An Integrated UAV Navigation System Based on Aerial Image Matching

Gianpaolo Conte and Patrick Doherty
Department of Computer and Information Science
Artificial Intelligence and Integrated Computer System Division
Linköping University
Linköping, SWEDEN
giaco@ida.liu.se

Abstract—The aim of this paper is to explore the possibility of using geo-referenced satellite or aerial images to augment an Unmanned Aerial Vehicle (UAV) navigation system in case of GPS failure. A vision based navigation system which combines inertial sensors, visual odometer and registration of a UAV on-board video to a given geo-referenced aerial image has been developed and tested on real flight-test data. The experimental results show that it is possible to extract useful position information from aerial imagery even when the UAV is flying at low altitude. It is shown that such information can be used in an automated way to compensate the drift of the UAV state estimation which occurs when only inertial sensors and visual odometer are used.

TABLE OF CONTENTS

1. INTRODUCTION

The work presented in this paper is done in the context of a larger research project on autonomous UAVs carried out at the Department of Computer and Information Science at Linköping University.The primary goal of such a project is in the development of an integrated hardware/software UAV platform for fully autonomous missions in an urban environment.

One of the main concerns 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 (except in rare cases such as war zones).

There are several problems which have to be solved before unmanned aircrafts can be introduced in the civilian airspace. One of them is GPS integrity. 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 a UAV navigation system using a suitable vision system.

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.

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 [1] 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

1-4244-1488-1/08/$25.00 ©2008 IEEE
IEEEAC Paper #1276, Version I Updated 23/10/2007.

Figure 1. The Rmax helicopter.

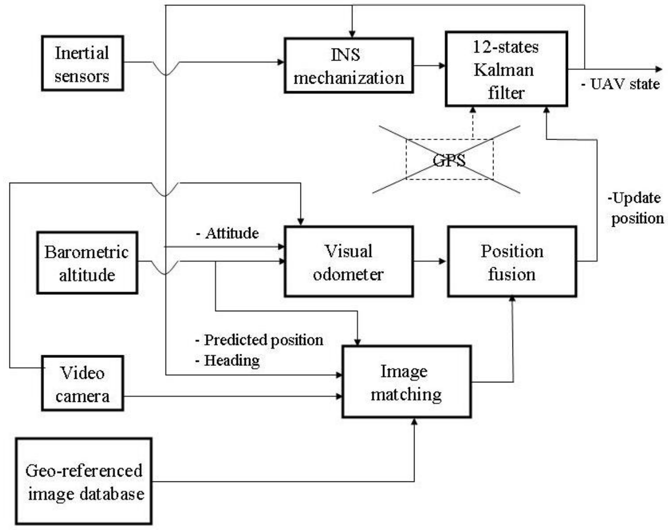

Figure 2. Vision-aided sensor fusion architecture.

GPS position information.

The 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. 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 [2] 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.

Due to the fact that registering the on-board image to an incorrect location may introduce an even larger position error, the fundamental problem to be solved is the detection of correct and incorrect image registrations. The contribution of this paper is in the development of a method showing how to detect incorrect image registration.

At this point one could think of using only the drift-free position calculated through image registration to update the navigation filter without the need for the odometer. The problem is that the success rate of the image registration process is very much related to the kind of terrain the UAV is flying over. Terrains with ”robust” features like road intersections are easier to match, while unstructured terrain such as rural areas are difficult to match. The visual odometer used here, works reasonably well also in unstructured environments. For this reason the combination of the two techniques gives robustness to the approach.

The vision-aided sensor fusion architecture proposed is displayed in Figure 2. 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. In particular the position calculated using the visual odometer and image registration are fused together and the resulting position is used to update the Kalman filter.

The architecture proposed in Figure 2 has been tested on real flight-test data and on-board video. The GPS track of the flight path shown in Figure 3 is used to validate the results of the non-GPS navigation approach presented in this work. During this flight, inertial data, barometric altitude and on-board video were acquired. Such data are used in this work to demonstrate the possibility, without using the GPS, to fly the closed loop path of Figure 3 without accumulating drift error at the end of the path. The total path length is about 1 kilometer.

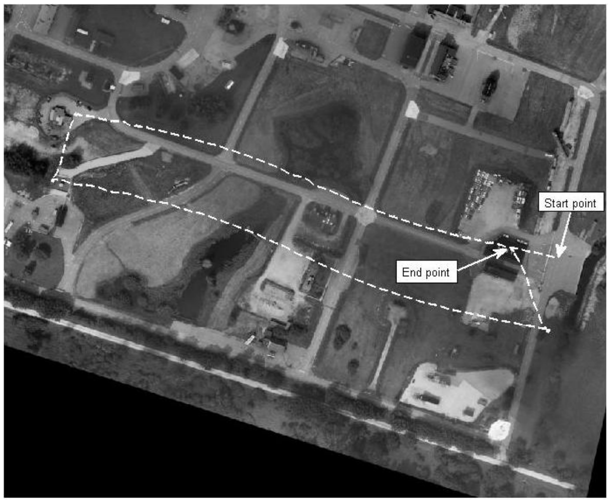

Figure 3. GPS track of the UAV flight path used for the experiment.

