A Direct Georeferencing System for Real-Time Position and Attitude Determi-Nation of Lightweight UAVS

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Keywords: UAV, Real-Time, Direct Georeferencing, RTK GPS, IMU, GPS Heading

SUMMARY

In recent years, unmanned aerial vehicles (UAVs) have been used increasingly as mobile mapping platforms in remote sensing applications. Examples can be found in the fields of surveying, precision farming or infrastructure inspection. Generally, for these applications a georeferencing of the collected data is required. This georeferencing can be done indirectly, using ground control points, or directly, using an onboard sensor system. The advantages of a direct georeferencing over an indirect georeferencing are that it is less time-consuming and it is real-time capable. Thus, a direct georeferencing system can also be used for the navigation of the UAV. However, the development of a precise direct georeferencing system for UAV platforms is very challenging, since the weight and the size of the system are restricted by space and the weight limitations of the UAV platform.

In this contribution a direct georeferencing system for the position and attitude determination of lightweight UAVs is presented. The system has a weight of 240 g and leads to position accuracies < 5 cm and attitude accuracies < 1 deg. As the main georeferencing sensors the system includes a dual-frequency GPS board (Novatel OEM615), which is used for an RTK GPS positioning, a single-frequency GPS board (Ublox LEA6T), which is in combination with the dual frequency GPS board used for the attitude determination via an onboard GPS baseline, an IMU (Analog Devices Adis 16488) and finally also a magnetometer. These sensors are all directly connected to a real-time processing unit (National Instruments sbRIO 9606).

The RTK GPS algorithms, the GPS baseline attitude algorithms and the sensor fusion algorithms, which are running on the system, are in-house developed. The main motivation for developing custom algorithms was to allow for a fast and reliable ambiguity resolution for both, the RTK GPS positioning and the onboard single frequency GPS baseline determination. Due to the fast ambiguity resolution algorithms, the system is able to provide GPS position and attitude information quickly after every loss of lock of the GPS signals.

Beside the system design and an overview of the implemented algorithms also results of different applications will be shown, to illustrate the functionality of the system.

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1. INTRODUCTION

Due to the possibility to cover wide areas in a short period of time, the acquisition of data from mobile platforms has become established in many communities and in many applications in recent years. In this context unmanned aerial systems (UASs) have been developed in the past ten years, with the capability to collect mapping data from above. In contrast to other mobile platforms, unmanned aerial vehicles (UAVs) have the advantage of being able to overfly inaccessible and also dangerous areas. Furthermore, they can get very close to objects to collect high resolution data with low resolution sensors and they allow for approaching objects from all viewing directions, without physical contact. Examples of UAV applications can be found in the fields of precision farming, such as phenotyping or plant monitoring, (Bendig et al. 2014), infrastructure inspection (Merz and Kendoul 2011) and surveying (Eisenbeiss et al. 2005).

Recently, there has been a discussion concerning the correct term for unmanned aerial vehicles. Beside the term 'UAV' also the terms 'drone', 'remotely piloted vehicle' and 'remotely piloted aircraft' exist. Since this paper is dealing with the application of lightweight UAVs for mobile mapping the term 'micro aerial vehicle' (MAV) 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).

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 for an indirect georeferencing. 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 a precise time synchronization of the onboard sensors. Furthermore, a real-time direct georeferencing also offers the opportunity to process collected mapping data already during the flight.

1.1 Mapping on Demand - a research project in Germany

The usefulness of a real-time direct georeferencing for MAV applications can be illustrated by the project the authors are working on: *Mapping on Demand*. The goal of this research project, which is funded by the Deutsche Forschungsgemeinschaft (DFG), 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 this project comes with the term 'on demand'. This means that apart from the classical 'mapping' part, where 3D information is extracted from aerial images, the MAV is intended to fly fully autonomous on the basis of a high-level user inquiry. During the flight, obstacles have to be detected and avoided (Holz et al. 2013). In order to extract semantic information (Loch-Dehbi et al. 2013), which can be used to refine the trajectory planning (Nieuwenhuisen et al. 2013), the mapping data has to be processed in real-time.

