Cooperative Navigation Aiding in Heterogeneous UAV/UGV Teams

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Abstract: This paper focuses on the teaming of a small unmanned ground vehicle (UGV) with an unmanned micro aerial vehicle (MAV) in order to mutually improve their navigation solutions. In the first scenario, the UGV is operated in an environment with limited or no GPS coverage like an urban canyon and the MAV accompanies the robot in sufficient height. The image data that is acquired by the on-board camera of the MAV is processed in order to detect the UGV marked by a colored pattern. After the identification of the UGV's location in an image, the location of the UGV with respect to a geo-coordinate system and its yaw-angle are estimated by taking the MAV's position and attitude into account. Finally, this information is processed in the system on-board the UGV to improve the navigation solution. In the second scenario, the MAV is operated near of walls in lower altitudes. Due to shading and multipath, the quality of the GPS' position information decreases especially in direction of the wall. If the UGV is positioned well, the data of the UGV's camera can in this case also be processed to improve the MAV's position estimation. The performances of the particular parts of the setup and also of the whole system are illustrated with experimental data.

Keywords: Micro aerial vehicle, unmanned aerial vehicle, unmanned ground vehicle, image processing, teaming capability, navigation

1. INTRODUCTION

Over the last years, the interest in small unmanned vehicles has increased constantly. The possible application areas of UAV's (unmanned aerial vehicle) as well as UGV's (unmanned ground vehicle) are widespread. They are especially useful for security and rescue operations for example in cases of industrial or natural disasters like earthquakes or fires and can significantly reduce the risk for the human rescue teams. Their application in urban environments has challenging demands concerning the navigation and guidance cases due to limited GPS coverage or bad signal quality as it happens especially in urban canyons. This paper describes the strategies for teaming of a UAV with a UGV in order to overcome these shortcomings in both directions.

Several homogeneous or heterogeneous UAV/UAV and also UAV/UGV teams have already been investigated for different purposes: In [10] a ground vehicle is for example used as launch and landing platform as well as for the refueling of a small VTOL-UAV. Furthermore, cooperative teaming has been explored to increase situational awareness: A system of cooperating UAV and UGV vehicles for the detection and geo-location of mines in aerial images is for example discussed in [8]. Their approach includes a similar geo-location algorithm as ours. The hardware setup consists of a small helicopter with six foot rotor and lift capability of around 15 pounds. The hardware including a stereovision camera system is isolated against vibrations of the aircraft.

For the extraction of navigation information vi-

sion based navigation systems including visual odometers have been developed to overcome GPS outages [3] [4]. In [1], a known mark on the ground is used to safely hover over this spot. A lot of work has also been done on the landing on a specially designed landing pad with known size, shape, and texture with great results [13] [12] [7].

In this paper the focus lays on the navigation aiding in a UAV/UGV team by processing the image data of monocular cameras. A color mark is used in order to be able to identify the ground vehicle. The MAV is detected and tracked with a multistage combination of detection algorithms. Depending on which platform needs navigation aiding, the image processing platform on the other one takes into account the detection result as well as the onboard navigation solution to estimate the necessary information. The concept of the cooperative teaming is discussed in detail in the next section. After the presentation of the used platforms in Section 3, the detection algorithms of MAV and UGV are covered in Sections 4 and 5 together with details about the implementation. Section 6 comprises the conversion to a geo-referenced coordinate system. In Section 7 the performances of the particular parts of the setup are illustrated with experimental data followed by a conclusion.

