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Article

Direct Georeferencing of Micro Aerial Vehicles – System Design, System Calibration and First Evaluation Tests

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Keywords: direct georeferencing, RTK GPS, IMU, Kalman filtering, real-time operating system

Summary: In this article, a direct georeferencing system for the position and attitude determination of micro aerial vehicles (MAVs) is presented. The system consist of two GPS receivers, inertial sensors, a magnetometer, a barometer and an external sensor input for the integration of visual odometry data from stereo camera systems. The main characteristics of the system are that (1) it is real-time capable, (2) it is lightweight, to be applicable to MAVs and (3) it provides results with accuracies < 5 cm for the positions and < 0.5 deg to 1 deg for the attitudes. In this contribution the hardware development and the implemented algorithms for the direct georeferencing are described. In this context especially the RTK GPS and the attitude determination will be highlighted. Finally, details on the system calibration, results of a test flight, including a comparison to a photogrammetric bundle adjustment, and an outlook on further developments will conclude this contribution.

Zusammenfassung: *Direkte Georeferenzierung von MAVs (Micro Aerial Vehicles) – Systementwurf, Systemkalibrierung und erste Tests.* In diesem Beitrag wird ein System zur direkten Georeferenzierung von kleinen unbemannten Flugobjekten präsentiert. Das System ist in der Lage, Positionen und Orientierungen mit Genauigkeiten von < 5 cm und < 0.5 bis 1 deg in Echtzeit zu bestimmen. Dazu werden zwei GPS Empfänger, Inertial- und Magnetfeldsensoren, ein Barometer und in Zukunft auch Informationen aus Stereo-Kamera-Systemen verwendet. Neben Aspekten der Systementwicklung stehen in diesem Beitrag die implementierten Algorithmen im Vordergrund. In diesem Kontext werden insbesondere Details zum aktuellen Stand der Entwicklung der RTK GPS Auswertung und der Orientierungsbestimmung vorgestellt. Abschließend wird die Systemkalibrierung beschrieben, und es folgen erste Ergebnisse aus Flugexperimenten inklusive einem Vergleich zu einer photogrammetrischen Bündelausgleichung sowie ein Ausblick auf zukünftige Arbeiten.

1 Introduction

The acquisition of data by use of mobile platforms has become established in many communities in the recent decades. For some years now also UAVs (unmanned aerial vehicles) are commonly used for mobile mapping applications, since UAVs have the advantage of being able to overfly inaccessible and also dangerous areas. Furthermore, they can get very close to objects to achieve high resolution data with quite low resolution sensors. Especially in the fields of precision farming (Xiang & Tian 2011), infrastructure inspection (Merz & Kendoul 2011) or surveying (Eisenbeiss et al. 2005) UAVs are meanwhile often deployed.

Recently, there has been a discussion concerning the term UAV. Since this paper is particularly dealing with lightweight UAVs the more specific term MAV (micro aerial vehicle) will be used throughout this paper. MAVs can generally be characterized having a weight limit of 5 kg and a size limit of 1.5 m (Eisenbeiss 2009).

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1.1 *Objectives*

This contribution is focused on the development of a real-time capable direct georeferencing system for MAVs. The reason for developing a direct instead of an indirect georeferencing system is that spatial and time restrictions often exclude the possibility to deploy ground control points. The demand for the real-time capability of the system results from the aim to also use the georeferencing for the autonomous navigation of the MAV and to enable precise time synchronization. (As a side note, in Germany currently only partially automatic flights are permitted.) Furthermore, the real-time direct georeferencing also offers the opportunity to process the collected mapping data during the flight. For example using the georeferencing as initial values for the bundle adjustment of collected images accelerates the processing time significantly.

The utility of a real-time direct georeferencing for MAV applications can also be illustrated by the project the authors are working on: *Mapping on Demand*.

The goal of this project is to develop an MAV that is able to identify and measure inaccessible three-dimensional objects by use of visual information. A major challenge within the project comes with the term 'on demand', which includes the search, the interpretation and the user specific visualization of spatial information. The MAV is intended to fly fully autonomous on the basis of a high-level user inquiry. During the flight obstacles have to be avoided (Holz et al. 2013) and the collected images have to be processed on-the-fly in order to extract semantic information (Loch-Dehbi et al. 2013), which can be used to refine the trajectory planning (Nieuwenhuisen et al. 2013) in real-time.

