High Accuracy Ground Target Geo-location Using Autonomous Micro Aerial Vehicle Platforms

Gianpaolo Conte, Maria Hempel, Piotr Rudol, David Lundström, Simone Duranti,

Mariusz Wzorek, Patrick Doherty

Dept. of Computer and Information Science, Linköping University, Sweden

giaco@ida.liu.se

This paper presents a method for high accuracy ground target localization using a Micro Aerial Vehicle (MAV) equipped with a video camera sensor. The proposed method is based on a satellite or aerial image registration technique. The target geo-location is calculated by registering the ground target image taken from an on-board video camera with a geo-referenced satellite image. This method does not require accurate knowledge of the aircraft position and attitude, therefore it is especially suitable for MAV platforms which do not have the capability to carry accurate sensors due to their limited payload weight and power resources.

The paper presents results of a ground target geo-location experiment based on an image registration technique. The platform used is a MAV prototype which won the 3rd US-European Micro Aerial Vehicle Competition (MAV07). In the experiment a ground object was localized with an accuracy of 2.3 meters from a flight altitude of 70 meters.

Nomenclature

MAV	Micro aerial vehicle
s	Image scale factor
f	Camera focal length
I_{res}	Reference image resolution
d	MAV's ground altitude
λ	Ground object distance to the MAV
x_p, y_p	Pixel coordinates
X_i, Y_i, Z_i	Inertial reference frame
X_v, Y_v, Z_v	Vertical reference frame
X_b, Y_b, Z_b	Body reference frame
X_g, Y_g, Z_g	Gimbal reference frame
X_c, Y_c, Z_c	Camera reference frame
CCD	Charge coupled cevice
FOV	Field of view

I. Introduction

Micro aerial vehicles represent a promising technology. What makes these kind of platforms interesting is their small size (order of centimeters) and affordable price. Their area of application includes target detection and localization but also more general tasks such as monitoring and surveillance.

The division of Artificial Intelligence and Integrated Computer System (AIICS) at Linköping University has been working with Unmanned Aerial Vehicles (UAVs) for many years during the WITAS Project.[1,2] In this project strong emphasis was put on autonomy. The main goal was to develop technologies and functionalities necessary for the successful deployment of a fully autonomous UAV helicopter for road traffic monitoring. With the WITAS Project completed the division additionally began to work with MAV platforms and developed a small autonomous coaxial rotorcraft[3] which won the 1st US-European MAV Competition (MAV05) as "best rotary wing".

In this paper a vision based approach for precise ground target geo-location is described. The platform used is a fixed-wing MAV named *PingWing* developed in-house (Figure 1). The PingWing won the 3rd US-European Micro Aerial Vehicle Competition (MAV07) which took place in Toulouse in September 2007.

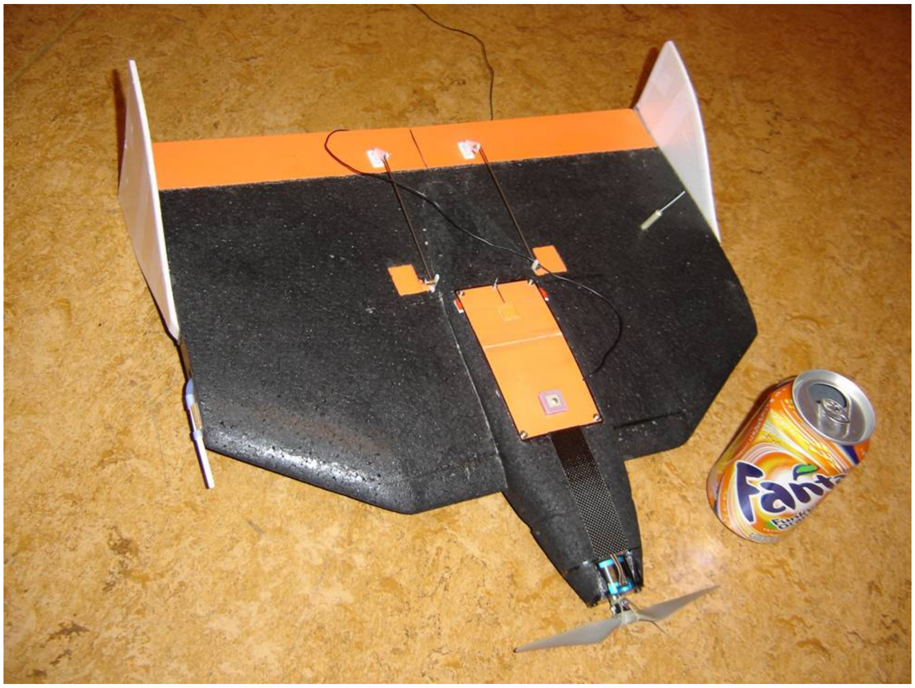

Figure 1. ***PingWing*** **micro aerial vehicle platform developed at Linköping University.**

Precise ground target localization is an interesting problem and relevant not only for military but also for civilian applications. For example, an UAV that will be used to automatically monitor road traffic behavior must be able to discriminate if an object (in this specific case a car) is on a road segment or off road. The target geo-location accuracy required to solve this kind of problem must be at least the road width. The geo-location accuracy reached with the method developed in this paper is below 3 meters. To achieve such accuracy is a great challenge when using MAV platforms due to fact that MAVs of a few hundred grams can only carry very light sensors. Such sensors usually have poor performance which prevents localizing a ground target with the necessary accuracy. The most common sensors used to geo-locate ground objects from a MAV platform are passive video cameras. The reason is that such sensors can be very light and have a low power consumption. The drawback is that they are sensitive to illumination conditions and do not provide direct range information. The miniaturization of active devices, such as radars and lasers, has not come far enough yet to allow airborne applications on small platforms.