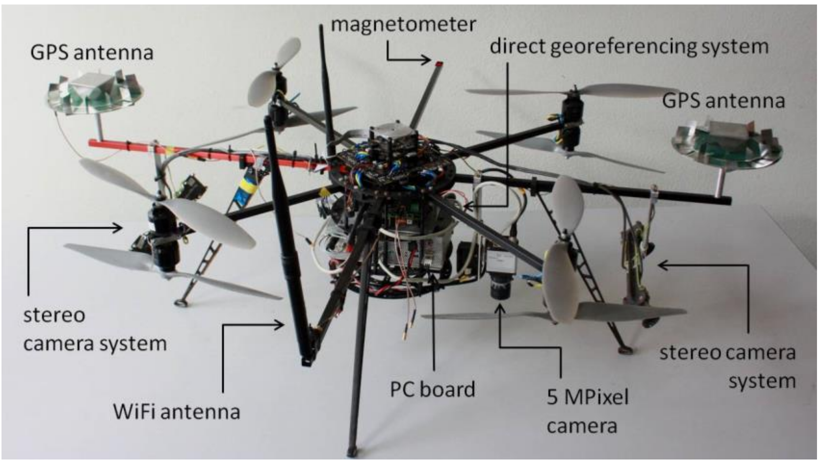

Fig. 1: The MAV, equipped with mapping and georeferencing sensors, as it was developed for the research project mapping on demand.

In the project *Mapping on Demand* the direct georeferencing is needed for the control and the navigation of the MAV, the georeferencing of the 3D reconstructions and to improve the image processing. For example, when the georeferencing information is used as initial values for the bundle adjustment the image processing can be significantly accelerated.
Fig.1 shows the current version of the MAV platform as it is developed within this project. It is based on a MikroKopter OktoXL assembly kit of HiSystems GmbH. For our application we customized this kit to a coaxial rotor configuration. Furthermore, we replaced the centerplates with more stable carbon fibre plates to stabilize the system and we installed the direct georeferencing and the mapping sensors. The two stereo camera pairs, which can be seen on the left and the right side of Fig.1, act as an additional sensory input for the position and attitude determination (Schneider et al 2013) and the 5MPixel industrial camera with global shutter is the actual mapping sensor. The PC board is used for the onboard image processing, the flight planning and the machine control and the WiFi module enables a connection to a ground station. More details to the research project mapping on demand can be found in (Klingbeil et al. 2014a).

1.2 The Objectives for the development of the direct georeferencing system

Although the direct georeferencing system has to be small and lightweight to be carried by the MAV platforms, the accuracy requirements for the position and attitude determination are high. Generally, these accuracy requirements are different for the machine control, navigation and mapping purposes.
In our project the MAV is intended to maintain a safety distance of about 0.5 m to obstacles. Hence, a position accuracy of 0.1 m is sufficient for the navigation. The absolute attitude ac-

curacy should be in the range of 1 deg - 5 deg. For the machine control the relative information is more important and for this the accuracies should be slightly higher.
For mapping purposes, the positions and attitudes have to be known better, since the absolute georeference 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 in the range of 1 cm - 3 cm and the attitude accuracy should be better than 1 deg. At this point it should 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 should be avoided.
Summarizing, the direct georeferencing system should have the following characteristics:

- The weight of the system has to be less than 500 g, to be applicable on MAVs.
- Especially for the control and navigation the system has to be real-time capable.
- All sensors have to be synchronized and outages of single sensors should be bridgeable by other sensors.
- The system is intended to provide accurate positions (σ_{pos} < 5 cm) and attitudes (σ_{att} < 1 deg) during flights.
- The integration of data from additional sensors, such as cameras, should be possible.

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.

1.3 Related work to the direct georeferencing of MAVs

Generally, direct georeferencing has extensively been researched for airborne applications, such as presented in Schwarz et al. (1993), Skaloud (1999) and Heipke et al. (2002). However, due to the weight and size restrictions on MAVs, these systems cannot be adopted easily for MAV applications. For instance, only lower quality IMUs can be used on MAVs, with the result that further sensors, e.g. cameras, are needed for many applications, to be able to bridge GPS losses of lock.
Usually, direct georeferencing of MAVs is done by means of single L1 C/A code GPS receivers, MEMS based inertial sensors and magnetometers (Yoo and Ahn 2003, Merz and Kendoul 2011, Xiang and Tian 2011). However, the resulting accuracies of these sensor combinations ($\sigma_{pos} \approx$ 2 - 10 m and $\sigma_{att} \approx$ 2 - 10 deg) are insufficient for geodetic applications. This is why the development of a more precise direct georeferencing system for MAVs is becoming more and more demanded (Bláha et al. 2011).
First approaches applying an RTK (real-time kinematic) GPS module on MAVs were presented in Rieke et al. (2011), Stempfhuber and Buchholz (2011), Bäumker et al. (2013), and Rehak et al. (2014). Nevertheless, in none of the referenced developments the position and attitude determination is performed in real-time on board of the MAV.