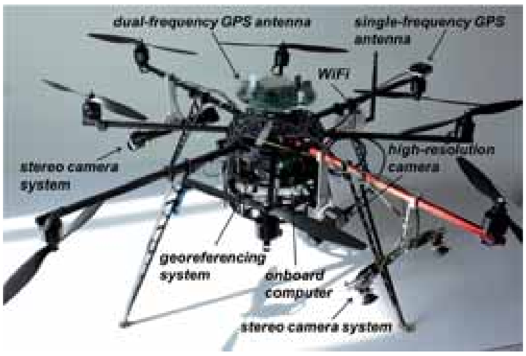

Fig. 1: The MAV (modified OktoXL, HiSystems) including the sensor and processing components, developed within the project *Mapping on Demand*.

Fig. 1 shows the current version of the MAV, as it is developed within the project.

It contains the direct georeferencing system, two stereo camera pairs, which will serve as an additional sensory input for the position and attitude determination (Schneider et al. 2013) and a 5 MPixel industrial camera as the actual mapping sensor. A small computer is used for the image processing, the flight planning and the machine control.

1.2 *Accuracy Requirements*

The position and attitude accuracy requirements are different for the navigation and the 3D object reconstruction within this project. Since the MAV is intended to maintain a safety distance of 0.5 m to obstacles, a position accuracy of 0.1 m is sufficient for the navigation. For the machine control the attitude accuracies should be in the range of 1 deg – 5 deg.

Compared to the navigation the positions and attitudes have to be known better for the 3D object reconstruction, since the absolute georeferencing of the final product, e.g. high-resolution 3D model of a building, is based on the positions and attitudes from the direct georeferencing system. Therefore, the position accuracy should be 1 cm – 3 cm and the attitude accuracy should preferably be better than 1 deg. At this point it has to be noticed that the relative accuracy of the exterior camera orientation can be improved by an ensuing photogrammetric bundle adjustment, but systematic georeferencing errors definitely have to be avoided.

1.3 *Structure of the Paper*

In section 2 the related work on direct georeferencing for MAVs is summarized. Details on the sensors and the overall system development will be shown in section 3. In section 4 the software and algorithm development follows. In this context details to the RTK GPS positioning algorithms and the concept to the attitude determination will be presented. Section 5 is focused on the system calibration. In section 6 results of a test flight including a comparison to results from a photogrammetric bundle adjustment will be presented. Since the algorithm development is not yet completed an outlook on future developments concludes this contribution (section 7).

2 Related Work

Direct georeferencing has extensively been researched in airborne applications, such as presented in Schwarz et al. (1993), Skaloud (1999), and Heipke et al. (2002). However, these systems cannot be adopted easily for MAVs operating in urban areas. There are two reasons for that: (1) Due to the lower flying altitude the GPS measurement conditions are often not ideal, since obstacles like trees or buildings lead to shadowing and multipath effects. Thus, additional sensors, e.g. an inertial measurement unit (IMU) play a more important role. (2) The choice of these sensors is restricted by space and weight limitations of the MAV. For instance, only a lower quality IMU can be used. For this reason, further sensors, e.g. cameras, are needed to also allow for a reliable georeferencing during GPS losses of lock.

Usually, direct georeferencing of MAVs is done by means of single L1 C/A code GPS receivers and low-cost inertial sensors as well as magnetometers (Yoo & Ahn 2003, Merz & Kendoul 2011, Xiang & Tian 2011). However, the resulting accuracies of these sensor combinations ($\sigma_{pos} \approx 2$ m – 10 m and $\sigma_{att} \approx 2$ deg – 10 deg) are insufficient for geodetic MAV applications. Therefore, the development of precise direct georeferencing systems for MAVs is currently highly demanded (Bláha et al. 2011). First approaches applying RTK (real-time kinematic) GPS on MAVs were presented in Rieke et al. (2011), Stempfhuber & Buchholz (2011), Bäumker et al. (2013) and Rehak et al. (2014).

Rehak et al. (2014) additionally use a Field-Programmable Gate Array (FPGA) for the processing of 4 redundant MEMS-IMU chips. Nevertheless, in none of the referenced developments the position and attitude determination is performed in real-time on board of the MAV.