When a ground target is within the image frame, the detection (picking the target out of the clutter) can be performed manually (i.e. by an operator "clicking" on the screen), or automatically using image processing methods. Subsequently, the world coordinates can be calculated using the MAV position, attitude and the camera orientation relative to the MAV body. The MAV position is given by an on-board GPS receiver, while the attitude angles are computed from a navigation filter which integrates the inertial sensors (gyroscopes and accelerometers) and the GPS. The problem is that the measurement of the MAV position, attitude and camera angles are affected by several error sources which leads to a ground target localization error of the order of tens of meters.

The problem of target geo-location has been addressed previously in the literature.[4–7] Several techniques have been used to improve the localization accuracy estimating the target position jointly with the systematic MAV and camera attitude measurement errors. In Ref. 4 the authors improve the geo-location accuracy by exploiting the structure inherent in the problem. In particular, a recursive least square filter is applied to remove the zero-mean sensor noise. The biases in the sensor measurement are also estimated and compensated. Moreover a study on the optimal flight path and wind estimation allows for a further improvement of the geo-location accuracy (below 5 meters).

The target geo-location method developed in this paper differs from the approaches cited above, it is based in fact on satellite image registration. Instead of using the MAV and camera state information to compute the geo-location of a ground object, the MAV camera view is registered to a geo-referenced satellite image with the coordinate of the ground object being calculated from the reference image. This method is based on the assumption that a satellite or aerial image of the area containing the object is available to the system beforehand. The fact that the availability of high resolution satellite or aerial images is rapidly growing and accessible to everybody makes this approach very attractive. In any case, even if this information would be missing, it is possible to imagine operational scenarios where the region of interest is photographed in advance. The experiment described in this paper makes use of satellite images downloaded from Google Earth.

The advantage of this method is that the errors related to the MAV and camera pose do not affect the target localization accuracy because they are not directly used for the calculation. The MAV sensor information is used instead as a first guess to restrict the search zone in the satellite image. It will be shown later that the accuracy of the method presented here is below 3 meters in a typical representative scenario. Another advantage of this method is that the ground target geo-location accuracy does not depend on the flight path or wind (in case of side wind the direction of travel is different from the MAV heading. Therefore, with traditional target geo-location methods wind estimation is required if a compass is not used). This fact reduces the complexity of the flight mission since it does not require a specific flight path around the target. Last but not least, the synchronization problem between the video image and the flight data does not represent an issue anymore. In fact while other approaches require very accurate synchronization between video and flight data (which is not trivial for MAV systems), this method is not sensitive to this problem.

The method is however sensitive to the type of terrain where the geo-localization takes place. While flying over urban areas the success rate of the image registration algorithm is high, while the success rate is lower when flying over rural areas. The reason is the fact that urban areas are more structured and easier to match compared to rural areas. From experience acquired during several flight-tests, we have verified that this method can be applied successfully for accurate geo-location of cars driving on a road system.

Another challenge is represented by the dynamic changes in the environment. It might occur that a reference image is obsolete after some time. For this reason, considering that small details change quite fast (e.g. car moving on the road) while large structures tend to be more static (e.g. roads, buildings...), flying at higher altitude makes the registration more robust to small dynamic changes. On the other hand, if small objects have to be localized, the flight altitude cannot be too high otherwise the object will not be visible. A trade-off between the two constraints must be found in order to choose the optimal flight altitude. In regard to seasonal changes, in general urban areas are less sensitive to this phenomenon than rural areas.

The problem of registering flight images to a satellite or aerial image is an object of great interest in the research community. A method based on the Hausdorff distance is used in Ref. 8 to match flight images to a satellite reference image. The images were taken from a full scale manned airplane and the purpose was to localize the airplane in the map. In Ref. 9 the authors have developed a method for registering aerial video images to a reference image for ground object geo-location. The registration experiment reported in Ref. 9 was performed using video images taken at a flight altitude of about 600 meters while, for our MAV application, the images are typically taken below 100 meters altitude which introduces different kinds of problems. Another difference is that video-to-video frame alignment is not performed in our approach, i.e. here an image mosaic is not built but each single image is matched to the reference image.

The emphasis of this paper is placed on describing the image registration method developed for ground object geo-localization. In addition an experimental comparison with a localization method based on standard ray tracing calculation is also discussed. The work presented here uses results from an ongoing research project where the goal is to use satellite images to navigate an UAV without the use of the GPS system.[10]

II. Ground target geo-location based on ray tracing

This section summarizes briefly the problem of ground target localization based on the ray tracing approach which will be used for comparison against our approach.

In the ray tracing method, a ray starting from the camera center and ending at the ground object is ideally drawn (Figure 2). If the distance between the aircraft and the object λ can be measured (typically with a laser range finder on larger platforms) or estimated, the problem of finding the object position in the world can be geometrically solved. If the range is unknown, a terrain elevation model of the area can be used. It is assumed that the MAV state is known (position, attitude and camera orientation) from the on-board sensors. The ground object is measured in the camera reference frame (X_c,Y_c,Z_c) but the goal is to determine the objects position in the world or inertial frame (X_i,Y_i,Z_i). A sequence of coordinate transformations must be applied to express the object position from the camera frame into the world frame. Such coordinate transformations follow a standard scheme and can be found in the literature. A detailed mathematical description of this problem can be found in Ref. 4.