2. THE DIRECT GEOREFERENCING SYSTEM

The current version of the direct georeferencing system is presented in Fig. 2. The dimensions of the system are 11 cm x 10.2 cm x 4.5 cm and the weight is 240 g without the GPS antennas. In order to reduce weight, the GPS antennas used in this system (NavXperience 3G+C) were dismantled. Due to the omission of the housing and the 5/8'' threads of the antennas, the weight of every antenna could be reduced from 350 g to 100 g (see Fig. 2, right). However, since the antenna reference point got lost in this process, the antennas had to be recalibrated in an anechoic chamber for further use (Zeimetz and Kuhlmann 2010). By comparison to the original antennas, the dismantling led to significant changes in the phase center offsets (ca. 4 cm in the Up, < 1 mm in the North and East component) and in the phase center variations (< 5 mm) of the antennas.

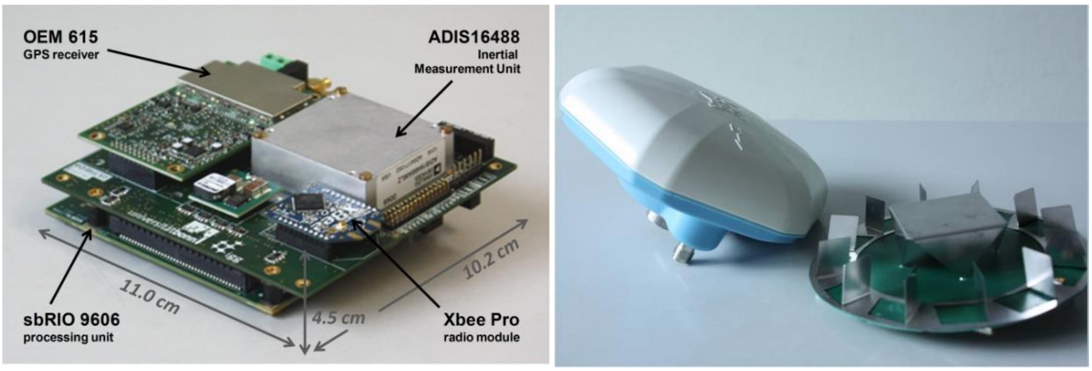

Fig. 2: The direct georeferencing system (left) and a comparison of the original and the dismantled GPS antenna (right).

In Fig. 3 a flow chart of the direct georeferencing system with the sensors and the main calculation steps is shown. As sensors the system consists of a dual-frequency GPS receiver (Novatel OEM 615), a single-frequency GPS receiver (Ublox LEA6T), an IMU (Analog devices ADIS 16488) and a magnetometer (Honeywell HMC5883L).
The dual-frequency GPS receiver is the main positioning device. Together with the GPS raw data of the master station (carrier phases ϕ_M, pseudoranges P_M), which is transmitted via a radio module (XBee Pro 868), the data of the dual-frequency GPS receiver (ϕ_R, P_R) is used for a RTK GPS positioning, leading to centimeter position accuracies.