2. CONCEPT OF THE COOPERATIVE TEAMING

The team consists of a small four rotor VTOL-UAV with a takeoff weight below 1 kg and a small, wheeled UGV. Provided that an accurate navigation solution is available, both vehicles are capable to follow autonomously a pre-defined trajectory. The two vehicles communicate via a digital data link. One digital camera is mounted on the chassis of the UAV and is pointing towards the ground and another digital camera is mounted on the UGV pointing towards the sky. The benefit of the team is their mutual improvement of the navigation solution if needed:

In the first scenario, the UGV operates in areas with bad GPS signal quality or coverage. The UAV accompanies the UGV in sufficient height to ensure good GPS signal availability and provides it with an accurate navigation solution: In the first step, the acquired image data stream is processed onboard

the UAV in order to detect and track the UGV over time. Furthermore, a geo-location algorithm is implemented that enables the ongoing determination of the UGV's position and heading with respect to a geo-referenced coordinate system. To ensure the correct integration of this position measurement in the UGV's navigation filter, the quality of the position information is estimated, and both are transferred to the UGV. This leads to a reliable navigation solution even if no GPS data is available on the ground vehicle.

In the second scenario, when the UAV is operated near of walls in lower altitudes, the quality of GPS's position information decreases especially in direction of the wall due to shading and multipath effects. The camera data acquired onboard the UGV can also be processed to determine the UAV's position. One possibility, is the use of a navigation system with higher accuracy due to the normally higher payload capacity onboard a UGV. As the quality of the geo-location results depends mainly on the position accuracy of the tracking device and on the viewing angle under which the object is visible, the UAV's position estimation can therefore be improved. Another possibility is to position the UGV with a viewing direction parallel to the wall or the building. As the accuracy of the geo-located position is higher in lateral direction than longitudinal relative to the cameras viewing direction, this approach can also improve the UAV's position estimation and avoid collision with the walls.

3. PLATFORMS

In this section, the used platforms are introduced including details about their navigation and guidance systems.

3.1. VTOL-MAV

The ability to hover is desirable for a wide range of applications like surveillance and reconnaissance missions as images being taken by an on-board camera give valuable information about the scenario. Therefore the developed MAV is a four-rotor helicopter shown in Fig. 1. The maximal diameter including the rotors is 92 cm and the takeoff weight without payload is around 800 g. The hardware setup of the electrically powered aircraft has been

optimized in order to maximize the flight time of up to 25 min. This results in a payload capability of 200 g.



Figure 1: MAV with camera and image processing platform used for the teaming function.

The core of the MAV is the guidance, navigation and control hardware platform. To determine position, velocity and attitude, an on-board navigation system integrates the information of different sensors. This is necessary because only low quality sensors can be used due to severe restrictions on weight, cost and power consumptions. The basic component is a MEMS-IMU with three orthogonal gyroscopes and three orthogonal accelerometers. For the absolute positioning and the correction of the IMU sensor errors like biases and scale factors a GPS receiver is included on-board. In case of GPS loss, the navigation solution based solely on the MEMS-IMU sensors would be only short time stable and diverge almost instantaneously. Therefore, the system is augmented by a barometric altimeter improving the altitude estimation and a three axis magnetometer that stabilizes together with a model of the Earth's magnetic field the yaw angle of the MAV [9]. This is also important during hovering flight when the yaw angle becomes otherwise unobservable.

An error state space Kalman filter, also known as indirect Kalman filter is used to integrate all sensor data and to estimate the biases of the inertial sensors. This filter estimates the errors of the necessary quantities and corrects the errors of the strapdown algorithm in a closed-loop procedure in order to ensure precise and longtime stable navigation information. The estimated quantities as well as the sensor data and some status information of the MAV are stored on-board on a flight recorder and can be analyzed

after the flight.

The guidance algorithms of the VTOL-MAV allow its operation in the semi-autonomous "position hold" mode as well as the autonomous "waypoint" flight mode [9]. In the position hold mode, the helicopter keeps its three-dimensional position fixed and autonomously compensates disturbances due to wind what significantly eases the pilot's job. The waypoint flight mode even allows the autonomously following of predefined flight path outside the range of sight and outside the range of the radio link. A wide range of payload control functions as well as safety functions are available and easy to use. The planning of the path is simplified by an autonomous path planning application where only the start and the landing point need to be defined. Based on the model of the flight area, a secure and fast route is autonomously planned and can be easily transferred to the helicopter.

