Absolute high-precision localisation of an unmanned ground vehicle by using real-time aerial video imagery for geo-referenced orthophoto registration

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Abstract. This paper describes an absolute localisation method for an unmanned ground vehicle (UGV) if GPS is unavailable for the vehicle. The basic idea is to combine an unmanned aerial vehicle (UAV) to the ground vehicle and use it as an external sensor platform to achieve an absolute localisation of the robotic team. Beside the discussion of the rather naive method directly using the GPS position of the aerial robot to deduce the ground robot's position the main focus of this paper lies on the indirect usage of the telemetry data of the aerial robot combined with live video images of an onboard camera to realise a registration of local video images with apriori registered orthophotos. This yields to a precise driftless absolute localisation of the unmanned ground vehicle. Experiments with our robotic team (AMOR and PSYCHE) successfully verify this approach.

1 Introduction

Cooperation among robotic teams has become a vibrant field of research in the recent past [1]. While many research projects in this special context focus on homogenous swarms of ground robots [2] the emphasis of this work lies on the cooperation between land-based and aerial vehicles. The complementary characteristics and features of these two types of robots suggest a combined usage in order to solve complex tasks in the field of outdoor robotics. The following explanations give a short overview of current research developments in the special context of (absolute) localisation and target detection with cooperative air/ground robot teams.

In [3] an extensive report on an adaptive system of heterogenous robots for urban surveillance using several aerial as well as land-based robots is presented. Beside performing mapping tasks the system is able to search and locate ground targets cooperatively. Cooperative ground target localisation has also been tackled in [4]. In [5] a method to realise an aerial image-to-GPS mapping is introduced which is used to generate a position measurement of a micro-UAV while the position of the accompanying ground vehicle is assumed to be known. This renders absolute localisation hardware unnecessary for the aerial robot. In [6] a vision-based target geo-location is achieved by using the position of the target in images taken from a UAV and the UAV's position, attitude and camera parameters to calculate the target's world coordinates. Furthermore extensive thoughts are spent on error reducing optimizations like RLS filtering or bias estimation. A method for self-localisation of an UGV by fusing high-resolution aerial LADAR data and local geometrical information of the environment recorded by the UGV is described in [7]. The structure of this approach is similar to our approach in this paper though the great difference of viewing points while recording the data to be matched induces problems that we overcame by using an additional UAV as external sensor platform. The registration of on-line aerial video images to prior geo-referenced imagery has been reviewed and successfully implemented in [8]. In this spirit our approach is similar to [8] but differs in several details. In [8] a feature based matching algorithm is proposed while we are using a template-based matching method. Furthermore we present a practical use case in the form of an GPS-less absolute localisation technique for an UGV which is described in detail in section 3.3.

2 Robotic platforms

Our cooperative robotic team consists of the unmanned ground vehicle AMOR and the unmanned aerial vehicle PSYCHE.

(a) (b)

Fig. 1. Cooperative robotic team: Autonomous Mobile Outdoor Robot AMOR (a) and Unmanned Aerial Vehicle PSYCHE (b)

AMOR (Fig. 1(a)) is built upon a commercial ATV (All Terrain Vehicle) platform by Yamaha. The mechanical platform allows a wide area of operational scenarios as it is robust and has notable cross-country capabilities on the one hand and is able to drive at high speeds while having a big operating range on the other hand. The sensor equipment of AMOR comprises various internal and external sensors enabling the robot to solve different autonomous tasks like obstacle detection/avoidance, vehicle/person following and textured 3D-map creation to mention only a few. Additional detailed information on AMOR and its system architecture can be found in [9,10].

The mechanical basis of the aerial robot PSYCHE (Fig. 1(b)) is a md4-200 quadrocopter by Microdrones. The basic platform which is already stabilized by inertial sensors and capable of holding the current GPS position, was extended at our institute by an additional ARM-microcontroller board, a 5,4 GHz wireless link and a self-constructed low-cost camera board to allow the real-time transmission of in-flight sensor and status information, video imagery and control commands using a standard PC equipped with a wireless link.