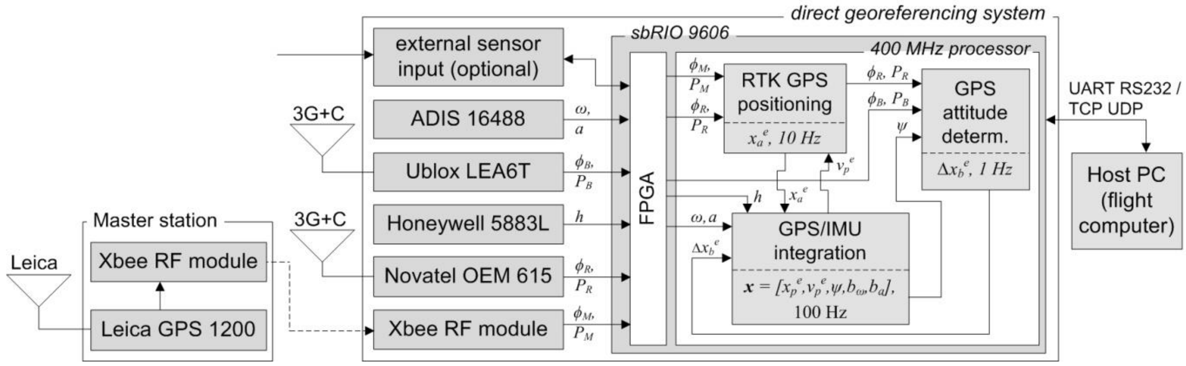

Fig. 3: Flow-chart of the direct georeferencing system.

Additionally, in collaboration with the data of the single-frequency GPS receiver (ϕ_B, P_B), the data of the dual-frequency GPS receiver is also used for the GPS attitude determination. As seen in Fig. 1, the corresponding GPS antennas of these two receivers form a short baseline (baseline length = 92 cm) on the MAV. The determination of the baseline-vector in an e-frame (earth-fixed) enables the yaw- and the pitch-angle determination.
The tactical grade MEMS IMU, which includes three axes gyroscopes, accelerometers and magnetometers, provides angular rates (ω), accelerations (a) and magnetic field observations (h) with high rates (100 Hz) for the position and attitude determination. To be unaffected by the electric currents as much as possible, an additional magnetometer is placed on the outer end of one of the rotor-free MAV arms (Fig. 1).
Beside the sensors, the direct georeferencing system also consists of a processing unit (National Instruments, sbRIO 9606), which is a reconfigurable IO board, including an FPGA (field programmable gate array) and a 400 MHz processor. In this combination, the FPGA is used for a fast and parallel communication with the sensors. Afterwards, the preprocessed sensor data are provided to the 400 MHz processor via direct memory accesses, avoiding delays and supporting the real-time capabilities of the system. Finally, the actual position and attitude determination is carried out on the 400 MHz processor.

3. METHODOLOGIES

All the position and attitude determination algorithms, which are running on the direct georeferencing system, are in-house developed. The main calculation steps of these algorithms are shown in Fig. 3: the RTK GPS positioning, the GPS attitude determination and the GPS/IMU integration. Generally, the integration of these steps could be realized in one tightly coupled approach. Nevertheless, in the current implementation, we decided to separate the different raw data calculation steps and we only use interactions at the level of parameters. This approach has the advantage that the integration is more reliable and more practical in the real-time programming.
In the following subsections the various calculation steps will be explained in more detail.

3.1 GPS/IMU integration

The GPS/IMU integration is the calculation step, where all available sensory input is fused, in order to determine the best position and attitude of the system that is currently available. Therein the GPS and the IMU measurements complement each other well, since the IMU provides short-term stable high-rate (100 Hz) data and the GPS provides long-term-stable low-rate (1-10 Hz) data.

Basically, the GPS/IMU integration can be separated into the Strapdown Algorithm (SDA) and the Kalman filter update. In the SDA the high dynamic movement of the system is determined integrating the angular rates and the accelerations of the MEMS IMU in real-time. Since the SDA is drifting over time, the long-term stable measurements of the magnetometer and the GPS receivers are needed to correct and bound the drift of the inertial sensor integration, which is realized in an error state space Kalman filter. Some advantages of estimating the full state outside the filter and subtracting the estimated errors after every Kalman filter update can be found in (Schmid et al. 2012).