3.2. Image processing hardware

The severe weight and power restrictions onboard the MAV place great demands on the acquisition and on-board processing of the image data. Due to the small size and weight of the aircraft, the on-board processing power was limited and restricted to navigation and guidance purposes so far. Therefore, an additional processing platform based on an *Analog Devices Blackfin DSP* was designed solely for the image processing visible in Fig. 2. This dual-core DSP has a clock frequency of 600 MHz, 8 MB flash memory and 2 x 64 kB SRAM. Additionally 64 MB external SDRAM and two light cameras of the company *OmniVision* with 1/4" lens, also used for cellular phones, were integrated. The resolution is scalable from UXGA to SVGA with frame rates from 15 to 30 fps and the cameras are able to directly deliver the image data in the desired color space. Camera and image processing hardware are regarded as payload and weigh altogether only below 50 g.

Acquired images can be saved on the integrated micro SD card, but as this takes around 70 s per image, this is too slow in order to be able to test and optimize the algorithms with the saved image data. In order to be able to extensively test and optimize the image processing algorithms offline, they have also been integrated on an *Intel® Atom™ Processor* together with a webcam. This image process-

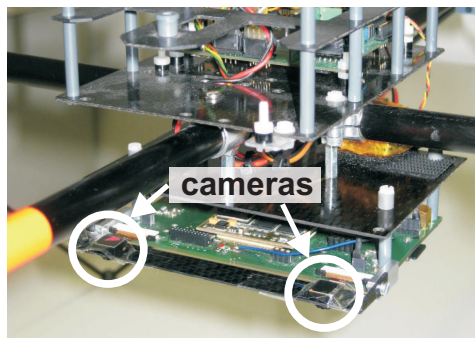


Figure 2: Image processing platform with cameras mounted under the chassis of the MAV

ing hardware weighs around 250 g. For the flight experiments with this setup a four rotor helicopter basic platform of the company *MikroKopter* is used. This platform can carry a payload of around 400 g but has a noticeable reduced flight time of 15 min. It is equipped with the same navigation, guidance and control hardware and algorithms as the target MAV.

3.3. Ground vehicle

The used four wheeler UGV has a weight of around 22.5 kg including a payload capacity of 9 kg. It is available as *MMP-30* from the company *TheMachineLab Inc.* The experimental platform has the dimensions 53 cm x 48 cm x 23 cm and is marked with a tricolored pattern (see Fig. 3) of the size 40.5 cm x 40.5 cm. For the evaluation of the geo-location

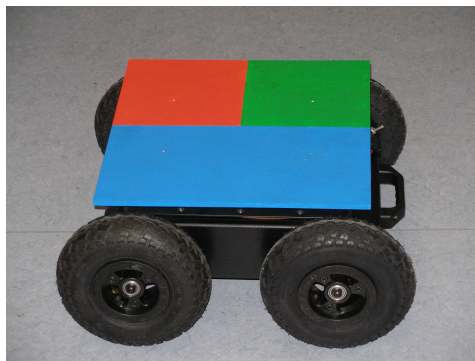


Figure 3: Unmanned ground vehicle with color mark for detection.

capabilities of the system, a similar navigation system is used as for the helicopter. In addition to the above mentioned sensors an odometer is integrated onboard the UGV. Provided that an accurate naviga-

tion solution is available, the UGV is capable to follow autonomously a pre-defined trajectory as well. The digital communication link between the MAV and the ground vehicle is realized with the radio frequency transmitter and receiver module *TinyOne Pro 868 MHz* from the company *One RF Technology GmbH*. The transceiver works in the 868 MHz ISM-band. Due to its range of up to 4 km line of sight, this module is also used for the wireless communication and data transfer between the MAV and the base station. Therefore the integration into the existing system of the MAV is simplified. Another advantage of the modules is their ability to form a mesh-network with several connections per participant. This could be used e. g. for the geo-location of more than one ground vehicle by a single MAV.

4. IMAGE BASED MAV DETECTION AND TRACKING

In this section, the used approach for detecting the MAV in images of a ground based camera and tracking are covered. The detection happens in a multi-stage process based on image segmentation and difference images. In the following the different detection possibilities are covered followed by the combination.