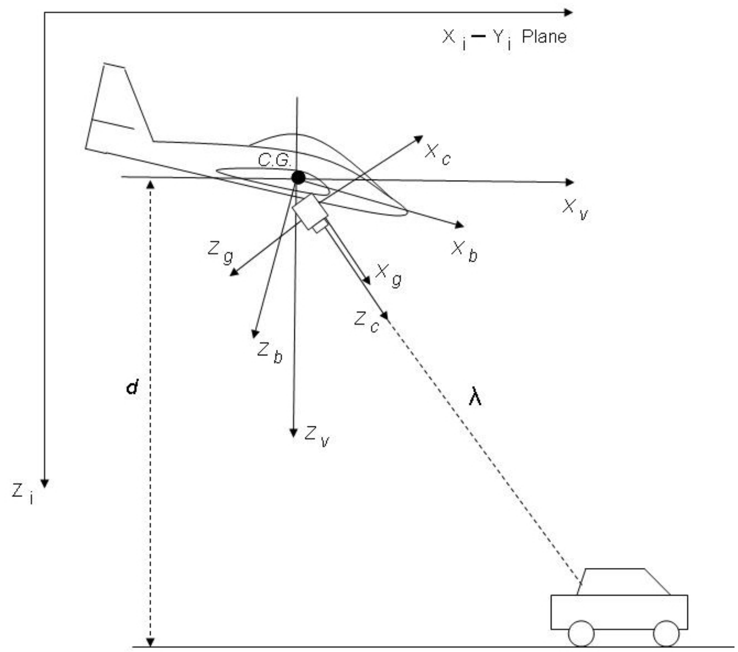

Figure 2. Geometry of the geo-location problem.

III. Ground target geo-location based on image registration

The MAV system used for the experimental tests will be described in detail in section IV. It is important to mention that the MAV flying platform is equipped with an autopilot which allows it to fly autonomously. This allows to plan optimized search patterns and relives the operator from flight control tasks, allowing to concentrate on the detection and classification task (tasks where the human is still better than the machine). In addition a video camera is placed in the bottom part of the airframe and is mounted on a pitch-roll unit being able to rotate around the airplane pitch and roll axes (Figure 6). The pitch-roll camera unit is controlled from the MAV autopilot and programmed to counteract the MAV's pitch and roll rotations in order to keep the video camera always looking downwards perpendicularly to the terrain. By doing this, the deformation due to perspective can in practice be neglected and the video images can be directly matched with ortho-rectified reference images.

The video stream is transmitted to a laptop on the ground which performs the image processing tasks and calculates the geo-location of the ground target. The reference image of the area where the MAV will perform the target identification and localization tasks is stored in the image processing laptop beforehand. The sensed images transmitted from the MAV are grabbed and processed on-line. Subsequently the images are aligned and matched with the reference image. A second laptop is used to communicate with the MAV autopilot and receive telemetry data. The telemetry data is transmitted through an Ethernet connection to the image processing laptop and used for ground object localization.

The ground object is identified and the tracker initialized manually in the down-linked video from a ground operator. After the initialization, the object is tracked in subsequent image frames automatically using a template tracking algorithm. Details of the tracking method are presented in section IV. The result from the tracking algorithm is a pixel coordinate (x_p,y_p) of the object in the image frame. The calculation from pixel to world coordinates is done automatically by the system using the image registration method presented in this section.

A. Image registration

Image registration is the process of overlaying two images of the same scene taken at different times, from different viewpoints and by different sensors. The registration geometrically aligns two images (the $reference$ and *sensed* images). It consists of a sequence of image transformations, including rotation, translation and scaling which bring the sensed image to overlay precisely with the reference image. Image registration has been an active research field for many years and it has a wide range of applications. A literature review on image registration can be found in.[11,12]

Two main approaches can be used for image registration: $correlation - based\ matching$ and $pattern\ matching$. In the correlation-based matching the sensed image is placed at every location in the reference image and then a similarity criteria is adopted to decide which location gives the best fit. In pattern matching approaches on the other hand, salient features (or landmarks) are detected in both images and the registration is obtained by matching the set of features between the images. Both methods have advantages and disadvantages.

Methods based on correlation can be implemented very efficiently and are suitable for real-time applications. They can be applied also in areas with no distinct landmarks. However they are typically more sensitive to differences between the sensed image and the reference image than pattern matching approaches.

Methods based on pattern matching do not directly use image intensity values. The patterns represent information of a higher level. This property makes such methods suitable for situations when illumination changes are expected. On the other hand these methods work only if there are distinct landmarks in the terrain. In addition, a pattern detection algorithm is required before any matching method can be applied.

The approach used in this work falls into the correlation-based matching category and it was chosen mainly because of the lower computational requirements. Contours (or edge) images are used for the experiment presented here. The choice of edge features derives from the fact that edges are quite robust to environmental illumination changes. The reference and sensed images are generally taken at different times, it can be months or years, therefore it has to be expected that the illumination conditions differ. The image registration scheme implemented is represented in the block diagram in Figure 3.

The sensed image is pre-processed as follows. The image is converted into gray scale and compensated for the camera lens distortion. A median filter is applied in order to remove small details which are visible from the sensed image but not visible from the reference image. The median filter, has the well-suited property of removing small details while preserving the sharpness of the edges. After filtering, the Sobel edge detector is applied. The edge image must then be scaled and aligned to the reference image. Scaling is performed by converting the edge image to the resolution of the reference image. The scale factor s is calculated using Equation (1):

$$\begin{pmatrix} s_x \\ s_y \end{pmatrix} = \begin{pmatrix} \frac{1}{f_x} \\ \frac{1}{f_y} \end{pmatrix} d \cdot I_{res} \tag{1}$$

where f_x and f_y are the focal lengths of the camera in the x and y direction of the image plane, I_{res} is the resolution of the reference image and d is the MAV ground distance (Figure 2).