In the GPS/IMU integration algorithms the navigation equations of the body-frame (b-frame) are expressed in an earth-fixed frame (e-frame). Therefore, the full state vector **x** includes the position $\boldsymbol{x}_p^e$ and the velocity $\boldsymbol{v}_p^e$, represented in the e-frame. For the attitude representation a quaternion $\boldsymbol{q}$ is used. Finally, the accelerometer bias $\boldsymbol{b}_a^b$ and the gyro bias $\boldsymbol{b}_\omega^b$ are also estimated:

$$\boldsymbol{x} = \left[\boldsymbol{x}_p^{e,T} \;\; \boldsymbol{v}_p^{e,T} \;\; \boldsymbol{q}^T \;\; \boldsymbol{b}_a^{b,T} \;\; \boldsymbol{b}_\omega^{b,T}\right]^T.$$

In the Kalman filter update the error state vector $\delta\boldsymbol{x}$, including the error vectors for the position $\delta\boldsymbol{x}_p^e$, the velocity $\delta\boldsymbol{v}_p^{e,T}$, the attitude $\delta\psi$, the accelerometer bias $\delta\boldsymbol{b}_a^b$ and the gyro bias $\delta\boldsymbol{b}_\omega^{b,T}$, is determined:

$$\delta\mathbf{x} = \left[\delta\boldsymbol{x}_p^{e,T} \;\; \delta\boldsymbol{v}_p^{e,T} \;\; \delta\psi^T \;\; \delta\boldsymbol{b}_a^{b,T} \;\; \delta\boldsymbol{b}_\omega^{b,T}\right]^T,$$

where the dimension of the attitude error is 3x1 here.

The observations in the measurement model are:

- the RTK GPS position $\boldsymbol{x}_a^e$ of the dual-frequency RTK GPS antenna reference point, expressed in the e-frame,
- the GPS attitude baseline vector $\Delta\boldsymbol{x}_b^e$, expressed in the e-frame,
- the magnetic field vector $\boldsymbol{h}^b$, expressed in the b-frame.

Since the reference point of the RTK GPS antenna is not identical with the system reference point, a lever arm between the system and the antenna reference point must be regarded in the measurement model of the RTK GPS positions. From calibration measurements the coordinates of the lever arm are precisely known in the b-frame.

In the SDA a coupling between the accelerations, measured by the IMU, and the positions, measured by the RTK GPS, exists. Due to this coupling also the yaw angle can be observed, but only in the presence of horizontal accelerations.

To determine an accurate and reliable yaw angle for every motion behavior, a short GPS baseline is realized on the MAV. A significant challenge in processing this baseline is the ambiguity resolution, since only single-frequency GPS observations can be used. Empirical tests have shown that the ambiguity resolution of a single-frequency GPS baseline generally takes several minutes (Odijk et al. 2007). Among other strategies, we use the additional information from a magnetometer, to improve the ambiguity resolution and to actually enable an instantaneous ambiguity fixing during kinematic applications (see section 4.3).
Ferromagnetic material on the UAV and the high electric currents of the rotors lead to significant disturbances of the magnetometer during the flights. While the influence of the material can be compensated by calibration procedures (Klingbeil et al. 2014b), the influence of the dynamically changing electric currents are more challenging. To minimize them, the magnetometer is placed at the outer end of one of the rotor free arms of the MAV. Also, the measurement model is arranged in the way that the magnetic field observations only have an impact on the yaw determination in our algorithms.

3.2 RTK GPS positioning

The RTK GPS positions, which are inputs to the GPS/IMU integration algorithms, are calculated in real-time with a rate of 10 Hz. These RTK GPS algorithms are in-house developed, although there are commercial (even for the Novatel OEM 615) and open source (RTKlib, Takasu and Yasuda 2009) RTK GPS solutions available. The main reasons for developing a custom RTK GPS software are: (a) The integration of other sensors and/or solutions is possible, to improve the ambiguity resolution and the cycle slip detection. (b) In commercial software there is generally no access to the source code. (c) In the development of a real-time capable system the implemented software has to meet the requirements of the operating system that is running on the real-time processing unit.

Generally, the implemented RTK GPS algorithm complies with a single baseline determination (one master, one rover), where the master station remains stationary on the ground and the rover is onboard of the MAV.