If the acquired images show the helicopter in the sky, the contrast between the dark MAV and the brighter sky is normally good enough in order to get good results with well-known grayvalue segmentation. After applying a small Gaussian filter in order to reduce image noise, a threshold is used to extract dark parts of the gray value image. For the dynamical choice of the threshold value, we tried several algorithms like the well known Otsu's method that maximizes the interclass variance between the two segmented parts of the image's histogram and also a similar approach to the expectation maximization algorithm described in [14]. Both approaches did give satisfactory results if the number of dark pixels compared to the number of all pixels was high enough. If the helicopter was far from the camera and the only visible dark part in the image, the results were not useful. Therefore a fixed threshold was chosen from data of several experiments that works well for most situations. After the thresholding, morphological

closing with a small structural element is then used to merge small holes and divided blobs in the binary image. The structural element needs to be chosen depending on the expected size of the helicopter in the image plane. If no information is available yet, it is advisable to choose the size rather too small. Divided blobs can then be merged by using a simple clustering, that takes into account the distances between the blob centers. Finally the binary image is labeled. This approach is very fast and can also be applied if the UGV with the camera itself is moving, but it can only be applied if the MAV is clearly silhouetted against the background (see Fig. 4). If only the segmented image is used for detection, the center position and size of the objects are used in the data association step described later in this section.

As the helicopter is normally not perfectly static

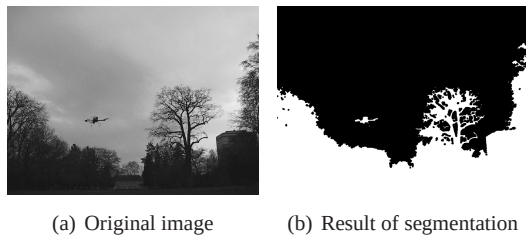


Figure 4: Original image and binary result after segmentation and filtering.

in the images, another possibility for the detection is the evaluation of gray value differences between subsequent images. This well known approach discovers parts of the image where grayvalues change what is supposed to result from moving objects in the scene provided that the camera is not moving. Similarly to the first method, a threshold is applied to the difference image, followed by morphological filtering, if necessary clustering and connected component labeling. As other motion in the scene for example of trees, is also detected in the difference image, we use a fusion of the results of the segmented image and the difference image in order to keep only objects with similar sizes in both partial results. Another disadvantage is that the sizes of the moving objects are not extracted correctly (compare Fig. 5(a)) and if the displacements between the images is large also the detected position is inaccurate.

To overcome this problem, an adaptive image is determined containing the grayvalue information of

the static background of the scene. This is done by observing the pixel values and if for a pre-defined time span no major changes have occurred, a sliding mean calculation is started for each pixel (compare Fig. 5(b)). As soon as a pixel value



(a) Difference image (b) Estimated background

Figure 5: Difference image with the image of Fig. 4(a) and subsequent image as well as estimated background information.

changes significantly, the update is paused until stable information is obtained again. If the camera is still, the acquired image information can be directly used. If this is not the case, but the background is structured for example a building, the background image can be determined from stabilized images as described in [5]. For those parts of the image where background information is available the difference image can be calculated between current image and background image. This approach gives very good results with correct sizes and positions of the objects even if the MAV is flying for example in front of buildings or trees (see Fig. 6).



(a) Original image with marked helicopter position (b) Detection result

Figure 6: Original image with marked helicopter position and binary result after background difference and filtering.

In order to increase the robustness of the detection algorithm, all described approaches are combined as follows: If a stabilized background image is available, the resulting objects of the difference image between background and current image are chosen as possible measurements. It is possible that at some time during the operation no reliable

background information is available for each pixel either because the camera is moving and due to lack of background structure no image stabilization can take place or because the camera has just stopped and the information is still under observation. In the first case, only the result of the segmentation approach can be used as measurements. In the second case, the fusion results of segmentation and difference approaches as described above are used.