2. RELATED WORK

Many research groups are dealing with non-GPS navigation problems. One technique which could be applied to this kind of problems is the so called Simultaneous Localization and Mapping (SLAM). The goal of SLAM is to localize a robot in the environment while mapping it at the same time. Prior knowledge of the environment is not required. Although SLAM is becoming a standard technique for indoor robotic applications, it still represents a challenge when applied to large outdoor environments. A rich literature is available on this topic [3], [4], [5], [6]. Some examples of SLAM applied to aerial vehicles can be found in [7], [8].

Compared to the navigation approach used in this paper, the SLAM technique has the advantage of not requiring any a priori maps of the environment. On the other hand, the SLAM approach makes sense when robots have to close loops, in other words, the robot has to come back to previously visited landmarks in order to decrease the position uncertainty. This could be a potential limiting factor for UAV applications. If a UAV has lost its GPS signal, probably the best navigation strategy is the one which minimizes the risk of crashing in populated areas. It is possible that flying back home using previously visited sites is not the safest strategy, while flying different routes might be more preferable. For this reason we think that a navigation functionality based on aerial image matching has great potential for this application and gives more flexibility as regards choosing emergency flight routes in case of GPS failure.

An application similar to the one described in this paper which uses aerial image matching for aircraft position estimation can be found in [9]. Here the authors try to estimate an aircraft position through matching a sequence of on-board images to a geo-referenced image. The on-board images are taken from a downward looking camera mounted on a manned aircraft. A matching method which uses the Hausdorff distance is investigated.

There also exists other kinds of terrain navigation methods which are not based on aerial images but on terrain elevation models. In this case a measurement of the flight altitude relative to the ground is required. Matching the ground elevation profile, measured with a radar altimeter for example, to an elevation database allows for aircraft localization. An application of this method can be found in [10]. The localization system has been implemented successfully on some military jet fighters. In the case of UAVs and more specifically for unmanned helicopters, this method does not appear to be appropriate. Compared to jet fighters, UAV helicopters fly short distances at very low speed so the altitude variation for such flying platforms is quite poor in terms of allowing ground profile matching.

3. SYSTEM DESCRIPTION

The vision-aided sensor fusion architecture tested in this work is composed of several modules (see Figure 2). A traditional Kalman filter is used to fuse an INS sensor (3 accelerometers and 3 gyros) with a position sensor (vision system in this case).

An INS mechanization function performs the time integration of the inertial sensors while the Kalman filter function estimates the INS errors. The errors estimated by the Kalman filter are then used to correct the INS solution. The Kalman filter implemented uses 12 states. 3 dimensional position error, 3 dimensional velocity error, 3 attitude angle error (pitch, roll, heading) and 3 accelerometer biases. The Kalman filter uses the position update from the vision system to estimate such errors.

As mentioned before the vision system combines two techniques to calculate the position of the UAV: visual odometer and image registration. The next two sections describe an implementation of the two methods in details. Both odometer and image registration calculate the UAV position. The odometer delivers 4Hz position update. The position update calculated from the image registration algorithm occurs only when a reliable matching is found. The method developed to discriminate between reliable and unreliable matching is described in section 5.

When a reliable position update from the image registration module is not available, the output from the visual odometer is directly taken to update the filter. When a reliable image registration is obtained, usually it produces a position jump when compared to the position calculated from the odometer. Such position discontinuity can be large especially when the time elapsed between two valid registrations is large. For this reason, the Kalman filter cannot be updated directly with the position calculated from the image registration module, the risk would be the generation of instabilities. The registration update is then introduced gradually over time and it is treated as a correction added to the odometer solution.

4. VISUAL ODOMETER

The visual odometer developed in this work is based on the KLT feature tracker. The KLT algorithm tracks point features from two subsequent frames [2]. The algorithm selects a number of features in an image according to a "goodness" criteria described in [11]. Then it tries to re-associate the same features in the next image frame. The association is done by a minimization of a sum of squared differences criteria over patches taken around the features in the first image. This association criteria gives very good results when the feature displacement is not too large. Therefore it is important that the algorithm has a low execution time. The faster the algorithm is, the more successful is the association process. The KLT algorithm is very efficient and can run at 20-30Hz.

In this application 50 features in the image are tracked. Once the features are detected in the image frame, they are projected onto the real world using Equation 1:

$$\mathbf{P}^n = \mathbf{R}_c^n \begin{bmatrix} x/f_x \\ y/f_y \\ 1 \end{bmatrix} d \tag{1}$$

where $\mathbf{R}_c^n$ is the transformation matrix between the camera frame (c) and the helicopter navigation frame (n). x and y represent the pixel position of the feature being tracked in the image plane. f_x and f_y are the focal lengths of the camera in the x and y directions. d is the feature depth.

