Use of Geo-referenced Images with Unmanned Aerial Systems

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Abstract. This contribution presents recent results on the use of geo-referenced satellite or aerial images with Unmanned Aerial Vehicles (UAV). The paper describes two different applications.
Outdoor autonomous UAVs rely on the GPS signal in order localize themselves in the environment. If the GPS is unavailable the UAV is blind and cannot navigate safely. The GPS signal is quite weak and can be jammed easily therefore a method how to cope with short and long term GPS fallouts is essential for a safe UAV operation. The first application shows how reference images can be used to localize and navigate a UAV in case the GPS is unavailable. Experimental results using a UAV helicopter platform will be presented.
The second application describes how the use of a reference image can improve the ground object geo-location capability of a fixed-wing Micro Aerial Vehicle (MAV) of only 400 grams. Such small platforms have a low kinetic energy therefore are reasonably safe for humans. On the other hand their limited payload capabilities does not allow to carry accurate sensors on-board. The use of reference images improves the ground target localization accuracy for MAV platform with limited sensor accuracy.

Key words: UAV, autonomous navigation, image processing, sensor fusion, vision based, target geo-location.

1 Introduction

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 [9, 7]. 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 which won the 1st US-European MAV Competition (MAV05) as "best rotary wing". Later, a fixed-wing MAV was also developed in-house and won the 3rd US-European Micro Aerial Vehicle Competition (MAV07) which took place in Toulouse in September 2007.

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One of the main concern which prevents the use of UAV systems in populated areas is the safety issue. State of the art UAV systems are still not able to guarantee an acceptable level of safety to convince aviation authorities to authorize the use of such a system in populated areas. There are several problems which have to be solved before unmanned aircrafts can be introduced in the civilian airspace. One of them is the GPS integrity problem. A standard UAV navigation system often relies on GPS and inertial sensors (INS). If the GPS signal for some reason becomes unavailable or corrupted, the state estimation solution provided by the INS alone drifts in time and will be unusable after a few seconds (especially for small-size UAVs which use low-cost INS). The GPS signal also becomes unreliable when operating close to obstacles due to multi-path reflections. In addition, it is quite vulnerable to jamming (especially for a GPS operating on civilian frequencies). A GPS jammer can be found on the market quite easily and instructions on how to build such device can be found on the Internet. Therefore UAVs which rely blindly on a GPS signal are quite vulnerable to malicious actions. For this reason, a navigation system for autonomous UAVs must be able to cope with short and long term GPS fallouts. The research community is making a great effort to solve this problem in different ways. One potential solution is based on enhancing the navigation system using a suitable vision system.

Visual navigation for UAVs has been a topic of great interest in our research group. Great effort has been put into the development of a vision-based autonomous landing functionality. In [11] a vision-based landing system which uses an artificial landing pattern is described. The system is capable of landing an unmanned helicopter autonomously without using the GPS position information.

A video camera is an appealing sensor which can be used to solve navigation related problems. Almost every UAV already has a video camera as a standard sensor in its payload package. Compared to other sensors, e.g. laser, video cameras are quite light and less power hungry. A color image contains a huge amount of information which could be used for several purposes. On the other hand passive video cameras are quite sensitive to environmental light conditions. Abrupt illumination changes in the environment (for example sun reflections) represent a great challenge for a vision system which is supposed to provide position information robustly.

The first problem addressed in this paper is concerned with the capability of an UAV to be able to navigate to home base in case the GPS signal is lost ("homing" problem). An experimental autonomous UAV platform based on the commercial Yamaha Rmax helicopter (Figure 1) is used as a test-bed for the development and testing of a navigation architecture which can cope with GPS failures. The navigation system proposed replaces the GPS signal combining together a visual odometer and an algorithm which registers the on-board video to a geo-referenced satellite or aerial images. Such images must be available on-board the UAV beforehand. The growing availability of high resolution satellite images (for example provided by Google Earth) makes this topic very interesting.

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Fig. 1. The Rmax helicopter.

In the near future, access to high resolution images for many areas of the world will not represent a problem any longer.