For the tracking of the helicopter, a simple Kalman filter with constant velocity model is used. Furthermore the approximate size of the helicopter is tracked. Due to rotation, the size of the MAV in pixels can change quickly and therefore the change of the size is not modeled in the state vector. To discard improbable measurements, a gating process with the Mahalanobis-distance is used. As the Kalman filter integrates the data in the pixel coordinate system, an occurring camera motion can falsify the prediction. In these cases, a higher system noise is used to still enable the data association and the size of the objects is weighted higher. At the moment, a Kalman filter integrating the data in navigation coordinates is under test with good results to improve this.

5. IMAGE BASED UGV DETECTION

In this section, the concept for the detection of the UGV in the images of the on-board camera of the MAV is outlined. As mentioned before, the UGV is marked with a tricolored pattern. More marks have been designed by just permuting the colors that can all be detected with this approach and allow for the detection of up to six marks at the same time. As the orientation of the asymmetric mark with regard to the UGV's body coordinate system is known, the heading angle can also be estimated from the images. In order to be able to realize the real-time operation onboard the MAV, several optimizations were necessary that are described together with the hardware platform as well.

5.1. Concept of the color mark detection

In order to detect the color mark, the acquired images are processed in the YC_bC_r color space that is widely used for color image segmentation. The color information is coded in the planes C_b and C_r ,

where C_b gives the differences of yellow and blue color and C_r comprises the differences of red and cyan color.

In the first step, the C_b and C_r image planes are thresholded in order to obtain the red, green and blue pixels. Next, the three thresholded images are filtered with a morphological closing filter operation to close possible holes and get compact blobs. The size of the quadratic structural element can then be chosen adaptively according to half the expected pixel edge length of the mark. This length can be roughly estimated from the intrinsic camera parameters and the distance between camera and color mark being known from the height estimations of both platforms. The attitude information of the MAV's navigation system can also be included in this estimation. Experiments have shown that this is not necessary if the camera is mounted perpendicular under the MAV's chassis. In the next step, the binary images are labeled and the centers and the sizes of all blobs are calculated. For each possible permutation of red, green and blue blobs the three distances between the blob centers Δ_{rg} , Δ_{gb} and Δ_{br} are calculated as well as the following measure.

$$\Delta_{rgb} = |\Delta_{rg} - \Delta_{gb}| + |\Delta_{gb} - \Delta_{br}| + |\Delta_{br} - \Delta_{rg}|. \quad (1)$$

As the centers of the red, green and blue part of the mark form an almost equilateral triangle, the distance Δ_{rgb} is supposed to be small for the red, green and blue blob that form the UGV's mark.

In order to choose the correct triple, the following criteria are used: At first, those triples are discarded that don't have the color orientation of the desired mark and that do not have the biggest blob in the desired color. From the remaining triples, the best triples are extracted with the distances Δ_{rg} , Δ_{gb} and Δ_{br} between the centers of the blobs being all around half the expected mark size in pixel and the numbers of pixels of the blobs matching the desired mark. Finally, the triple with maximal similarity with an equilateral triangle given by the measure in Equation (1) is chosen. The estimated center pixel of the UGV is calculated from the centers $\vec{x}_r$, $\vec{x}_g$ and $\vec{x}_b$ of the chosen blobs as

$$\vec{x}_{det} = 0.25 \cdot (\vec{x}_r + \vec{x}_g) + 0.5 \cdot \vec{x}_b. \quad (2)$$

For estimating the heading angle of the UGV, the

orientation between the mark and the body-frame of the ground vehicle needs to be known. In our test scenario the mark is fixed in order to align the body x-axis with $\vec{x}_{gr} = (\vec{x}_g - \vec{x}_r)$.

5.2. Optimized implementation

In order to enable the on-board image processing with the lightweight hardware setup presented in section 3.2, the implementation of the described detection algorithm needed to be optimized. As the image data exceeds the internal memory of the used Analog Devices Blackfin DSP, the external SDRAM of the board needs to be used. As this results in significant time delays for memory access, most effort has been made to need only minimized memory access.