3.2.1 The parameter estimation

The key to the RTK GPS positioning is the ambiguity resolution, which is the process of resolving the unknown number of integer cycles of the carrier phase observations. In order to resolve the ambiguities and finally to determine the RTK GPS positions the parameter estimation is performed in three steps: (1) float solution, (2) integer ambiguity estimation and (3) fixed solution.
The float solution is the step, where the ambiguities are estimated as real-numbers. This estimation is realized in an extended Kalman filter (EKF). Beside the rover position $\boldsymbol{x}_a^e = [x_{a,x}\ x_{a,y}\ x_{a,z}]^T$, represented in the e-frame, the EKF state vector $\boldsymbol{x}_{SD}$ also contains single-difference (SD) ambiguities N^j on the GPS L1 and the GPS L2 frequency. The reason for estimating SD

instead of double-difference (DD) ambiguities is to avoid the hand over problem that would arise for DD ambiguities, when the reference satellite changes (Takasu and Yasuda 2009).

$$\boldsymbol{x}_{\boldsymbol{SD}} = \left[x_{a,x}^{e} \; x_{a,y}^{e} \; x_{a,z}^{e} \; N_{L1}^{1} \ldots N_{L1}^{n} \; N_{L2}^{1} \ldots N_{L2}^{n} \right]^{T}$$

To allow for an instantaneous ambiguity resolution the observation vector $\boldsymbol{l}$ consists of DD carrier phases $\phi_{RM,}^{jk}$ and DD pseudoranges $P_{RM,}^{jk}$ on the GPS L1 and the GPS L2 frequency:

$$\boldsymbol{l} = \left[\phi_{RM,L1}^{1k} \ldots \phi_{RM,L1}^{nk} \; \phi_{RM,L2}^{1k} \ldots \phi_{RM,L2}^{nk} \; P_{RM,L1}^{1k} \ldots P_{RM,L1}^{nk} \; P_{RM,L2}^{1k} \ldots P_{RM,L2}^{nk} \right]^{T},$$

where the subscripts *M* and *R* stand for master and rover and *k* is the reference satellite.
In the current implementation a random walk model is assumed as dynamic model of the MAV in the EKF. Even if this is a simple model, it agrees with the movement of every vehicle, when the process noise is chosen appropriate.
From the float solution real-valued ambiguities and their covariance matrix are resulting. In step (2) of the RTK GPS determination these ambiguities now have to be fixed to their correct integer values, to fully exploit the high accuracy of the carrier phase observables. The authors decided to apply the MLAMBDA method (Chang et al. 2005) for the integer ambiguity estimation.
Finally, in the validation step, a decision must be made, if the result of the integer ambiguity estimation can be accepted or not. This is done by the simple ratio test (Verhagen and Teunissen 2006). With the ambiguities fixed, the final rover position $\boldsymbol{x}_a^e$ is estimated with cm-accuracies. More details to the implemented RTK GPS algorithms can be found in (Eling et al. 2014a).

Usually, the time to fix the ambiguities with the algorithm described above takes a few epochs, but often the ambiguities can already be fixed instantaneously. Once the ambiguity resolution has been successful, the ambiguities can be held fixed, as long as no cycle slip or loss of lock of the GPS signals occur.
Due to the GPS/IMU integration we have a very precise prediction of the RTK GPS positions between two epochs. Thus, the integration of the inertial sensor readings enables us to detect and also repair cycle slips very reliably (Eling et al. 2014b).

3.2.2 The task scheduling

As it was already mentioned in section 3, the observations of the master receiver have to be transmitted via radio to the direct georeferencing system. In practice, this data transmission can only be realized with a rate of 1 Hz. In order to be less dependent on this potentially unreliable master data transmission and the lower sampling rate, not the actual but simulated master observations are used for the RTK GPS position determination. Hence, in the actual processing, the true master observations are only used to update the simulation errors in the master task (Fig.4), which have to be applied to correct the simulation results in the rover task.

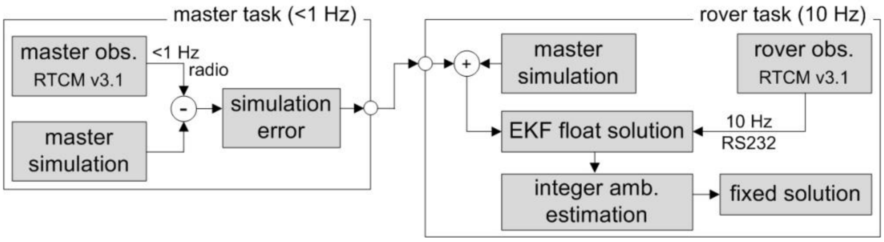

Fig. 4: The task scheduling of the RTK GPS algorithms.