The ground distance is calculated using the flat world assumption. This is a common practice in MAV applications since, due to their small size, it is difficult to find range sensors which have the capability of measuring distances of hundreds of meters with a power consumption affordable for such platforms. In any case, since typical flight distances covered by MAV platforms are relatively short, the altitude variation can be considered negligible (of course this assumption does not apply in extreme cases such as mountain regions). The ground distance is then calculated using a barometric pressure sensor (the atmospheric pressure at the ground level is taken before take-off so that the differential pressure during flight can be converted into ground altitude). An alternative option to the flat world assumption, is to use a ground elevation database to compute the MAV's ground distance. Software like Google Earth has begun to include an elevation database together with the satellite images. This option will be the focus of future experiments.

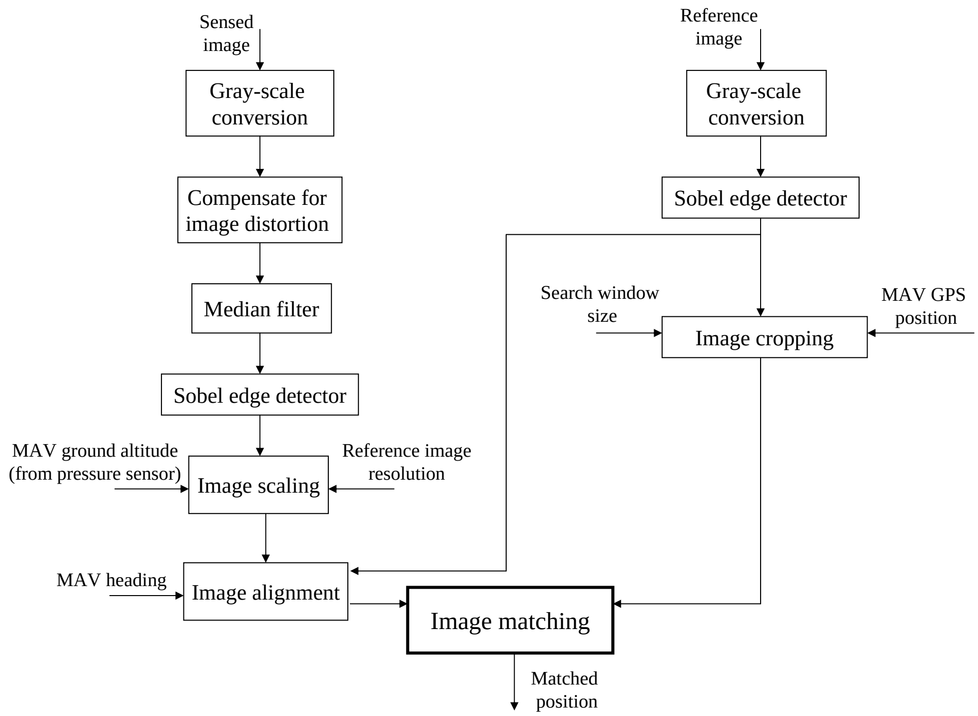

Figure 3. Image registration schematic.

The sensed image is then aligned to the same orientation as the reference image. The alignment can be made using the heading information available on-board the MAV. Unfortunately, the heading accuracy needed for a successful matching is not enough. Therefore a method as to how to accurately align the sensed images to the reference image was developed and will be described in subsection C. The on-board heading is used as an initial guess in the alignment calculation.

The reference image is processed as follows. It is converted into gray scale and the Sobel edge detector is applied. This is done only once, prior to flight, the resulting edge image is then kept in memory and used during flights. The MAV position taken from the on-board GPS receiver is used as the center of a restricted search area in the reference image. The purpose is to speed up the registration process, disregarding areas of the image too far from the ground target.

After both images have been processed and aligned as explained above, a correlation-based matching algorithm computes the 2D image translation which gives the best matching position. The method proposed gives the best success rate over road networks. Once the match is obtained, the sensed image containing the target can be geo-referenced. A screen shot which shows how the two images are processed and then matched is shown in Figure 4.

Ongoing experiments using normalized-cross correlation[13] of intensity images (instead of contour images) have shown better matching performances. In any case, contour images are still needed in order to apply the image alignment algorithm described in subsection C.

B. Image distortion compensation

Prior to acquiring any images during flight the on-board camera is calibrated using a Calibration Toolbox for Matlab.[14] It is a convenient tool for determining the intrinsic camera parameter, namely focal length (f_x,f_y), principal point (c_x,c_y), radial distortion (k_1,k_2,k_3), tangential distortion (k_4,k_5) and the skew coefficient ($alpha$). Distortion from the images acquired by the on-board camera is removed at the beginning of the image processing pipeline.