3 System Design

This research is focused on the development of a direct georeferencing system with the following characteristics: (1) The weight of the system has to be less than 500 g to be applicable to MAVs. (2) The system has to be real-time capable. (3) Outages of single sensors should be bridgeable by other sensors. (4) The system is intended to provide accurate positions ($\sigma_{pos} < 5$ cm) and attitudes ($\sigma_{deg} < 1$ deg). (5) The system should allow for the integration of data from additional sensors, such as cameras or laser scanners.

The ability to include additional sensors to the system was – apart from the size and the weight constraint – the main reason for developing an own system instead of using a commercial unit with similar capabilities.

3.1 *Georeferencing Unit*

Fig. 2 shows the prototype version of the georeferencing unit. It measures 11.0 cm × 10.2 cm × 4.5 cm and has a weight of roughly 240 g without the GPS antennas.

The main positioning device is a Novatel OEM615 dual-frequency GPS board. Together with a radio link (XBee Pro 868) to a GPS master station it allows for a precise RTK GPS position determination (see section 4.1). Additionally, the unit contains a small low cost sin-

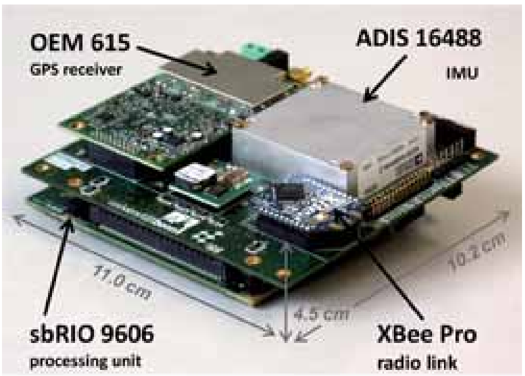

Fig. 2: The direct georeferencing unit.

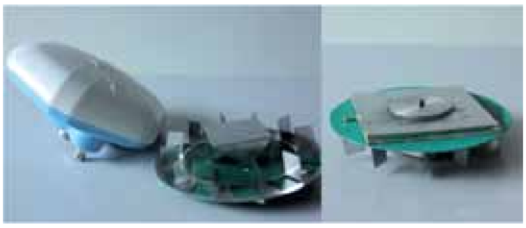

Fig. 3: The original (left) and the dismantled (right) dual-frequency GPS antenna.

gle-frequency GPS receiver (u-blox LEA6T), which is mainly intended to be used for the heading determination (see section 4.2).

As a sensor for the attitude determination and for supporting the position estimation, the georeferencing unit contains a tactical grade MEMS IMU (Analog Devices ADIS16488), including three axis gyroscopes, accelerometers, magnetometers and a barometer.

Finally, the georeferencing unit also consists of a real-time processing unit (National Instruments sbRIO 9606), which is a re-configurable IO board, including a 400 MHz processor and an FPGA. The FPGA allows for a very fast and parallel communication with several serial interfaces. Afterwards, the pre-processed sensor data are provided to the 400 MHz processor via direct memory accesses (DMAs), avoiding delays and supporting the real-time capabilities of the system.

Fig. 4 shows the different sensors and the implemented interfaces of the direct georeferencing system.

3.2 *GPS Antennas*

Preferably, a dual frequency GPS receiver is connected to a geodetic grade dual frequency GPS antenna. However, these antennas are usually too heavy for MAV applications. Therefore, we dismantled such an antenna (navXperience 3G+C, see Fig. 3). In this way the protective housing and the 5/8“ screw thread in the bottom of the antenna could be omitted so that the weight of the antenna could be reduced from 350 g to 100 g.

Certainly, by dismantling the antenna, the external reference point was lost. Thus, the antenna had to be recalibrated in an anechoic chamber (Zeimetz & Kuhlmann 2010). By comparison to the original antenna the dismantling led to significant changes in the phase centre offset (Δup $\approx$ 4 cm, Δnorth and Δeast < 1 mm) and in the phase centre variations (< 5 mm).

As antenna for the single-frequency GPS receiver (LEA6T), a low-cost antenna from u-blox (ANN-MS) is mounted on the outer end of one of the riggers of the MAV (see Fig. 1). Together, both antennas form a short baseline on the MAV, which can be used for the attitude determination.