The navigation architecture proposed to solve this problem fuses information obtained from an INS composed of three gyros and three accelerometers, a monocular video camera and a barometric pressure sensor. Sensor information is fused using a Kalman filter to estimate the full UAV state (position, velocity and attitude). Two image processing techniques, feature tracking and image registration, are used to update the navigation filter during the time the GPS is unavailable. A KLT feature tracker implementation [14] is used to track corner features in the on-board video image from subsequent frames. An odometer function uses the KLT results to calculate the distance traveled by the UAV. Since the distance calculated by the odometer is affected by drift, a mechanism which compensates for the drift error is still needed. For this purpose a geo-referenced image registration module is used. When the image registration is performed correctly, it is possible to calculate the absolute position of the UAV which is drift-free. In other words, the position information obtained is similar to the one provided by the GPS.

Furthermore this paper addresses the problem of vision-based ground object geo-location using reference images. The platform used for this experimentation is a fixed-wing micro aerial vehicle named $PingWing$ (Figure 2).

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. To achieve such accuracy is a great challenge when using MAV platforms due to the fact that MAVs of a few hundred grams can

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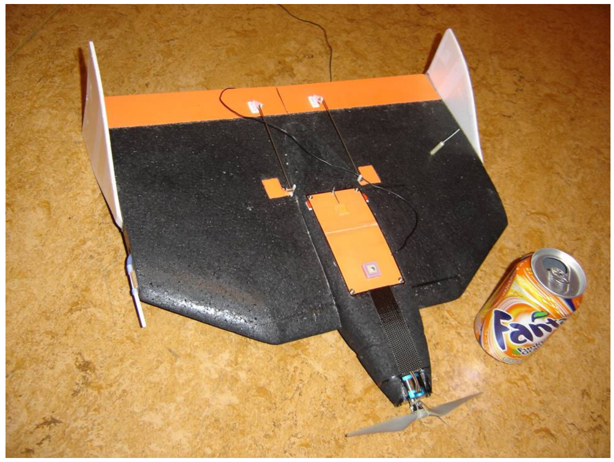

Fig. 2. *PingWing* micro aerial vehicle platform developed at Linköping University.

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 use of reference images for target localization relaxes the dependency from the on-board sensor accuracy. In other words the localization accuracy depends mainly from the reference image accuracy.

The paper is structured as follows. Section 2 describes the vision-based state estimation architecture and in particular how the reference images are used to navigate an UAV in case the GPS is unavailable. Section 3 describes how the reference images are used to improve the geo-location accuracy of a ground object observed from a MAV platform.

2 Vision-based UAV state estimation based on reference images

The vision-aided sensor fusion architecture proposed for the non-GPS navigation is displayed in Figure 3. A standard 12-state Kalman filter estimates the full UAV state (position, velocity and attitude) fusing inertial sensors with a position source like GPS for example. It can be noticed how the GPS position signal, when it is not available, is replaced with the position information provided by the vision system.

The vision system computes the UAV position update fusing together the position calculated from the visual odometer and the position calculated from the image registration module. The position fusion algorithm is based on a grid-based approach, called Point-mass filter [2], which computes a discretized solution for the Bayesian filtering problem.

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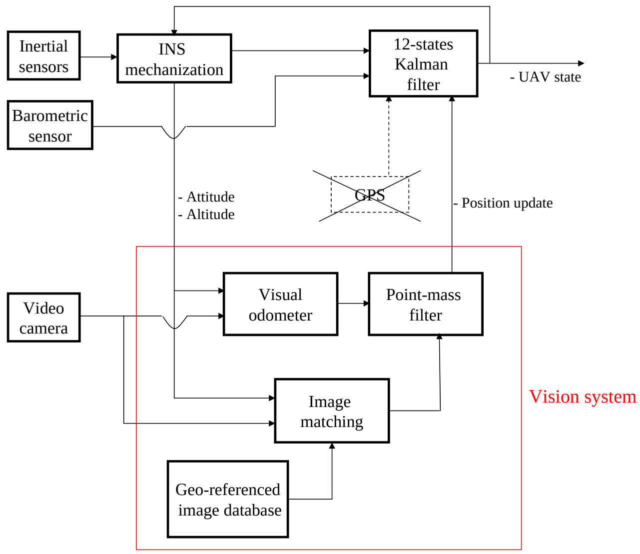

Fig. 3. Vision-aided sensor fusion architecture.