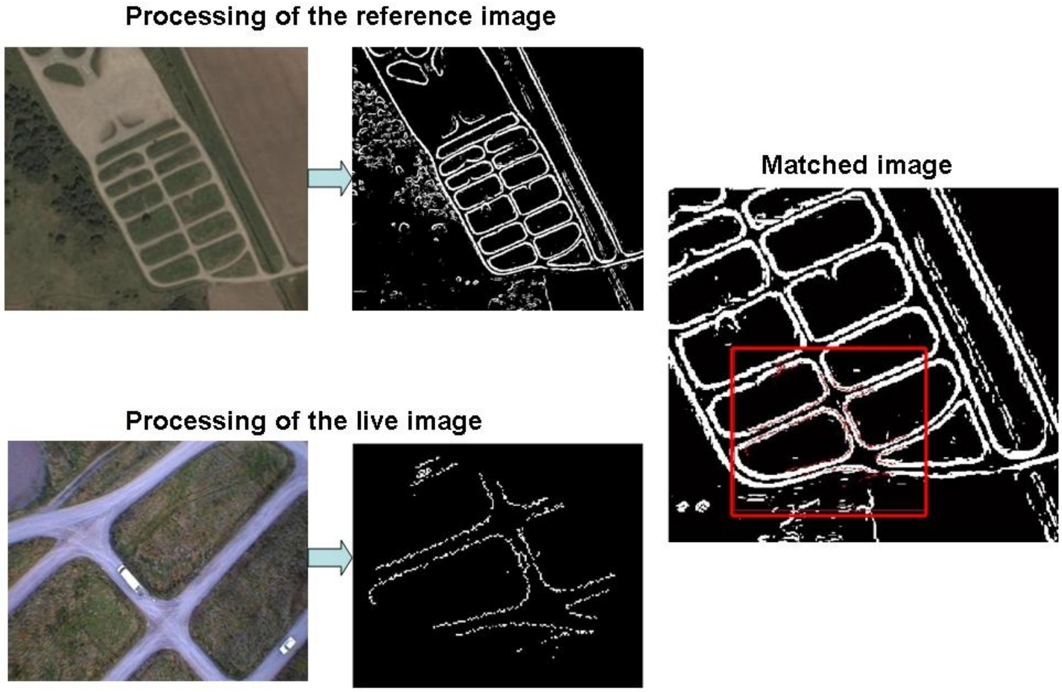

Figure 4. Processing of the reference and sensed images with final match.

C. Image alignment

This subsection describes the algorithm developed to align the sensed image to the reference image. For alignment we mean the rotation of the sensed image around the Z_v axis (Figure 2) until the orientation coincides with the one of the reference image. During the experiment the camera Z_c axis is parallel to the Z_v axis, i.e. the camera is pointing downwards.

Algorithm 1 represents the image alignment block in Figure 3. It is based on the *Standard Hough Transform* which is a well known image processing technique used to detect lines in an image. The lines are parametrized as follows:

$$\rho = x \cdot cos(\theta) + y \cdot sin(\theta) \tag{2}$$

where ρ is the distance from the origin to the line along a vector perpendicular to the line and θ is the angle between the image X axis and this vector. The Hough Transform finds the parameter space θ-ρ which identifies the eventual lines in the image.

Algorithm 1 **Algorithm for image alignment**

1. Rotate the sensed image after scaling (see Figure 3), to the north direction (the reference image is also oriented to north) using the MAV heading information coming from the telemetry data. The resulting image is called $image1$.
2. Extract a cropped image from the reference image where the center point coincides with the MAV GPS coordinates and window size equal to the size of $image1$. This image is called $image2$.
3. Compute the Standard Hough Transform of $image1$ and $image2$ and detect the corresponding lines in both images.
4. Compute the angle differences between the corresponding lines of $image1$ and $image2$ and calculate the average angle difference θ_{avg}.
5. If $|\theta_{avg}|$ is less than 45 degrees, rotate $image1$ of θ_{avg} degrees otherwise keep the orientation of $image1$ (this step assumes that the maximum heading error coming from the telemetry data is 45 degrees).

Using Algorithm 1, the matching success rate improves dramatically. Experimental results have shown that using Algorithm 1 to align the images gives up to 3 times less false matches than using only the heading coming from telemetry.

D. Ground object position calculation

The final ground object position is obtained as follows. After an object is selected by the ground operator, the template matching algorithm is initialized and every time the object is in view it is automatically recognized by the template matching algorithm and the relative image saved together with the pixel coordinates of the template (the middle point of the template is considered to be the target position). Subsequently, the stored images (sensed images) are automatically registered to the reference image using the method previously described. After the sensed image has been geo-referenced, the world coordinates of the object can be calculated using the pixel coordinates of the tracked template. Since the sensed image has been rotated before the matching, the template coordinates must be rotated using the same angle before the object world position can be extracted. The final object position is estimated using a recursive least square filter.

IV. MAV system overview

The following section describes the system which has been used as a flying testbed for the validation of the method presented. All functional subcomponents and interconnections between them are depicted in Figure 5. The main components of the MAV system are a fixed-wing MAV flying platform and a ground control station which includes 2 laptop computers. Three types of communication links are used as presented in Figure 5.

1. The communication with the autopilot is realized using an AeroCom AC4868 868MHz modem.[15] The communication is bidirectional as can be seen from Figure 5. A ground control computer can interact with the MAV sending flight instructions to the autopilot. The operator can change or add new waypoints dynamically during autonomous flight. The autopilot delivers the MAV state at 5Hz rate which is transmitted to the ground control computer for flight monitoring. In addition, the MAV state is transmitted to the image processing computer through an Ethernet connection and used for image registration.
2. An on-board analog video transmitter working on 2.4GHz frequency transmits the video to the ground. A diversity video receiver is connected to the image processing computer where the video is sent for image analysis. Both transmitter and receiver are from Black Widow A/V.[16]
3. The third communication link is between the backup pilot and the MAV. It is realized using a standard R/C transmitter and receiver and used in case of emergency, such as loss of navigation capability (GPS