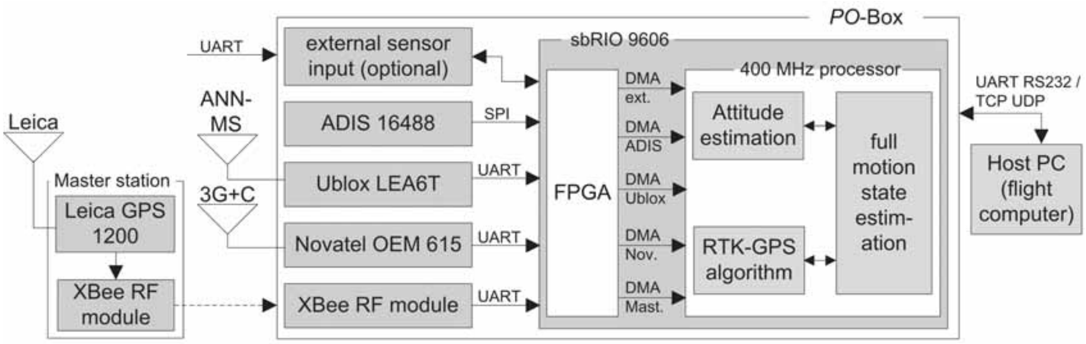

Fig. 4: Block diagram of the direct georeferencing system, which is named the *PO*-Box (3G+C = galileo, gps, glonass + compass, ADIS = Analog Devices (company), ANN MS = active gps antenna from Ublox, DMA = direct memory access, FPGA = field-programmable gate array, Nov. = Novatel, OEM = original equipment manufacturer, *PO* = Position and Orientation, sbRIO = single board remote input/output, SPI = serial peripheral interface, TCP UDP = transmission control protocol, user datagram protocol, UART = universal asynchronous receiver/transmitter, Ublox = swiss company, XBee RF = XBee radio frequency).

4 Software Development

The final goal of the algorithm development is the fusion of the GPS observations, the measurements from the IMU, the magnetometer and the barometer as well as information from the stereo camera systems in a tightly coupled approach. In doing so, precise and reliable positions and attitudes should be provided in real-time. In the current state of the development, the GPS based position estimation and the IMU / magnetometer based attitude estimation are separate, independent algorithms. Although this is not yet the final envisaged state, it already provides the full exterior orientation of the system. Furthermore, it is an excellent basis for future developments.

In the following, the basics of the RTK GPS algorithms and the concept of the attitude determination will be presented. All algorithms are developed in C++ and compiled as dynamic link libraries (dll), which are then imported into the real time operating system running on the 400 MHz processor. The programming of the FPGA and the 400 MHz processor is done using LabView.

4.1 *The RTK GPS Software*

RTK GPS is the most suitable procedure to obtain kinematic GPS positions with cm-accuracies in real-time.

The RTK GPS algorithms used on the georeferencing system, are in-house developed although there are commercial (even for the Novatel OEM 615) and open source (RTKLIB, Takasu & Yasuda 2009) RTK GPS solutions available.

The main reasons for developing an own RTK GPS software are: (1) The final goal of the algorithm development is a tightly-coupled GPS processing. The advantages of such an implementation are that the ambiguity resolution is getting faster and the cycle slips can be detected more robustly. In order to achieve this goal RTK GPS algorithms with its data management first have to be implemented. (2) In commercial software there is generally no access to the source code. Thus, adaptations according to special uses, e.g. modification of the motion model, are generally impossible. (3) In the development of a real-time system the implemented software has to meet the requirements of the operating system that is running on the real-time processing unit.

4.1.1 The RTK GPS algorithms

The key to RTK GPS positioning is the ambiguity resolution, which is the process of resolving the unknown number of integer cycles. In order to achieve this, the RTK algorithm contains the following steps:

- float solution,
- integer ambiguity estimation,
- fixed solution.