To reduce the memory usage, the result of the thresholding process is not coded in three binary images but in one single image where red, green and blue object pixels are coded with different numbers. All SDRAM access is done by MDMA (memory-to-memory direct memory access) transfers. In order to reduce the processing time, the closing algorithm being erosion followed by dilation has been reduced to the erosion process. Possible holes in the blobs are filled later during the labeling process. For the erosion, different algorithms have been compared. As described in the last section, the size of the structural element is adapted depending on the expected size of the mark in the image and therefore needs to be variable without influencing significantly the processing time. An algorithm based on a distance transform followed by thresholding the resulting distance information was chosen: At first, the city block distances, also known as Manhattan distances, to the closest background-pixels are calculated by double passage to the thresholded image. The first run goes row-wise from top left to bottom right and the second run from bottom right to top left, always taking into account two rows at the same time. Then a threshold corresponding to half the size of the desired structural element is applied to the distance values resulting in the eroded binary image. This approach corresponds to the morphological erosion with a rhombus or diamond shaped structural element [11]. In order to save computation time, the thresholding and the first part of the city block distances are calculated together during the first run

through the image data. In the second run, the calculation of the distance transform is finished and the distances are thresholded immediately.



(a) Original image

(b) Image after thresholding and erosion

Figure 7: Original image and result after grayvalue thresholding and erosion by allowing a maximal city block distance of 5.

For the labelling, an efficient process was implemented that was published by Change et al. [2]. The process goes once through the image and if an object pixel is found that has not been labeled yet, the algorithm follows the contour of the attached structure and labels all contour pixels with the same label. If the algorithm returns to the first pixel of this structure, the label is also assigned to all pixels enclosed by the contour. This approach closes possible holes resulting from the thresholding. During the labeling process, the center of the blobs and the number of pixels per blob are directly calculated. In the last step, the best triple is chosen from all permutations of red, green and blue blobs.

The described algorithm has been optimized to run on the above describe hardware platform with 1.4 Hz. In order to be able to extensively test and optimize the algorithm, it has also been integrated on an *Intel® Atom™ Processor* together with a webcam. With this setup, frame rates up to 16 Hz can be processed. The results and the images are stored onboard and can be analysed and visualized after the flight.

6. GEO-LOCATION

In this section, the geo-location of the UGV as well as the MAV has been summarized. After the definitions of the used coordinate systems, the projection equations and the quality estimation are covered.

6.1. Definitions of coordinate systems

In this section, the coordinate systems and definitions being used in the following are described:

The on-board navigation system estimates the attitude, the position, and the velocity of the MAV platform. The attitude describes the rotation between the body-fixed coordinate system (denoted by index b) and the so-called navigation coordinate system (denoted by index n) pointing in a northward, eastward, and downward direction. The attitude can be expressed with the three Euler angles $(\phi_{nb}, \theta_{nb}, \psi_{nb})$ (see Fig. 8) or the direction cosine matrix $\mathbf{C}_{n,b}$ being especially useful for coordinate transformations. The MAV's position $\vec{x}_{\text{MAV}}^e$ is expressed in the navi-

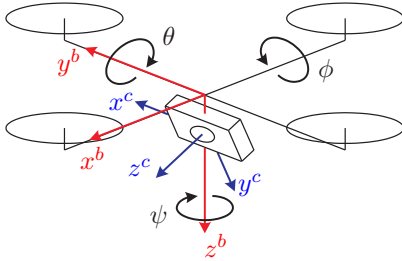


Figure 8: Definitions of Euler angles as well as body-fixed and camera coordinate systems.

gation system in ECEF-coordinates (Earth-Centered Earth-Fixed)¹. Due to the operating range of the helicopter of some kilometers, the earth's surface can be approximated by its tangent plane with fixed attitude $\mathbf{C}_{n,e}$. For simplification, the position of the MAV is in the following expressed as the differential position $\Delta \vec{x}_{\text{MAV}}^n$ from the helicopter's initial position $\vec{x}_{\text{MAV,init}}^e$ with coordinates in northward, eastward, and downward direction

$$\Delta \vec{x}_{\text{MAV}}^n = \mathbf{C}_{n,e} \cdot (\vec{x}_{\text{MAV}}^e - \vec{x}_{\text{MAV,init}}^e). \quad (3)$$