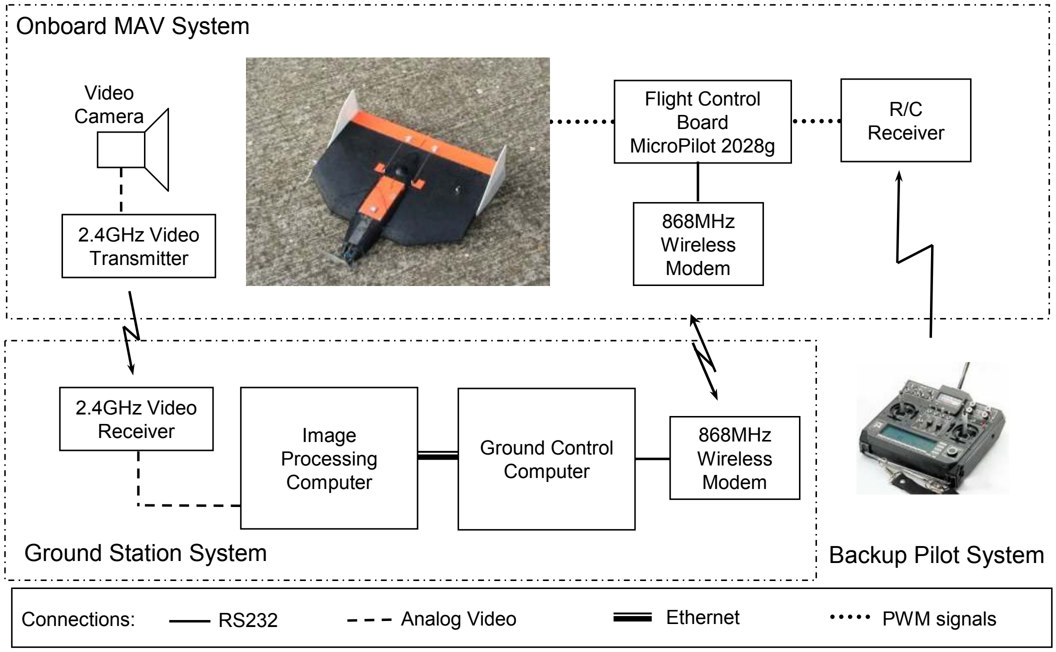

Figure 5. MAV system setup.

unlock) or failure of the autopilot.

A. Airframe

The MAV flying platform used in the experiments is called *PingWing* (Figure 1), an in-house designed and manufactured flying wing. It is electrically powered with a brushless engine and Li-Po batteries. It has a wing span of 41 centimeters and a total weight of 434 grams. The flight endurance is 25 minutes with a cruise speed of 19m/s. The PingWing weight distribution is shown in Table 1.

Airframe	108 g
Propulsion (incl. batt.)	122 g
Servos/receiver	31 g
Video system (incl. camera gimbal)	62 g
Data link	25 g
Autopilot	86 g
TOTAL	434 g

Table 1. PingWing weight distribution.

B. Autopilot

The autopilot used on-board is a commercial flight control board MP2028g manufactured by the Micropilot company.[17] It is a lightweight system equipped with a 3-axis gyro, 3-axis accelerometer, a 4Hz Ublox GPS receiver, a pressure altimeter and a pressure airspeed sensor integrated on a single board. The autopilot is furnished with a standard control system implemented but can also be programmed and personalized by the user using the Xtender^{mp} software. The software is used to configure the autopilot telemetry in order to send the flight data from the ground control computer to the image processing computer. The compass sensor was not used in this experiment and heading information is derived from the GPS.

C. Video system

The PingWing is equipped with a lightweight CCD camera Videotronik VTQ-56. Details of the video camera and lens used are reported in Table 2.

Image sensor	1/4" CCD
Resolution	490 TV lines
Sensitivity	1 lux
Lens	f=3.6mm (53° FOV)
Dimensions	25 x 25 x 22 mm

Table 2. Details of the video camera and lens used for the experiment.

The camera is mounted in an in-house developed pitch-roll gimbal (Figure 6) which allows automatic image stabilization.

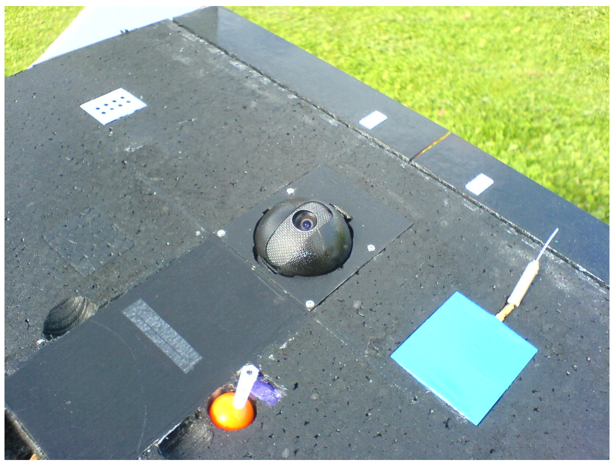

Figure 6. Pitch-roll camera gimbal.

The image processing functionalities have been implemented in the LabVIEW environment.[18] The software developed is capable of the following tasks: simultaneous recording of camera images and corresponding telemetry, tracking of a ground object, computation of the targets position in world coordinates using the ray tracing method (see section II) and the automatic image registration method described in this paper.

The images coming from the video receiver are grabbed using the IMPERX VCE-PRO[19] frame grabber with a resolution of 720x576 pixels. To reduce the amount of data only those images in which the ground target is visible are recorded. This is accomplished by utilizing a color pattern tracker provided by the NI Vision module available in the LabVIEW environment. For an extensive description of the color tracker the reader may refer to Ref. 20, 21.