The float solution is the step, where the ambiguities are first estimated as real values. This is done in an extended Kalman filter (EKF). In this filter the observation vector $\boldsymbol{l}$ consists of double-difference (DD) carrier phases Φ_{RM}^{jk} and pseudoranges P_{RM}^{jk} on the GPS-L1 and the GPS-L2 frequency, to allow for an instantaneous ambiguity resolution.

$$l = \left[\Phi_{RM,L1}^{1k} \ldots \Phi_{RM,L1}^{mk} \; \Phi_{RM,L2}^{1k} \ldots \Phi_{RM,L2}^{mk} \ldots \right. \\ \left. P_{RM,L1}^{1k} \ldots P_{RM,L1}^{mk} \; P_{RM,L2}^{1k} \ldots P_{RM,L2}^{mk} \right]^T \quad (1)$$

Beside the rover position r_R, the state vector $\boldsymbol{x_{SD}}$ contains single-difference (SD) ambiguities N_{RM}^{j}:

$$x_{SD} = \left[r_{R,x} \; r_{R,y} \; r_{R,z} \; N_{RM,L1}^{1} \ldots N_{RM,L1}^{n} \ldots \right. \\ \left. N_{RM,L2}^{1} \ldots N_{RM,L2}^{n} \right]^T \quad (2)$$

The reason for estimating SD instead of DD ambiguities is to avoid the hand over problem that would arise for DD ambiguities, when the reference satellite changes (Takasu & Yasuda 2009).

The chosen motion model is a random walk model, which is a simple but efficient model, when no additional information is available. Due to the use of own RTK GPS algorithms the process noise of the positions can be adopted according to the planned motions, which are known from the flight planning. In contrast, the ambiguities are assumed to be constant. This is why the process noise of the ambiguity parameters is set to a very small value (σ_{amb} = $1 \cdot 10^{-4}$ *cycles*).

In the measurement noise a distinction must be made between the carrier phases and the pseudoranges. Therefore, a factor f is used, which is 1 for carrier phases and 100 for pseudoranges:

$$\sigma_{\varphi,P}^2 = 2 \cdot f^2 \cdot (a^2 + (b / \sin el)^2) \quad (3)$$

This model is split into a constant and an elevation (el) dependent part. The author's experience is that $a = 2$ mm and $b = 2$ mm lead to the best results for the MAV applications.

Once the ambiguities are estimated in the float solution the integer ambiguity estimation follows. In this step the float ambiguities and their covariance matrix are used to search for the integer ambiguities. This is done by the modified least squares ambiguity decorrelation adjustment (MLAMBDA) (Chang et al. 2005). After the ambiguity search a decision must be made, if the resulting set of ambiguities can be accepted or if it has to be rejected, since there is the risk of incorrectly fixing the ambiguities. This decision is made by the simple ratio test (Verhagen & Teunissen 2006). Finally, in case ambiguities could be fixed successfully, the fixed solution can be computed, leading to rover positions with cm-accuracy.

More details to the implemented RTK GPS algorithms can be found in Eling et al. (2014).

4.1.2 Task scheduling

The RTK GPS processing is realized in two parallel tasks, the master task and the rover task (Fig. 5). The actual position determination is carried out in the rover task with a rate of 10 Hz. Since the master station remains on ground, the master observations have to be transmitted via radio to the direct georeferencing system with a rate of 1 Hz. In order to be less dependent on the potentially unreliable master data transmission and the lower sampling rate, not the actual but simulated master observations are used for the position determination. The true master observations are only used to update the simulation error in the master task. The simulation error has to be applied to correct the simulation results in the rover task. There, the assumption is made, that the simulation error keeps constant over a short time. With this method, a position accuracy better than 10 cm can still be maintained in most cases, even when the link to the master station is interrupted for about 30 s.

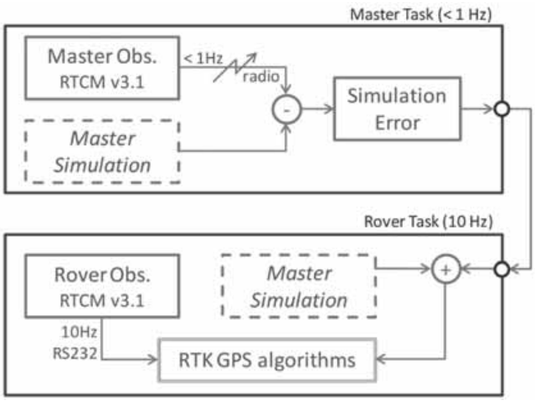

Fig. 5: The rover and the master task as they are realized on the 400 MHz processor (RTCM = Radio Technical Commission for Maritime Services).