3 Cooperative UGV/UAV localisation

The precise self-localisation of a robotic system is an integral feature for a robust behaviour in an outdoor environment. Especially the absolute localisation of current state-of-the-art robotic systems is heavily dependent on a reliable signal by a GPS sensor. This signal is obviously determined by various uncontrollable external factors (e.g. vegetation, building density, satellite positions, ...) which forbid the assumption that a global position measurement of a robot can always be guaranteed by exclusive usage of GPS. Several ways of GPS-loss coverage have been investigated. These concepts - if depending on a GPS signal - always assume that there has been a valid GPS measurement in the past. At least for the problem of finding an initial GPS position at a mission starting point of a robotic system this assumption is not applicable. Beside this fact our system aims at a higher precision and sensor drift avoidance concerning the global position measurement of a robot while a GPS signal is unavailable.

Therefore we took a different approach to this problem by combining an unmanned aerial vehicle to the unmanned ground vehicle as we found that the negative factors influencing the GPS signal only apply to land-based vehicles in the majority of cases. Assuming that an aerial vehicle operating at a certain height always has a valid GPS signal (neglecting any weather-originating effects) we deduce the GPS position of the ground vehicle by the position of aerial vehicle using different techniques which will be presented in the following subsections.

3.1 Video tracking of UGV

At the beginning the most straight-forward solution for the task described in the previous section should be mentioned here shortly. To realize a very rough estimation of where the ground robot is located it is sufficient to enable the aerial vehicle to track the ground robot and while doing that submitting its current GPS position to the ground robot. The detection and tracking is realized solely by the application of digital image processing methods using data from the onboard camera of the UAV. Our implementation is able to detect our ground robot AMOR by applying a color segmentation technique which is detecting the prominent color of the back section of AMOR. Using this data it is possible to track our ground vehicle. Obviously the quality of the tracking is highly dependent on the quality of the detection of the UGV via color segmentation. Due to the fact that no further model-like information on our UGV is used the maximal error of the detection is approximately 50 centimeters while the typical detection error is approximately 25 centimeters with our implementation.

Clearly this method is only suited to generate a very rough global position estimation as it does not take parameters like the camera model or the aerial vehicle's pose into account and it cannot be assumed that the aerial robot is always located directly above the ground vehicle. These considerations will be discussed in the next subsection.

3.2 Pitch and roll compensation

To enhance the method described in the previous subsection an integration of aerial robot's pose and the camera model of the camera attached to it is of big importance. The pitch, roll and yaw angles of the aerial robot are used to realise a transformation into a fixed coordinate system originating from the center of gravity of the UAV. The x-axis of this coordinate system is pointing north while the y-axis is pointing west and the z-axis is parallel to the gravity vector. As the ground is assumed to be flat within our considerations the projection of the center of gravity of the UAV along the z-axis onto the ground plane can be calculated in the following using the height over ground of the UAV. Now the position of the ground vehicle has to be determined relating to the fixed coordinate system of the UAV. The previously measured position of the ground vehicle in camera coordinates (see 3.1) is subsequently transformed using the pose and the height over ground of the UAV. The result is the position of the UGV on the flat ground plane in the fixed coordinate system of the UAV. With that the position of the UGV and the projected position of the UAV on the ground plane are known in the same coordinate system and can therefore be used to deduce the UGV's absolute position in world coordinates from the UAV's absolute position.

This method appears to yield to an acceptable solution to our problem of localising a GPS-less UGV with a cooperating UAV. The inspection of the UGV positioning error introduced by even small errors in the relevant parameters unfortunately leads to a somewhat different assessment. Although the effect of erronous angle or altitude measurements is linear it is big enough to compromise the precision of the results severly. When flying at a height of 20 meters an error of 1 degree in either the pitch or roll angle of the UAV results in a positioning error of approximately 0.35 meters if the UGV is located directly in center of the camera image. If the UGV is located in the peripheral region of the aerial image the error even increases. Altitude measurement errors increases the positioning error further. With an average positioning error of 0.26 meters per erronous altitudal meter the effect is not as severe compared to the angular errors. These facts demand a high-precision measurement of pose and height of the UAV to realise an acceptable position measurement of the observed UGV which is not available due to limited hardware capabilities of small UAVs like our robot PSYCHE. This lead us to developing a fundamentally different concept which is presented in the following.