The navigation frame is a local geodetic frame which has its origin coinciding with that of the INS sensor with the X^n axis pointing toward the geodetic north, the Z^n axis orthogonal to the reference geodetic ellipsoid pointing down, and the Y^n axis completing a right-handed orthogonal frame. The transformation matrix $\mathbf{R}_c^n$ is composed by a sequence of rotations which take into account the camera orientation relative to the UAV body and the UAV attitudes (the UAV attitude angles are taken from the Kalman filter as it is shown in Figure 2). Details on the definition of the different reference frames and coordinate transformation from the camera to the navigation frame can be found in [12].

Since the camera in the experiment presented here is looking perpendicular downward, the feature depth d is assumed to be equal to the UAV altitude relative to the ground. The depth is then calculated using a barometric pressure sensor (the atmospheric pressure at the ground level is taken before take-off, then the differential pressure during flight can be converted into ground altitude). This way of calculating the ground altitude works if the ground is essentially flat. The flatness assumption can be removed by a direct measurement of the ground altitude. For this purpose our group is investigating the possibility of using a radar or laser altimeter on-board the UAV. There are also other methods to estimate the ground altitude. One way is to use passive vision (downward looking camera). Several works have shown that this is possible achieving good accuracy [13], [14].

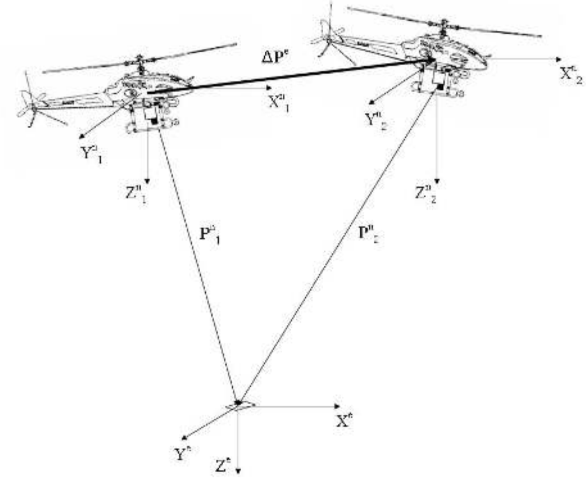

Figure 4. Visual odometer between two consecutive UAV positions.

Figure 4 represents the UAV observing the same feature (which will be addressed with the j index) from two different locations. The UAV displacement $\Delta\mathbf{P}^e$ relative to an Earth-fixed reference frame (e) and calculated using the feature j, is given by Equation 2:

$$\begin{aligned}\Delta\mathbf{P}_j^e &= \mathbf{P}_{j,2}^n - \mathbf{P}_{j,1}^n \\ &= \mathbf{R}_{c2}^n \begin{bmatrix} x_{j,2}/f_x \\ y_{j,2}/f_y \\ 1 \end{bmatrix} d_2 - \mathbf{R}_{c1}^n \begin{bmatrix} x_{j,1}/f_x \\ y_{j,1}/f_y \\ 1 \end{bmatrix} d_1 \end{aligned} \tag{2}$$

The Earth-fixed reference frame (e) has the same orientation of the navigation frame (n) but it is fixed relative to the Earth.

The UAV displacement between two subsequent frames is calculated by averaging the displacement of all the features tracked in the image. The resulting averaged displacement is then:

$$\Delta\mathbf{P}_{avg}^e = \frac{1}{nfeat} \sum_{j=1}^{nfeat} \Delta\mathbf{P}_j^e \tag{3}$$

where $nfeat$ is the number of features tracked. In the experiment described in this paper 50 features were tracked in each frame.

Finally, the position at a certain time t calculated by the odometer function is:

$$\mathbf{P}(t) = \mathbf{P}(t_0) + \sum_t \Delta \mathbf{P}^e_{avg}(t) \tag{4}$$

where $\mathbf{P}(t_0)$ is the position at time t_0 when the last useful GPS reading was available. As is shown in Figure 2, the position calculated from the odometer is used to update the navigation filter.

Experimental results show that the visual odometer alone combined with the INS gives drift-free velocity and attitude estimation (it would not be possible using only the INS). This means that once the GPS is lost the UAV can still be controlled using proper attitude and velocity information. This result is obtained without image registration, i.e. without using any given information of the environment. The position uncertainty grows though. The next section describes the technique used to solve this problem.

5. Image registration

The image registration technique developed here is based on edge matching. A Sobel edge detector is applied to both the geo-referenced image and the image taken from the on-board video camera. The choice of using edge features derives from the fact that edges are quite robust to environmental illumination changes. The geo-referenced and the video camera image are generally taken at different times, it can be months or years, it has to be expected that the illumination conditions will differ. Therefore, it is necessary to choose features which are robust to illumination changes.