4.2 *Attitude Determination*

The georeferencing unit includes several sensors, which can be used for the attitude determination: gyroscopes, accelerometers, magnetometers, an onboard GPS baseline, RTK GPS and stereo camera pairs. Even if the stereo camera pairs are not directly connected to the georeferencing unit they also provide precise relative orientation information (Schneider et al. 2013).

4.2.1 The attitude filter

Only using the angular rates, the accelerations and the magnetic field observations would generally deliver enough information to determine all three attitude angles (roll, pitch, yaw) of the MAV. However, ferromagnetic material on the MAV and the high electric currents of the rotors lead to significant distortions of the magnetometer during a flight, even if the magnetometer is well calibrated (Caruso 2000). Hence, in order to avoid the need for the magnetometer readings as much as possible, the onboard GPS baseline has been established on the MAV.

In the current status of the implementation, the attitude determination is realized in a quaternion based EKF, e.g. Sabatini (2006), which is currently still decoupled from the position determination. The state vector $\boldsymbol{x}_{Att}$ contains the following parameters:

$$x_{Att} = \left[q_0\, q_1\, q_2\, q_3\, \Delta\omega_x\, \Delta\omega_y\, \Delta\omega_z\;\, a_{tr,x}\, a_{tr,y}\, a_{tr,z} \right]^T . \quad (4)$$

Thus, beside a quaternion $\boldsymbol{q}$, representing the attitude, and the gyro bias $\Delta\boldsymbol{\omega}$, also the translational accelerations $\boldsymbol{a}_{tr}$ are estimated, to allow for a separation of the dynamics of the MAV from the gravitation vector.

In the system dynamics model the bias corrected angular rates are used to predict the quaternion vector $\boldsymbol{q}$. The prediction of the translational accelerations $\boldsymbol{a}_{tr}$ is based on a Gauss-Markov process, assuming that they are tending to zero.

Finally, the measurement vector $\boldsymbol{l}_{Att}$ includes the magnetic field observations $\boldsymbol{m}$, the accelerations $\boldsymbol{a}$ and the onboard GPS baseline vector $\boldsymbol{r}$.

$$l_{Att} = \left[m_x\; m_y\; m_z\; a_x\; a_y\; a_z\; r_E\; r_N\; r_U \right]^T \quad (5)$$

4.2.2 The ambiguity resolution

The difficulty in using the onboard GPS baseline is that only single-frequency GPS observations are available for their determination and usually, the time to fix the ambiguities of single frequency GPS data takes a few minutes (Odijk et al. 2007). To improve this, the attitude determination is performed in three steps: (1) an approximate attitude solution, based on the magnetometer and the accelerometer readings, (2) the ambiguity resolution and (3) the final attitude determination, also including the baseline parameters in the measurement model.

Hence, the idea is to use an approximate attitude solution to shrink the search space of possible ambiguity candidates in the integer ambiguity estimation (Eling et al. 2013). In doing so, the ambiguity resolution can be improved significantly, with the result that the ambiguities can mostly already be fixed within the first epoch.

5 System Calibration

In order to correctly fuse all sensory information and to provide a precise georeference of the taken images, the relative positions and attitudes of all sensors within the system have to be known. Although it is in principle possible to determine these values by sophisticated calibration procedures, we decided to measure them using a high resolution laser scanner.

The used measurement equipment for the system calibration consists of a 3D laser scanning portable coordinate-measuring machine arm (Romer Infinite 2.0) and a 3D laser scanner (Perceptron ScanWorks V5). Together, this equipment leads to accuracies of σ ≤ 45 μm for single points. One of the resulting point clouds is shown in Fig. 6. After the scanning, the translations and rotations between the georeferencing sensors and the high-resolution camera were measured in the point-cloud by 3D-modeling of the different sensors. We estimate that the accuracy of this method is below one millimeter for the translations and below some tenth of one degree for the rotations.

Of course, even if the sensors are firmly fixed to the platform, slight changes of the calibration parameters during a flight cannot be excluded. Furthermore, the IMU axes directions, which are best possibly mechanically aligned with the body frame axes, cannot be calibrated precisely via the laserscanner approach. Thus, the full system calibration still can be improved. Currently, the authors are working on the realization of a calibration field, where ground control points allow for the determination of the calibration parameters during a flight.