The lever arm $\vec{l}_{bc}^b$ and the attitude between the camera and the helicopter, described by the three angles $(\phi_{bc}, \theta_{bc}, \psi_{bc})$ or $\mathbf{C}_{b,c}$, are estimated before the flight and are supposed to be fixed during the operation. The definitions of the body coordinate system and the camera coordinate system are visualized in Fig. 8 with the optical axis of the camera pointing towards ground. The attitude and position of the UGV as

¹In the following the superscript character after a variable specifies the coordinate system with respect to which the variable is given.

well as the relation between the it's body coordinate system and it's camera coordinate system are determined and expressed equivalently.

6.2. Projection to geo-referenced coordinate system

The navigation Kalman filter processes all sensor data in the navigation frame. Therefore, the image based information needs to be transformed to the navigation coordinate system, in order to be able to integrate it in the same filter. At first, the result of the detection process is the image point with 2D pixel coordinates $(x_{\text{det}}, y_{\text{det}})^T$. If the camera has significant lens distortion, it is supposed that this has already been corrected. With the help of homogeneous coordinates, the connection between pixel and camera coordinates is given by

$$\vec{x}_{\text{scal}}^c = \begin{pmatrix} x^c/z^c \\ y^c/z^c \\ 1 \end{pmatrix} = \mathbf{K}^{-1} \cdot \begin{pmatrix} x_{\text{det}} \\ y_{\text{det}} \\ 1 \end{pmatrix}. \quad (4)$$

with $\mathbf{K}$ being the camera calibration matrix [6]. With the attitude estimation of the navigation coordinate system, the normalized direction vector $\vec{x}_{\text{scal}}^c$ can be transformed to the navigation coordinate system:

$$\vec{x}_{\text{dir}}^n = \mathbf{C}_{n,b} \cdot \mathbf{C}_{b,c} \cdot \vec{x}_{\text{scal}}^c. \quad (5)$$

The straight line connecting the camera's projection center and the position of the UGV in the world is now defined by the position of the camera $\Delta \vec{x}_{\text{cam}}^n = \Delta \vec{x}_{\text{MAV}}^n + \mathbf{C}_{n,b} \cdot \vec{l}_{bc}^b$ and the direction vector $\vec{x}_{\text{dir}}^n$. If, furthermore, information about a plane is known, defined as $\vec{n}^{nT} \cdot \vec{x} = d$ with the normal vector $\vec{n}^n$, where the UGV is located on, the intersection point is

$$\Delta \vec{x}_{\text{UGV}}^n = \Delta \vec{x}_{\text{cam}}^n + \frac{d - \vec{n}^{nT} \cdot \Delta \vec{x}_{\text{cam}}^n}{\vec{n}^{nT} \cdot \vec{x}_{\text{dir}}^n} \cdot \vec{x}_{\text{dir}}^n. \quad (6)$$

As the UGV's height h_{UGV}^n with regard to the start point is given from the barometric altimeter, such a plane is defined by $\vec{n}^{nT} = (0, 0, -1)$ and $d = h_{\text{UGV}}^n$. Finally, the position can be transformed to the ECEF-coordinate system. The determination of the MAV's position is equivalent.

For the extraction of the UGV's heading angle, a second point $\vec{x}_{\text{head}}$ in body x-direction of the robot can be calculated from the center $\vec{x}_{\text{det}}$ and

the known heading direction $\vec{x}_{gr}$ in pixel coordinates (see section 5.1). With the equations described above, this point is transformed to the navigation coordinate system resulting in $\vec{x}_{head}^n = (x_{head,n}^n, x_{head,e}^n, x_{head,d}^n)^T$. The yaw angle ψ_{nb} between the body and the navigation coordinate system of the UGV is then given by

$$\psi_{nb} = \arctan \left(\frac{x_{head,e}^n - x_{UGV,e}^n}{x_{head,n}^n - x_{UGV,n}^n} \right). \quad (7)$$