Another important factor to be considered is the altitude of the UAV from the ground. The higher the UAV flies the more structure from the environment can be captured. The consequence of this is that image registration is more reliable at higher altitude. Another challenge lies in the fact that the environment changes over time. It can be that a reference image is obsolete after some time due to the change in the environment. 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 in the environment.

The image registration process is represented in the block diagram in Figure 5. After the on-board color image is converted into gray scale, a median filter is applied. The filter is applied in order to remove small details which are visible from the on-board camera but not visible from the reference image. The median filter, has the well-suited property of removing small details while preserving the edges sharp. After filtering, the Sobel edge detector is applied. The image is then scaled and aligned to the reference image. Scaling is performed converting the on-board image to the resolution of the reference image. The scale factor s is calculated using Equation 5 and it is different in x and y direction of the image plane since the

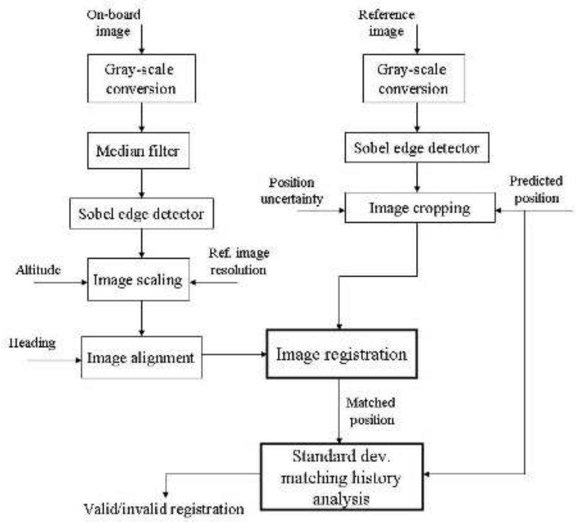

Figure 5. Image registration schematic.

on-board images used do not have squared pixels:

$$\begin{pmatrix} s_x \\ s_y \end{pmatrix} = \begin{pmatrix} \frac{1}{f_x} \\ \frac{1}{f_y} \end{pmatrix} d \bullet I_{res} \tag{5}$$

d, as for the odometer, is the ground altitude given by the pressure sensor and I_{res} is the resolution of the reference image. The alignment of the on-board image with the reference image is done using the heading information estimated by the filter.

The reference image is processed as follows. It is converted into gray scale and the Sobel edge detector is applied. This is done only at the beginning, the resulting edge image is then kept in memory and used during the visual navigation. The UAV position predicted by the Kalman filter (Figure 2) is used as the center of a restricted search area in the reference image. The purpose is to disregard areas of the image too far from the estimated UAV position. Since the position uncertainty grows when there is no update from the registration process, also the search area should grow in the same way. This is not implemented yet in the system, the experimental results which will be presented later are obtained using a fixed size uncertainty window.

After both images have been processed as explained above, a matching algorithm tries to find the position in the cropped reference image which gives the best match with the video camera image. The position that results the greatest number of overlapping pixels between the edges of the two images is taken as matching result. The matching criteria used, although quite simple, give a reasonable success rate. Moreover, it can be used for on-line applications. The registration algorithm described runs at around 1Hz on a normal laptop computer. A screen shot which shows how the two images

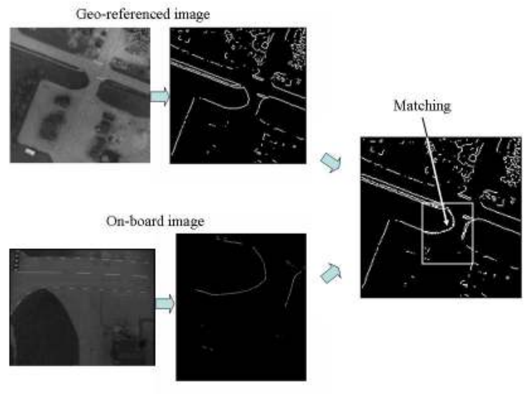

Figure 6. Processing and matching of the geo-referenced image and of the on-board image.