3.3 Orthophoto registration

As pitch and roll compensation suffer from a high dependency on the measurement quality of the pose of the aerial vehicle an alternative cooperative localisation method is presented here that takes advantage of the broad availability of high-quality geo-referenced aerial photos recorded by specially equipped airplanes or satellites. The root idea of this approach is to find the position of the image taken by the aerial robot in a global database of orthophotos to realize a global registration of a real-time locally recorded aerial photo.

To ease this process and to narrow down the set of orthophotos which come into consideration the GPS position, heading and height of the aerial robot are used to choose the right map section and to rotate and scale the current image from the aerial robot as a pre-processing step for the following registration procedure. To realize a rotational correction of the aerial image in the way that the y-axis of the image is pointing into a northern direction the heading of the UAV is directly used as the heading angle describes the angular difference between current attitude of the UAV and the vector pointing north in our case. The scaling of the aerial image is a bit more complicated as it depends on the altitude of the aerial vehicle and the parameters of the onboard camera. Thus we first had to determine the horizontal camera opening angle using a calibration procedure. After that the width w_{pixel} of the area that one camera pixel covers in real world coordinates is (h_{og} denotes the height over ground and α_h the horizontal opening angle of the recording camera)

$$w_{pixel} = 2h_{og} \tan \frac{\alpha_h}{2}. \tag{1}$$

The pixel width ratio $r = \frac{w_{uav}}{w_{map}}$ of the UAV's image and the geo-referenced images can now be used to scale the image of the UAV to have the same per-pixel-width so that a direct template matching is possible. After obtaining all needed parameters the rotation and scaling is realized by an affine transformation. In our experiments the scaling procedure of the images leads to bilinear interpolated geo-referenced images with a grid width of 0.06 meters. The physical resolution of the geo-referenced imagery is approximately 0.30 meters. The images recorded with our aerial robot PSYCHE have a grid width of 0.052 meters when taken at an altitude of 20 meters.

After the pre-processing of both images a template matching is performed to uncover the exact location of the local aerial photo in the global aerial photo. This of course implies that the global aerial photo is covering a bigger map section than the local aerial photo. Our experiments show that combining global aerial photos taken at a virtual height of 100 meters and local aerial photos taken at a height of 20 meters yield to good matching results. This finding has several reasons. The altitude at which an aerial photo is recorded has a direct effect on the area in the world that one pixel of the image covers. Therefore, it is on the one hand advisable to choose an image recording altitude which is low enough to preserve as much details as possible in the image and on the other hand high enough to have sufficient visual context information to allow a unambigous matching result.

The matching algorithm itself is implemented with the Fast Template Matching method proposed in [11] which is based on the template matching functionality that is provided by the well-known open-source image processing library OpenCV. The implemented template matching method uses an image pyramid to speed up the actual matching process. The bigger the images and/or templates are the more image pyramid levels should be used. Our experiments show that this decreases the runtime of the algorithm by the factor 2 per pyramid level without sacrificing much of the matching result's quality when using a small number (≤ 3) of pyramid levels. After generating the image pyramids the template matching is executed on the down sampled images with the lowest resolution. The result R of this step is a normed cross-correlation image obtained by the application of the following equation. I denotes the source image in which the template T is to be found.

$$R(x,y) = \frac{\sum_{x'y'} T(x',y')I(x+x',y+y')}{\sqrt{\sum_{x'y'} T(x',y')^2 \sum_{x'y'} I(x+x',y+y')^2}} \tag{2}$$

A search for the maximal value in the normed cross-correlation image uncovers the template location with the highest confidence in the next step. To optimize the template's position an additional search in a small area around the previously found location of the template is performed as a fine-tuning post-processing step. If the confidence increases by this step the position of the template is corrected. As we are only looking for a single object in the aerial image all matching results with a lower confidence are discarded. In summary our approach realises a real-time subpixel cross-correlation method depending on the above mentioned accuracy of the geo-referenced imagery.