Fig. 6: Point-cloud of a laser scan, which has been used for the system calibration.

The interior orientation of the camera has been determined via a laboratory test field calibration. By means of this calibration the calibrated focal length, the principal point, and the non-linear distortion of the camera were estimated.

6 Results

By comparing the GPS-positions of the georeferencing system with the results of other recognized GPS software packages, e.g. RTKLIB and Leica Geo Office, the correctness of the implemented RTK GPS algorithms could already be confirmed (Eling et al. 2014). This is of course only an evaluation of the correctness of the implementation, as the same data are used. At the moment, we do not have an independent check on the absolute accuracy of the direct georeferencing system. However, we can use the results of a free photogrammetric bundle adjustment (BA), which is independent of ground control points, to evaluate the form of the trajectory. The direct georeferencing trajectory, both in the translation and the rotation, should only differ by a spatial similarity transformation from the BA trajectory.

For the comparison to a BA trajectory, the following steps were performed:

- time synchronized image and position/attitude data collection during a MAV flight,
- photogrammetric BA on the collected images,
- 7-parameter Helmert transformation between the GPS and the camera coordinates,
- position and attitude difference determination.

In Fig. 7 the GPS track of the manually flown test flight is shown (red line). During the flight the GPS ambiguities could be fixed for all epochs. From the starting point the MAV was first navigated to a building. Afterwards, in the green marked area, images of the façade of the building on the right were taken with a rate of 1 Hz.

Finally, the images were orientated via a photogrammetric BA. Since the flight path along the building did not follow a regular pattern, the image overlap was uneven, but the geometric point distribution was good. The re-

Fig. 7: The RTK-GPS positions during the test flight. Images were taken in the image acquisition area to observe the building on the right.

sulting standard deviations of the BA translations and rotations relative to the first camera position, which defines the photogrammetric coordinate frame, are better than 4 mm and 0.02 deg for all epochs.

For comparison of the BA positions with the direct georeferencing positions a 7-parameter Helmert transformation between the GPS and the camera positions was performed, considering the system calibration parameters.

In Fig. 8 the differences between the camera positions, determined via GPS and via BA are shown. Thus, the differences of the trajectories are mostly less than ± 5 cm in all components. A mean value and a standard deviation can also be calculated from the differences. The mean values are zero and the standard deviations are 1.4 cm – 2.3 cm. Hence, the precisions of the positions meet the requirements of 1 cm – 3 cm. Please note that the GNSS measurement conditions were challenging during this test flight, since the MAV flew close to trees and a building.

For the attitude evaluation the BA results, representing the rotations from the camera- to the photogrammetric-frame R_{Cam}^{Photo}, have to be transformed into rotations from the body- to the navigation frame R_{Body}^{Nav}, which then should match the output of the direct georeferencing system:

$$R_{Body}^{Nav}(t) = R_{Photo}^{Nav} \cdot R_{Cam}^{Photo}(t) \cdot R_{Body}^{Cam} \quad (6)$$

Therefore, the system calibration rotation matrix R_{Body}^{Cam} and the rotation matrix from the 7-parameter Helmert transformation R_{Photo}^{Nav}

have to be applied. The only time-dependent variable on the right side of (6) is the result of the BA $(R_{Cam}^{Photo}(t))$.

The differences between the direct georeferencing system and the camera attitudes are presented in Fig. 9. Here, two different time series are shown for each attitude angle: The blue dots represent the differences to the approximate attitudes (see section 4.2), which were determined only using the IMU and the magnetometer observations and the red dots represent the differences to the attitudes based on the IMU, the magnetometer and the on-board GPS baseline.

Since the magnetometer is the only sensor in the "IMU+magnetometer" combination, providing yaw-information, significant deviations are visible in the "IMU+magnetometer"-yaw-angles. These deviations, looking like a trend here, result from a distortion of the magnetometer readings. Adding the GPS baseline improves the yaw-results enormously. Thus, the standard deviations of the "IMU+magnetometer+GPS" differences are < 1 deg for all attitude components. However, the mean value of the pitch angle is approximately 1 deg. Thus, there seems to be a remaining offset in the calibration, which has to be reviewed.