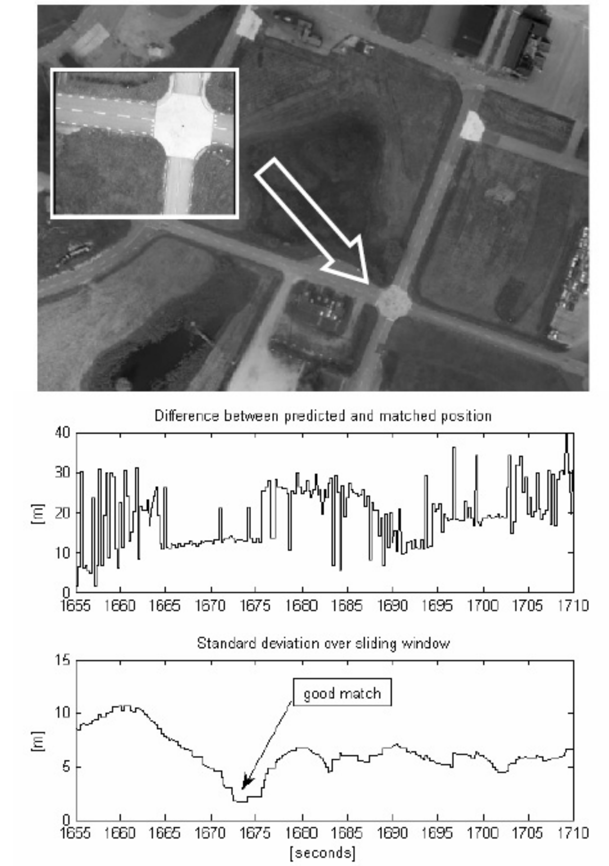

Figure 7. Detection of a good match.

are processed and then matched is shown in Figure 6.

Once the matching is obtained the on-board image can be geo-referenced and the absolute position of the UAV can be calculated. The most difficult part is to decide whether to take the position as a good match or not. In other words, it has to be detected whether the matching is an outlier and then rejected or can be used to update the filter. The outlier detection is not an easy matter since there are areas where the outliers are predominant compared to the good matches. One idea would be to segment the reference image and assign different matching probability values for different areas. Prior knowledge can be applied in this process. For example, it is known that image registration in urban areas is more reliable than in rural areas, or that road intersections result in more stable matching than road segments. By doing this a different degree of uncertainty can be assigned to the matching based on the location where the match has occurred. The uncertainty can then be used to update the navigation filter. This method would require a huge amount of off-line image preprocessing which should be applied to the reference image before it could be used and would be unpractical for large images.

The outliers detection method applied here does not require any image preprocessing. It is based on the observation that in areas where the matching is unreliable, the matched position is very noisy. While in areas where the matching is reliable, the position noise decreases. The rejection criteria applied is based on the analysis of the position difference between the predicted position coming from the filter and the position given by the matching algorithm. This difference, when the algorithm is matching the right location, is usually quite constant with a low noise level. The outlier rejection method implemented is based on the standard deviation analysis of such a difference. The standard deviation is calculated over a sliding time window of a fixed size. The algorithm analyzes the position difference of for example the last 30 matching results and if the standard deviation is below a certain threshold, the averaged position in such time window is taken as good match. If the standard deviation is above the threshold the matched position is rejected.

Figure 7 shows how this method has the potential for detecting good matches. In the upper part of Figure 7 there is a picture of an area where a good match was detected (big picture) and a picture of an on-board camera view (small picture). In the lower part of Figure 7, the time history of the difference between the predicted position and the matched position is depicted. The standard deviation of the position difference calculated using a sliding window with the last 30 matches is shown at the bottom of the picture. It can be observed that when the match becomes stable the standard deviation drops. A good choice of threshold value and size of the sliding window is essential for the success of the method.

6. UAV PLATFORM

The algorithm proposed has been tested using flight-test data collected from an autonomous UAV helicopter. The helicopter is based on a commercial Yamaha RMAX UAV helicopter (Figure 1). The total helicopter length is 3.6 m (including main rotor). It is powered by a 21 hp two-stroke engine and it has a maximum take-off weight of 95 kg.

The avionic was developed in the Department of Computer and Information Science at Linköping University and has been integrated in the RMAX helicopter. The platform developed is capable of fully autonomous flight from take-off to landing.

The sensors used for the navigation algorithm described in this paper consist of an inertial measurement unit (three accelerometers and three gyros) which provides the helicopter's acceleration and angular rate along the three body axes, a barometric altitude sensor and a monocular CCD video camera mounted on a pan/tilt unit.

The avionic system is based on 3 embedded computers. The primary flight computer is a PC104 PentiumIII 700MHz. It implements the low-level control system which includes the control modes (take-off, hovering, path following, landing, etc.), sensor data acquisition and the communication with the helicopter platform. The second computer, also a PC104 PentiumIII 700MHz, implements the image processing functionalities and controls the camera pan-tilt unit. The third computer is a PC104 Pentium-M 1.4GHz and implements high-level functionalities such as path-planning, task-planning, etc.

Network communication between computers is physically realized with serial line RS232C and Ethernet. Ethernet is mainly used for remote login and file transfer, while serial lines are used for hard real-time networking.

7. EXPERIMENTAL RESULTS

The flight data shown were collected during a flight-test campaign in a training area in south of Sweden. The resolution of the reference image used for image registration is of 0.5 meters/pixel.

Sensor data and on-board video were recorded during an autonomous flight. The helicopter autonomously flew a pre-planned path using a path following functionality implemented in the software architecture [15]. The helicopter flew at 60 meters above the ground at a flight speed of 3m/s. The video camera was looking downwards and fixed with the helicopter body. The video was recorded on-board and synchronized with the sensor data. The synchronization is performed by automatically turning on a light diode when the sensor data starts to be recorded. The light diode is visible in the camera frame. The video is recorded on tape using an on-board video recorder and the synchronization with the sensor data is done manually off-line. The video sequence is recorded at 25Hz frame rate. For the experiment described here, the video frames were sampled at 4Hz. The on-board sensor data are recorded at different sample rates. Table 1 provides the characteristics of the sensors used in the experiment.