The visual odometer is based on the KLT feature tracker [14] and it computes the helicopter displacement form frame-to-frame. More details on the visual odometer used in this work can be found in [5]. The position calculated from the visual odometer is affected by drift therefore a mechanism which compensates for the odometer drift is needed. An image registration technique is used to provide absolute position measurements to compensate for such drift.

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. 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 [3, 15]. In this context it is used to extract global position information for terrain relative navigation.

The matching approach used for this work is based on normalized cross-correlation technique of intensity images [13]. The reason for this choice is that it can be implemented efficiently on a standard computer allowing real-time performance [10]. Cross-correlation is the basic statistical approach to registration. Cross-correlation is not a registration method, it gives a measure of the degree of similarity between an image and a template. Image registration is the sequence of image transformations, including rotation, translation and scaling which bring the sensed image to overlay precisely with the reference image. Here, the reference and sensed images are aligned and scaled using the information provided by the Kalman filter (Figure 3). The cross-correlation function measures the similarity for each translation. The result of the normalized cross-correlation

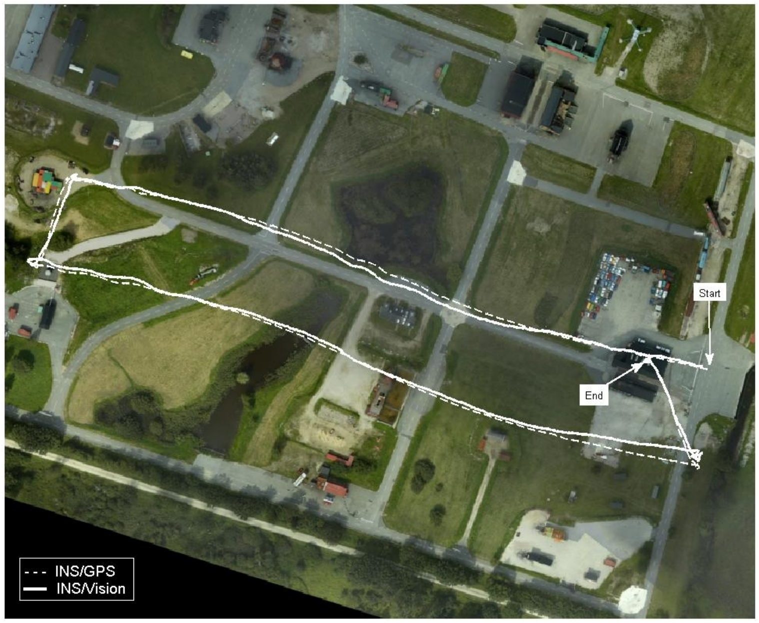

Fig. 4. The UAV path computed from the vision-based navigation filter (continuous line) is compared to the INS/GPS solution (dashed line).

computation is a correlation map which is used as position likelihood over the search region.

The Point-mass filter fuses the odometer position with the position likelihood from the image registration and provides drift-free position update for the Kalman filter. The reader can refer to [2] for more in-depth theoretical details on this fusion technique.

The architecture proposed in Figure 3 has been tested on real flight-test data and on-board video. The platform used for the flight-test is the Yamaha Rmax helicopter (Figure 1). The platform is capable of fully autonomous flight from take-off to landing. It weights 100Kg and its avionics package includes three embedded computers PC104 for flight control, image processing and high-level mission functionalities such as path-planning. Synchronized inertial data, barometric altitude and on-board video were acquired during an autonomous flight and used off-line to demonstrate the possibility to estimate the helicopter state without using the GPS information. The off-line results of the approach are depicted in Figure 4. A GPS based Kalman filter solution is used as reference instrument to validate the results. The length of the helicopter path is about 900 meters and was flown at 60 meters altitude. The resolution of the reference image used is of 1 meter/pixel. From Figure 4 can be observed that the complete path was reconstructed using the vision-based architecture. It can also be noticed that the position error from the GPS reference is small during the whole path.