The ground target geo-location procedure is implemented as follows. The first step consists in creating a template image representing the search object. This is done by the user only at the beginning when the object is first seen in the transmitted camera image. The object to be tracked has to be selected by the operator and a window with a predefined size is automatically drawn with the selected point as middle pixel. Subsequently to creating the template image the algorithm has to learn the relevant features of the template. The learning process depends on the setup parameters specified for the learning phase. The appropriate parameters used in the learning phase and during the matching process have been determined empirically and depend on the object to be tracked and differing environmental conditions. The pattern matching algorithm searches for the template in each of the following images using color and shape information. Since searching the entire image for matches is extremely time consuming a coarse-to-fine search strategy first locates a rough position. The location is refined in a second step using a hill climbing algorithm around each match.[20] The result of the template tracker is the position of the template in the image plane (pixel coordinates). The objects position is assumed to be at the center of the template. The size of the template is predefined for convenience and it is chosen according to the predicted object size and the typical flight altitude. The calculation from the pixel coordinates to world coordinates is done using the image registration approach described in section III. Before the sensed images are registered, they are reduced to half resolution 360x288 to speed up the computation. The results are compared with the actual coordinates of the target, in our case measured with a stationary GPS, and employed for error analysis.

The program can be utilized for various scenarios, i.e. in any environment because any geo-referenced image can be loaded. Parameters specifying essential attributes of the reference image, e.g. image dimensions and image resolution, as well as camera parameters, e.g. focal length, principal point, radial and tangential distortion, have to be entered in user interface.

V. Experimental results

This section presents the experimental results of a ground object geo-location using the approach described in this paper. The MAV system used for the experiment has been described in section IV. The experiment consists in flying the PingWing autonomously over a road system with the task of computing the location of a truck parked on one of the roads. The truck does not move during the experiment. As soon as the truck is in the camera view, the ground operator selects the template window in the image and starts the tracking algorithm (Figure 7).

The PingWing flies autonomously in a figure of eight centered on the ground target (Figure 7) at a constant altitude of 70 meters. Every time the template tracking algorithm recognizes the target, it saves the image together with the target pixel position. The images are then registered to a geo-referenced image of the area and the truck position calculated as described in section III. The image registration algorithm runs at about 3Hz rate while the template tracking algorithm tracks the object at about 5Hz frame rate.

Figure 7. On the left picture is displayed the MAV's flight path during the ground object localization task. On the right, the ground object is automatically tracked in the image (red square).

The geo-referenced image used for this experiment was acquired from Google Earth. The truck position is measured with a GPS receiver (used as a reference position instrument) which has an accuracy of about 2-3 meters. A bias of 3 meters was found between the measurement taken with the reference GPS and the corresponding position calculated using the Google Earth image. In order to avoid errors introduced by the reference GPS, the bias of the Google Earth image was compensated using the GPS measurement.

Figure 8 shows the results of the target geo-location calculated with the image registration method. It can be observed that there are some outliers due to incorrect matches. The incorrect matching occurs because, as can be seen in Figure 7, the road system presents repetitive structures which are quite similar to each other. It can happen that the matching algorithm registers the sensed image to a similar location which is not the right one. Anyway the number of false matchings are sporadic and can be filtered out. Figure 9 displays the position error of the measurement samples (top) and the result of the recursive least square filter applied to the measurement data (bottom). The error stabilizes after 20-30 samples. The estimated target position error is about 2.3 meters. The outlier measurements are also included in the filtering process but do not have a major influence in the final result.

As a comparison, using the same data set the ground target position was calculated with the ray tracing

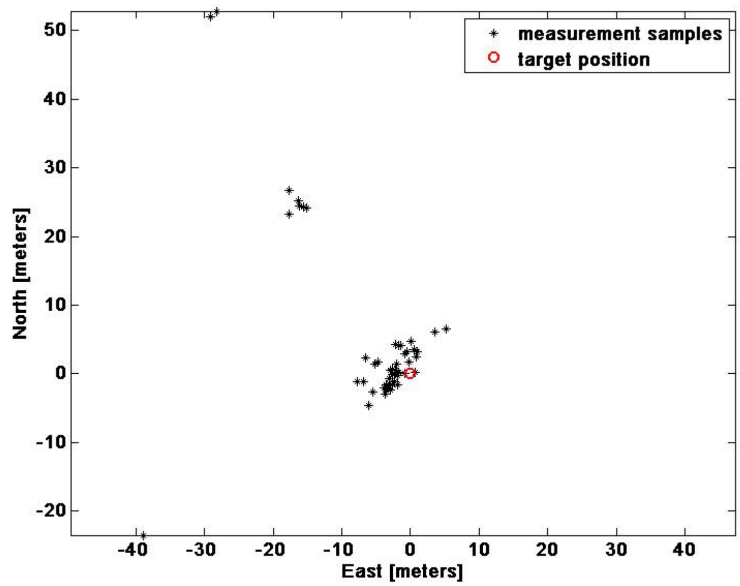

Figure 8. Ground target position measured from the MAV system using the image registration technique described in the paper. The target position is in (0,0).