The results of the navigation algorithm proposed in this paper are compared with the navigation solution given by an on-board INS/GPS Kalman filter running on-line. The Kalman filter fuses the inertial sensors with GPS position data and provides the full helicopter state estimate.

Sensor	Output Rate	Resolution	Bias
Accelerometers	66 Hz	1 mG	13mg
Gyros	200 Hz	0.1 deg/s	$<$ 0.1deg/s
Barometer	40Hz	0.1 m	-
Vision	4 Hz	384x288 pixels	-

Table 1. Available characteristics of the sensor used in the navigation algorithm.

Figure 8 displays the results of the UAV position and velocity obtained from the integration between INS and visual odometer without image registration. The position calculated using the odometer is used to update the Kalman filter. The figure shows a comparison between the reference position and velocity given by the on-board INS/GPS system, the solution INS/visual odometer described in this paper and the INS alone. GPS failure has been simulated and occurs at time t = 1660sec.

It can be observed that the INS solution alone starts to drifts rapidly, thus the helicopter cannot be controlled safely after GPS failure. The solution given by the INS/odometer stabilizes the velocity, in the sense that the velocity drift is removed. In addition the position drift is reduced dramatically compared to the INS stand alone solution. Plots of the attitude angles are not reported here but the INS/odometer provides drift-free attitude angle estimation. INS/odometer integration could be used to survive temporary GPS black-out by controlling UAV attitude and velocity. This result is obtained without using prior environment information.

If the UAV has to cover small distances the solution obtained from the INS/odometer could be enough. On the other hand, if the distance to cover is large, a mechanism to compensate for the position drift is needed. The full drift-free solution proposed here using geo-referenced image registration has been tested on flight-test data and the results are shown in Figure 9.

The helicopter flew a closed loop path of around 1 kilometer length. GPS failure was simulated after few seconds from the starting point. From this point, the drift-free vision system using odometer and image registration replaces the GPS in the Kalman filter. The dashed line represents the flight path measured by the GPS while the continuous line represents the solution given by the vision-aided navigation scheme described in this paper and represented in Figure 2. The visual odometer and the image registration module run in parallel. As discussed in section 3, when an update from the image registration is available, it usually gives a position discontinuity compared to the odometer. Introducing a position jump in the Kalman filter could cause instability problems. In order to avoid this problem, the update correction from the image registration is introduced gradually over time. Figure 9