The vision-based sensor fusion architecture presented has been implemented on-board the Rmax helicopter and runs in real-time. An ongoing flight-test campaign aims at demonstrating the fully autonomous non-GPS navigation capability of the helicopter.

3 Vision-based ground object geo-location

The problem of target geo-location has been addressed previously in the literature [1, 12, 4, 8]. 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 [1] 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 adopted 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. 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 a specific flight path around the target is not required. 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, 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.

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The MAV flying platform used for this experiment is depicted in Figure 2 and is equipped with an autopilot and capable of performing autonomous flight missions. 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. 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 in the image processing laptop. 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. The result from the tracking algorithm is a pixel coordinate of the object in the image frame. The calculation from pixel to world coordinates is done automatically by the system using an image registration method. A detailed description of the image processing implemented and the hardware used for this work can be found in [6].

The experiment performed to validate this approach 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 5). The PingWing flies autonomously in a figure of eight centered on the ground target (Figure 5) 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 extracted after the registration. The image registration algorithm runs at about 3Hz rate while the template tracking algorithm tracks the object at about 5Hz frame rate.

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

Fig. 5. 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).

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 6 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. Figure 7 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 accuracy obtained in this experiment is greater than the one reached with other methods in the literature using MAV platforms of the same category.

4 Conclusion

The aim of this paper has been to show how a reference image of the flight area can be used to improve the navigation safety of a UAV relative to the GPS integrity problem. Moreover it has been shown how the use of reference images can improve the geo-location accuracy of a ground object in case the sensor performance of the platform does not allow to reach an acceptable localization accuracy.

The experiments presented rely on the assumption that the reference image of the area is available and also that the area presents matchable features. Usually urban environments are suitable for image registration while in homogeneous rural areas the image registration is less reliable.

The direction of future work is to build navigation maps where the areas suitable for image registration are labeled. Such information can be used as knowledge during the mission planning phase in order to take advantage as much as possible of the techniques discussed in this paper.

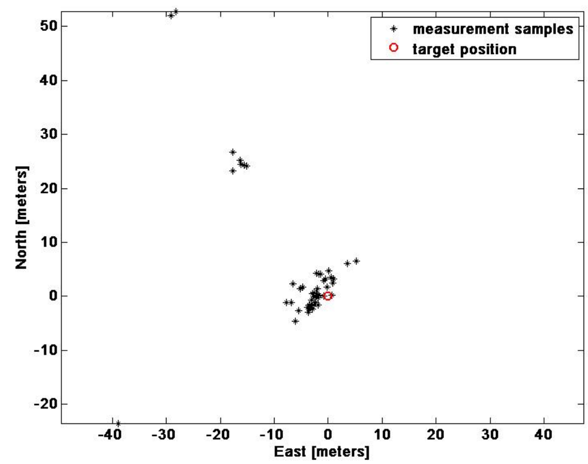

Fig. 6. Ground target position measured from the MAV system using the image registration technique described in the paper. The target position is in (0,0).

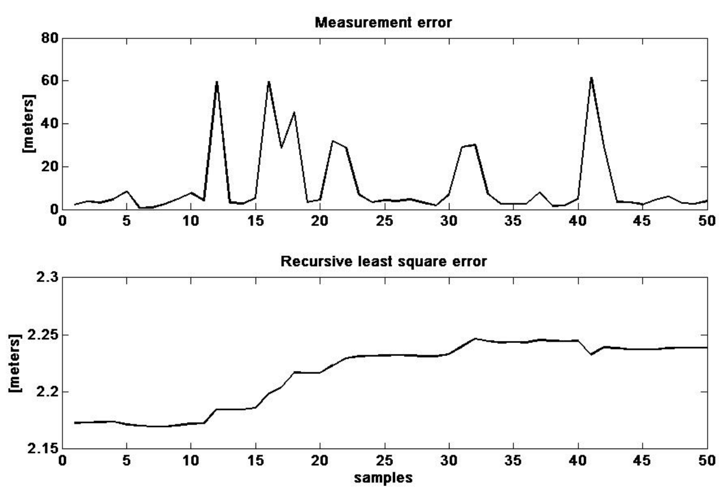

Fig. 7. Top figure: target collocation error using image registration technique. Bottom figure: estimated target error using recursive least square filter.

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