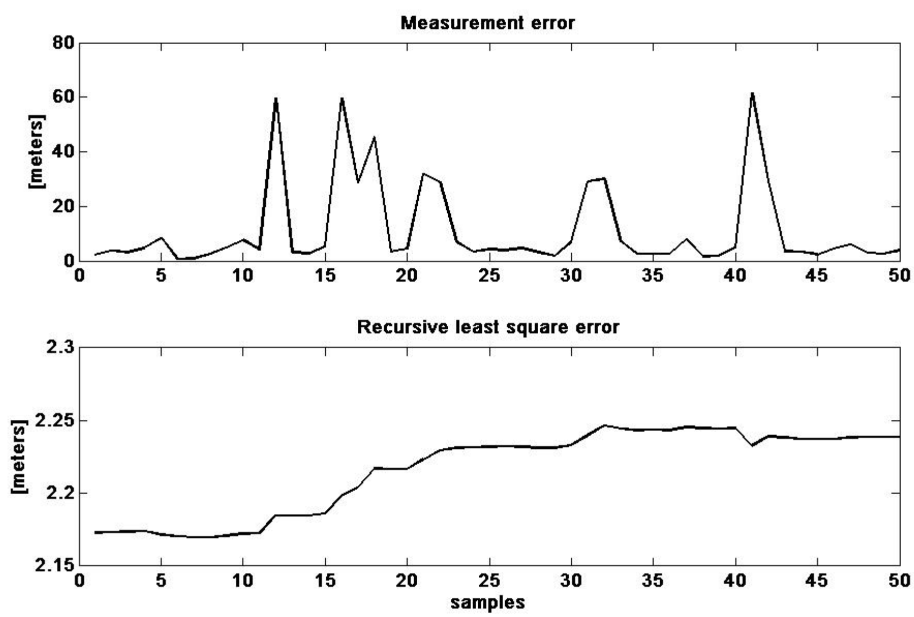

Figure 9. Top figure: target collocation error using image registration technique. Bottom figure: estimated target error using recursive least square filter.

method described in section II. For this calculation the MAV sensor data coming from the telemetry was used. In Figure 10, it can be observed how the measurement samples are spread over a larger area compared to Figure 8. In addition the sample distribution has a bias which leads to an estimated target position error of about 22 meters as it is displayed at the bottom of Figure 11. The bias could be compensated by choosing a flight path which makes a circle around the target as it is shown in Ref. 4.

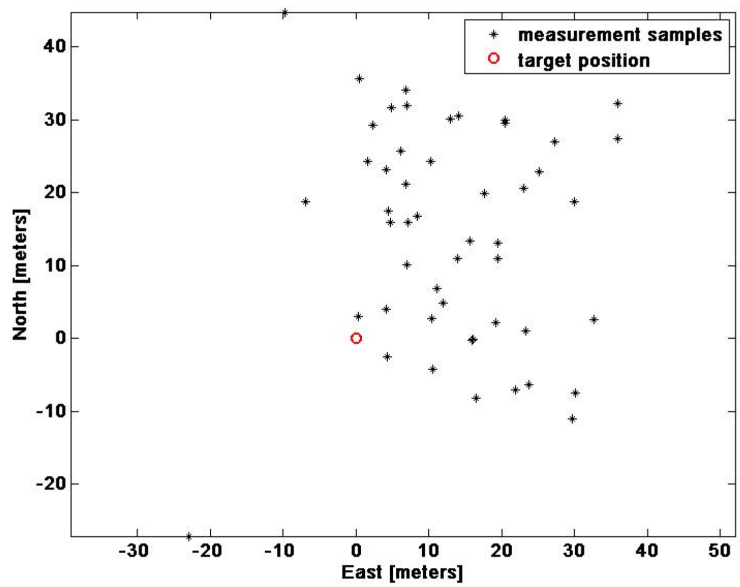

Figure 10. Ground target position measured from the MAV system using the standard ray tracing technique. The target position is in (0,0).

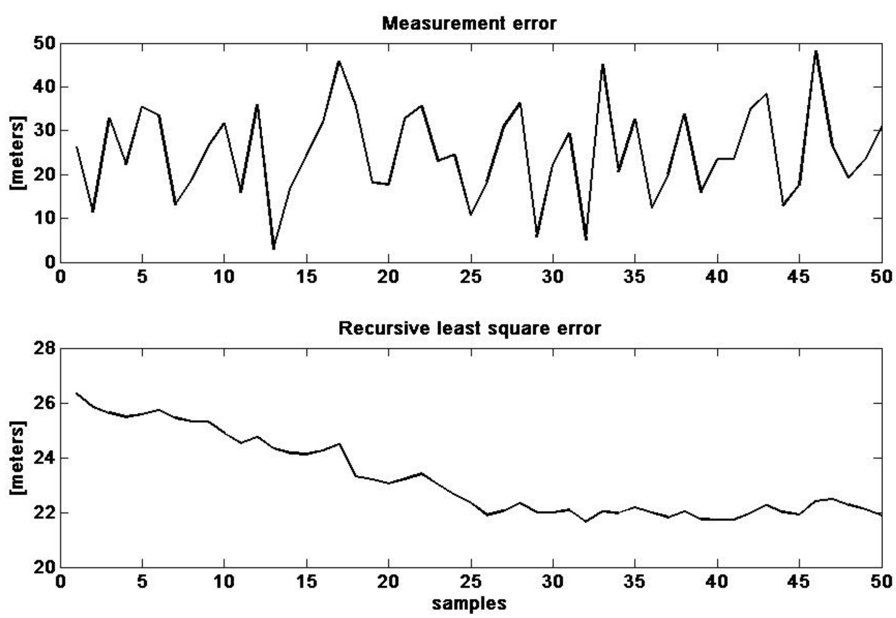

Figure 11. Top figure: target collocation error using the ray tracing technique. Bottom figure: estimated target error using recursive least square filter.

VI. Conclusion

This paper describes a vision based approach to ground object geo-location based on satellite image registration. The method has been implemented successfully using a MAV platform. The main advantages using this method can be summarized in the following points:

1. High accuracy ground target localization is reached also using low performance sensors.
2. Instantaneous performances (vs. asymptotic). In contrast to other approaches which require many measurement samples, this method allows high accuracy using only a few samples.
3. A specific flight path around the target is not required for a successful application of the approach.

The method is applicable in urban areas where the road network is dominant, or in any other environment with a relevantly structured clutter.

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