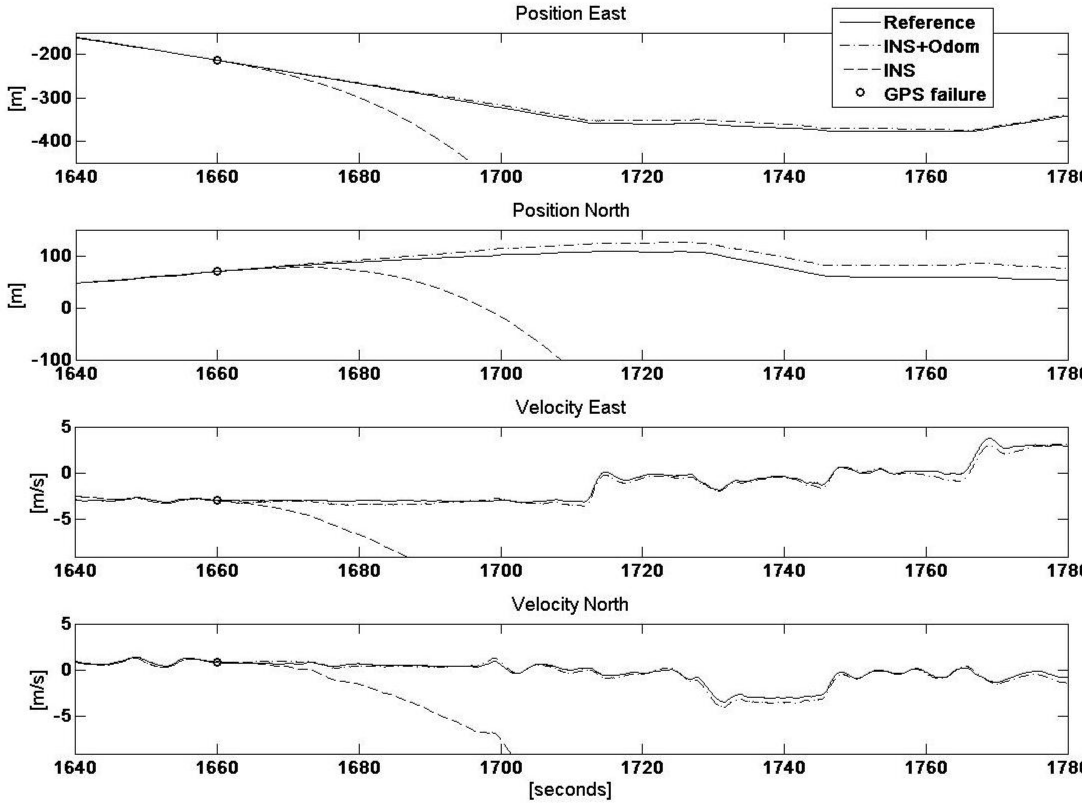

Figure 8. Integration of the odometer and INS without using image registration. Prior knowledge of the environment has not been used yet.

shows that after the GPS failure the position begins to drift. This means that the image matching has not detected a stable match. The choice of the standard deviation threshold was set to 1.4 meters. The first stable match detected was approximately at the first road intersection. It can be noticed that the helicopter position begins to return on the actual path flown by the helicopter. The second stable match was detected almost at the end of the path. The drift correction is introduced in the navigation system and the final position error at the end of the path is around 3 meters. Other features during the path were matched correctly but they were not stable enough to be taken as position update. This experiment shows that even only few good matches are enough to compensate for the position drift.

8. CONCLUSIONS AND FUTURE WORK

The experimental vision-aided navigation system architecture described in this paper has the potential to provide a drift-free navigation solution. The results presented are quite encouraging although more tests are needed in order to fine tune the method. It is essential also to collect data from different kind of terrains in order to exploit the potential of the method.

In the future experiments a wide angle camera lens will be tested. The one used here was of 45 degrees. We expect that using a wide angle lens will improve the image registration robustness as a larger part of the environment structure can be captured in the image. A radar altimeter will also be integrated in the helicopter in order to provide direct ground altitude measurement. In this way the flat world assumption can be removed. Another interesting investigation which will be done in the future is to verify the possibility of using satellite images from Google Earth. The interesting part is that they are available and for free. Google Earth contains an enormous amount of information and in the future it is not unlikely that they could be used to navigate UAVs.

ACKNOWLEDGMENTS

This work is supported in part by the National Aeronautics Research Program NFFP04-S4202 and the Swedish Foundation for Strategic Research (SSF) Strategic Research Center MOVIII.

I would also like to acknowledge my colleague Maria Hempel for reading this paper and giving useful comments.

REFERENCES

[1] T. Merz, S. Duranti, and G. Conte, "Autonomous landing of an unmanned aerial helicopter based on vision and inertial sensing," in *Proc. of the 9th International Symposium on Experimental Robotics*, 2004.