4 Results

Figure 2 demonstrates the capability of our registration method to successfully match aerial imagery from an UAV to previously taken orthophotos from a global database of geo-referenced aerial images. As the global aerial images are already geo-referenced the absolute position of the unmanned ground vehicle can easily be deduced by using the previously determined width-per-pixel measure w_{pixel}. The processing is all done on the UGV as the UAV's processing capabilities are limited and would not yield to a desirable runtime of the algorithm at the moment.

The precision of our implementation can be quantified as follows. Due to our sub-pixel cross-correlation approach we realised a maximal registration precision of approximately 0.06 meters (see Section 3.3). Additionally the precision

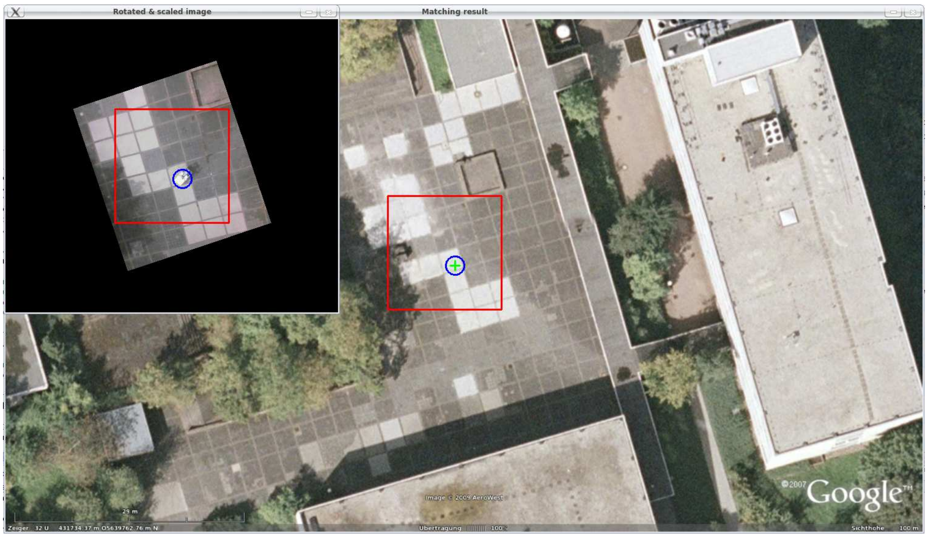

Fig. 2. Template matching results with localised UGV. The UAV's photo after rotation and scaling is shown in the top left corner. The red rectangle marks the area which is used for template matching. The blue circle marks the UGV.

of our UGV segmentation is approximately 0.25 meters (see Section 3.1). These facts produce an overall precision of approximately 0.30 meters of our system. Certainly the applied segmentation technique is very simple and has a big potential of improvement which lets us hope to achieve a registration precision of approximately 10-15 centimeters in the future. Nevertheless the precision of our implementation at present is already comparable to a DGPS sensor system which is definitely a satisfactory performance.

Concerning the runtime of our system it can be stated that our implementation achieves an average runtime of 76 ms per processed video frame on a *Intel Core2Duo L7100@1.20GHz* when using a 3-level image pyramid and thus the system is perfectly suited for real-time application.

5 Conclusion

In this paper we presented an alternative approach to the absolute localisation problem of an unmanned ground vehicle by considering different cooperative behaviours involving an additional unmanned aerial vehicle. The direct usage of the UAV's GPS position to deduce the UGV's absolute position turns out to be very error-prone. Therefore we implemented a registration method to match real-time imagery from an UAV to geo-referenced images from a global database. By doing that the absolute position of the UGV can be calculated from its position in the onboard camera image. Our absolute localisation method has a localisation precision of approximately 0.30 meters and is able to perform in real-time which is both remarkable. Finally the system has been successfully verified with our robots AMOR and PSYCHE to prove the practical usability of our method in the context of outdoor robotics. Future developments of the system will focus on an optimised UGV video image segmentation technique as this component induces the biggest error in our system. Besides geo-referenced images with a higher resolution will be used to increase the accuracy of the system.

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