6.3. Covariance estimation

For the successful integration of different sensor data with the help of a Kalman filter, the knowledge about realistic measurement noise is essential. The quality of the geo-located position depends on several factors. The first factor is the quality of the detection itself that can significantly vary over time for example due to motion blur or colored background. In addition, the camera calibration as well as the relation between camera and body coordinate system are not ideal. These errors are supposed to be fixed during the flight. Furthermore, the navigation information about position, attitude and altitude is noisy and significantly influences the quality of the geo-location result. Finally, the precision depends on the current geometry between plane and line of sight. If the direction vector associated to the detected position is getting closer to orthogonal to the planes normal vector the problem becomes increasingly ill-conditioned.

The propagation of uncertainty for a function $f(x_1, x_2, \dots, x_n)$ with several input variables can be done with the help of the partial derivatives

$$\sigma_f^2 = \frac{\partial f^2}{\partial x_1} \cdot \sigma_{x_1}^2 + \dots + \frac{\partial f^2}{\partial x_n} \cdot \sigma_{x_n}^2. \quad (8)$$

This simplification works only if the input variables are uncorrelated and if the function is sufficiently linear for the considered range of the input values. This can be assumed if for example the camera is mounted perpendicular under the MAV. To roughly estimate the quality of the current constellation, the partial derivatives of equation (6) are therefore calculated and combined with the variances of the input variables. The standard deviations of position and attitude related to the body coordinate system are known from the navigation Kalman filter. The uncertainty of the transformation between body and

camera coordinate system are estimated before the flight. The resulting calculated variance gives a good indication on the quality of the estimation.

7. RESULTS

The different parts of the setup have been verified with experimental data. Therefore the *MikroKopter* platform in combination with the *Intel® Atom™ Processor* and the webcam was used to detect and geo-locate the UGV. To verify the located positions the UGV's GPS receiver positions are used for comparison. Figure 9 shows the geo-located positions

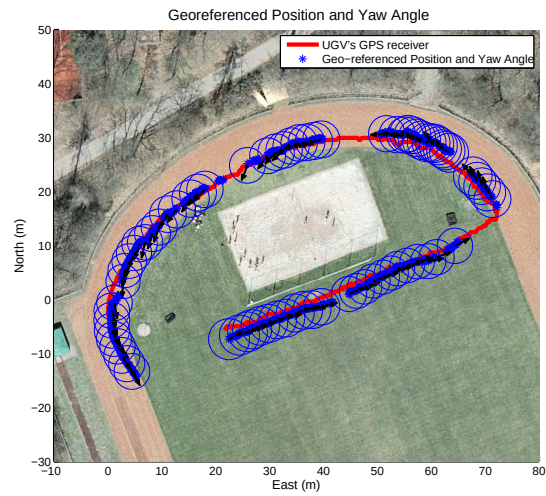


Figure 9: Comparison of geo-located positions (blue crosses) and positions of the UGV's GPS receiver (red line) and the yaw angle (arrows).

of the UGV in comparison to the UGV's GPS receiver positions. The position and the yaw angle of the UGV are determined with an update rate of 16Hz. The difference between the positions comes from errors of the GPS positions as well as from errors in the camera's orientation to the MAV body frame. The determined yaw angle also is correct as the UGV always headed in the direction of motion. The calculated variance of the position shows the correct estimation of the errors. This allows an useful integration of the data in the UGV's navigation computer.

8. CONCLUSIONS

This paper described the complete integration of detection and geo-location of UAV/UGV teams. The

detection of a MAV as well as a UGV in the image data of onboard cameras has been implemented in an optimized way to ensure high update rates on small computer platforms. The detected positions are transformed into geo-referenced coordinates and are completed with variance informations to allow the correct integration in the navigation systems. At the moment an adapted color mark is successfully tested to enable an autonomous landing as well. The detection and geo-location of the MAV from several UGVs is explored to improve the MAV's position information.

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