7 Conclusions and Future Work

In this contribution a newly developed direct georeferencing system has been presented. The system combines two GPS receivers, in-

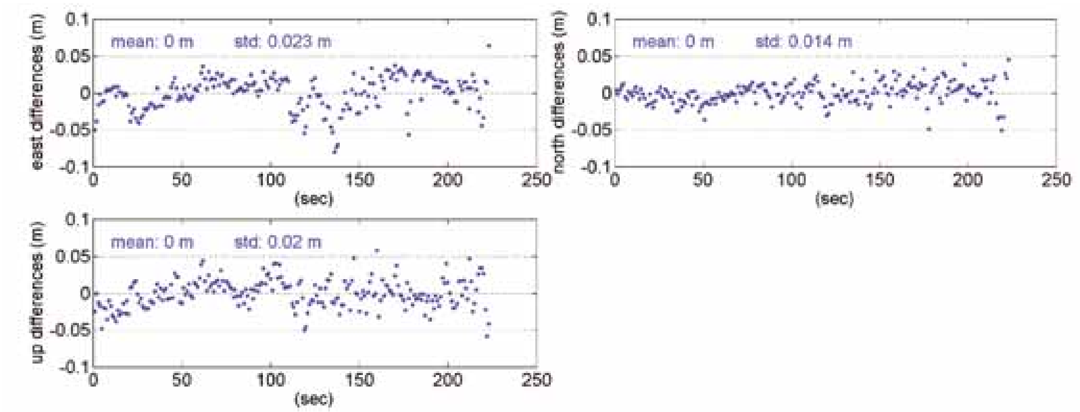

Fig. 8: Differences between the camera positions, determined via GPS and via BA.

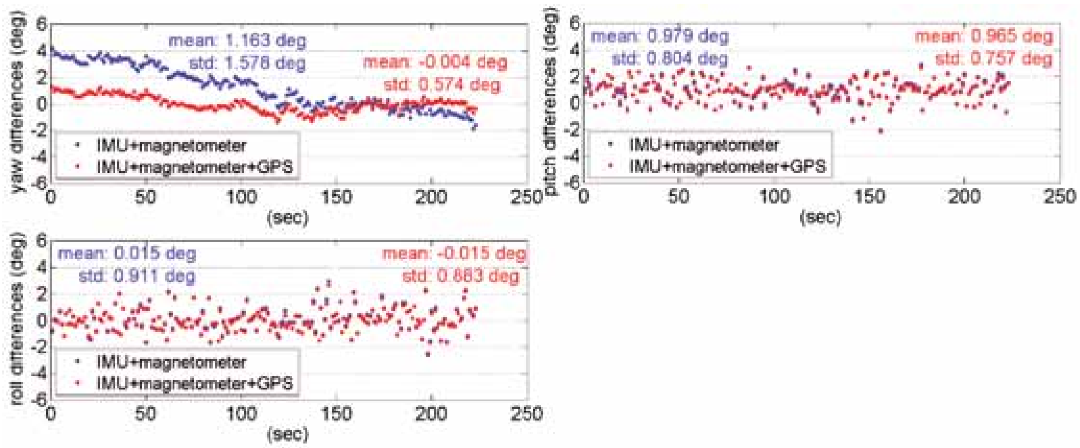

Fig. 9: Differences between the attitudes from the bundle adjustment and the attitudes from the georeferencing system.

ertial sensors, magnetic field sensors, a barometer and a real-time processing unit. The main advantages of the system are that (1) it is lightweight, (2) it is real time capable, (3) it leads to accurate results and (4) it is able to bridge gaps of single sensors. In the current state the system is already providing positions and attitudes in real-time with accuracies in the order of a few centimetres and degrees. However, the intended robustness of the full motion state estimation, especially in non-ideal GPS conditions, has not yet been achieved.

The authors are currently working on the implementation of tightly coupled GPS algorithms. In such a full motion state filter the positions will then also have a positive impact on the attitude determination. Furthermore, the optical flow information from the stereo cameras still has to be integrated in the position and attitude determination. A challenge of this development will be the consideration of the latency time of the position and attitude changes from the camera systems with respect to the GPS and IMU data.

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