[2] C. Tomasi and T. Kanade, "Detection and tracking of

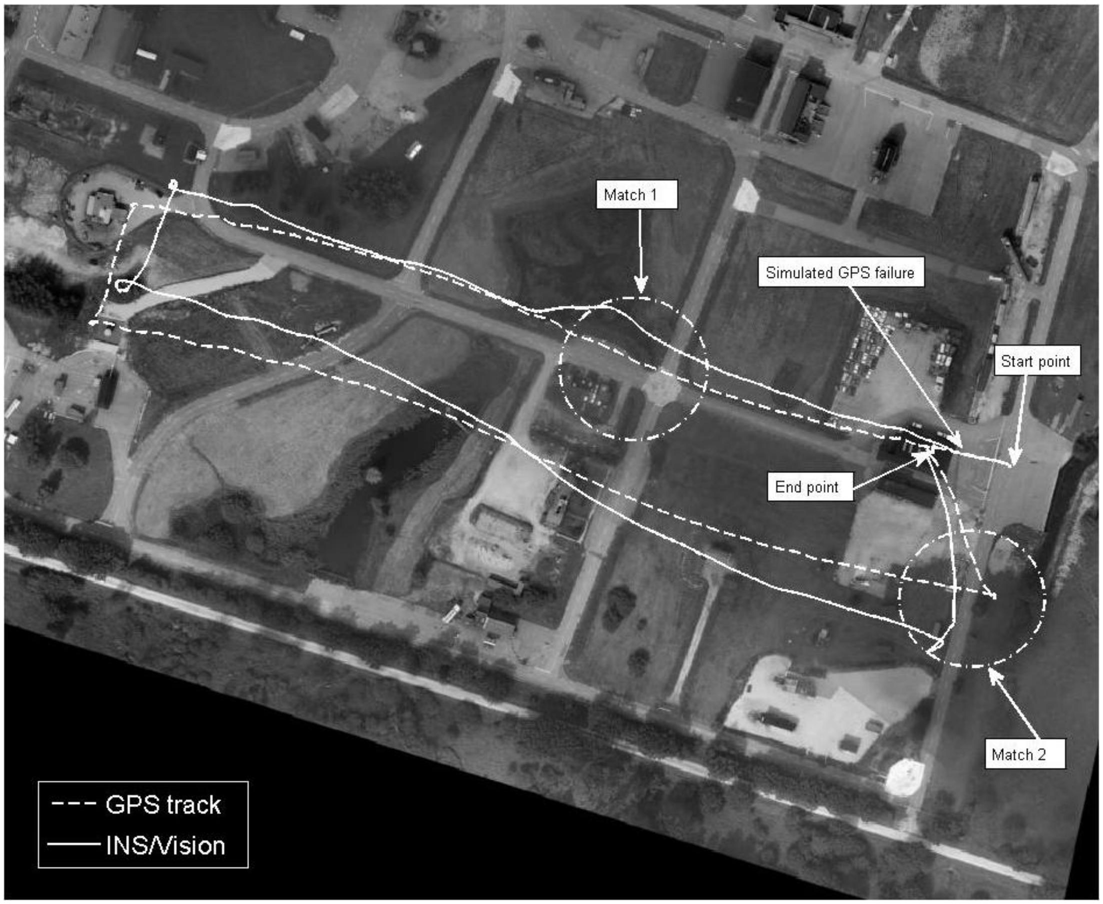

Figure 9. Vision-aided navigation experiment using image registration for position drift compensation.

point features," Carnegie Mellon University, Tech. Rep. CMU-CS-91-132, April 1991.

[3] T. Bailey and H. Durrant-Whyte, "Simultaneous localization and mapping (SLAM): Part II," *IEEE Robotics & Automation Magazine*, vol. 13, no. 3, pp. 108–117, Sep. 2006.

[4] H. Durrant-Whyte and T. Bailey, "Simultaneous localization and mapping (SLAM): Part I," *IEEE Robotics & Automation Magazine*, vol. 13, no. 2, pp. 99–110, Jun. 2006.

[5] S. Thrun, W. Burgard, and D. Fox, *Probabilistic Robotics*, ser. Intelligent Robotics and Autonomous Agents. Cambridge, MA, USA: The MIT Press, 2005.

[6] A. Davison, "Real-Time Simultaneous Localization and Mapping with a Single Camera," in *IEEE International Conference on Computer Vision*, October 2003, pp. 1403–1410.

[7] J. Kim and S. Sukkarieh, "Real-time implementation of airborne inertial-slam," *Robot. Auton. Syst.*, vol. 55, no. 1, pp. 62–71, 2007.

[8] T. Lemaire, C. Berger, I. Jung, and S. Lacroix, "Vision-based slam: Stereo and monocular approaches," *IJCV*, vol. 74, no. 3, pp. 343–364, September 2007.

[9] D. G. Sim, R. H. Park, R. C. Kim, S. U. Lee, and I. C. Kim, "Integrated position estimation using aerial image sequences," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 24, no. 1, pp. 1–18, 2002.

[10] N. Bergman, L. Ljung, and F. Gustafsson, "Pointmass filter and cramer-rao bound for terrain-aided navigation," in *Proc. of the 36th IEEE Conference on Decision and Control*, 1997.

[11] J. Shi and C. Tomasi, "Good features to track," in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR'94)*, Seattle, 1994.

[12] D. B. Barber, J. D. Redding, T. W. McLain, R. W. Beard, and C. N. Taylor, "Vision-based target geo-location using a fixed-wing miniature air vehicle." *Journal of Intelligent and Robotic Systems*, vol. 47, no. 4, pp. 361–382, 2006.

[13] A. Moe, "Passive aircraft altitude estimation using computer vision," Dept. EE, Linköping University, SE-581 83 Linköping, Sweden, Lic. Thesis LiU-Tek-Lic-2000:43, September 2000, thesis No. 847, ISBN 91-7219-827-3.

[14] L. Matthies, R. Szeliski, and T. Kanade, "Kalman filter-based algorithms for estimating depth from image sequences," Robotics Institute, Carnegie Mellon Univer-

sity, Pittsburgh, PA, Tech. Rep. CMU-RI-TR-88-01, January 1988.

[15] G. Conte, “Navigation functionalities for an autonomous uav helicopter,” Dept. of Computer and Information Science, Linköping University, SE-581 83 Linköping, Sweden, Lic. Thesis LiU-Tek-Lic-2007:16, March 2007, thesis No. 1307, ISBN 978-91-85715-35-0.

BIOGRAPHY

Gianpaolo Conte is a PhD student at the Department of Computer and Information Science, Linköping University, Sweden. He obtained the Licentiate degree at the same University and the Aerospace Engineering degree at Turin Polytechnic. He is interested in navigation and control problem for UAVs. He is also working on the development of Micro Aerial Vehicles platforms.

Patrick Doherty is a Professor at the Department of Computer and Information Science (IDA), Linköping University (LiU), Sweden. He is director of the Artificial Intelligence and Integrated Computer Systems Division at IDA and his research interests are in the area of knowledge representation, automated planning, autonomous systems, approximate reasoning and UAV technologies.