3.3 GPS attitude determination

The GPS baseline is determined with a rate of 1 Hz on the direct georeferencing system. Basically, the GPS attitude determination is quite similar to the RTK GPS position determination, since it is also a relative positioning procedure. However, the difference is that both GPS devices of the attitude baseline are mounted on the MAV, with the result that the complete baseline is moving. Furthermore, the baseline length is constant and known from calibration measurements. Nevertheless, the GPS attitude determination also consists of the three steps: (1) float solution, (2) integer ambiguity estimation and (3) fixed solution.
The float solution is also based on an EKF where the single-frequency SD ambiguities N^j of the attitude baseline are estimated. Further parameters in the state vector are the baseline parameters $\Delta \boldsymbol{x}_b^e$ and the first deviation of the baseline parameters $\Delta \dot{\boldsymbol{x}}_b^e$:

$$\boldsymbol{x}_{SD} = \left[\Delta \boldsymbol{x}_b^{e,T} \;\; \Delta \dot{\boldsymbol{x}}_b^{e,T} \;\; \boldsymbol{N}^{j,T}\right]^T .$$

As observations DD carrier phases ϕ_{AB}^{jk} and DD pseudoranges P_{AB}^{jk} on the GPS L1 frequency are used. Furthermore, to improve the ambiguity resolution the attitude from the GPS/IMU integration is added to the observation vector, by transforming the known b-frame baseline parameters into the e-frame: $\Delta \bar{\boldsymbol{x}}_b^e$. Finally, also the known baseline length s can be added as a constraint to the observation vector. Then the observation vector reads:

$$\boldsymbol{y} = \left[\phi_{AB}^{1k} \;\ldots\; \phi_{AB}^{nk} \;\; P_{AB}^{1k} \;\ldots\; P_{AB}^{nk} \;\; \Delta \bar{x}_{b,x}^e \;\; \Delta \bar{x}_{b,y}^e \;\; \Delta \bar{x}_{b,z}^e \;\; s\right]^T .$$

As system dynamics model a simple random walk model is used.
In the integer ambiguity estimation we first apply the MLAMBDA method again. Due to the prior information about the attitude of the baseline, the float ambiguities can already be estimated with high accuracies in the float solution. Therefore, in more than 80% of the epochs the ambiguities can already be fixed instantaneously at this stage of the ambiguity resolution during flights. If the ambiguities could not be fixed with the MLAMBDA method the ten best solutions from the MLAMBDA method are considered any further. Unreliable ambiguity parameters are eliminated in a random order and the MLAMBDA method is applied again. Afterwards we use the ambiguity function method (Eling et al. 2013) and the known baseline length to exclude false candidates of the ten best solutions. If only one solution remains the

ambiguities can be fixed to integer values. Tests have shown, that this approach leads to an instantaneous ambiguity resolution success rate of ca. 95%.

Similar to the RTK GPS positioning the IMU readings are also used to detect cycle slips for the attitude baseline determination, when the ambiguities have been fixed successfully.

With the ambiguities fixed the baseline parameters can be determined with mm- to cm-accuracies. Since the yaw angle accuracy of the GPS baseline is also dependent on the base-line length, the distance between the both baseline antennas should be as long as possible. On our MAV we can realize a baseline with a length of 92 cm. This leads to yaw angle accuracies in the range of ca. 0.2-0.5 deg.

4. APPLICATIONS AND RESULTS

In the following subsections some applications for the mapping with MAVs and the direct georeferencing system will be presented.

4.1 Mapping on Demand

As it was already mentioned in section 1.1, one of the goals of the research project Mapping on Demand is the 3D reconstruction from visual information. Fig. 5 shows the results of a mapping with the Mapping on Demand MAV. During four flights images were collected with a sampling rate of 1 Hz and the position and the attitude of the camera was determined in real-time using the direct georeferencing system. Furthermore, a bundle adjustment was processed, using these positions and attitudes as initial values. Afterwards, dense point clouds could be generated from the orientated images using an open source software package (PMVS2, Furukawa and Ponce 2010). Due to the georeferencing of the collected images also the point clouds are georeferenced. Fig. 5 shows the results of the four different flights in one scene, to demonstrate the consistency of the georeferencing.
A detailed evaluation of the direct georeferencing for flight tests can be found in (Eling et al. 2014c).

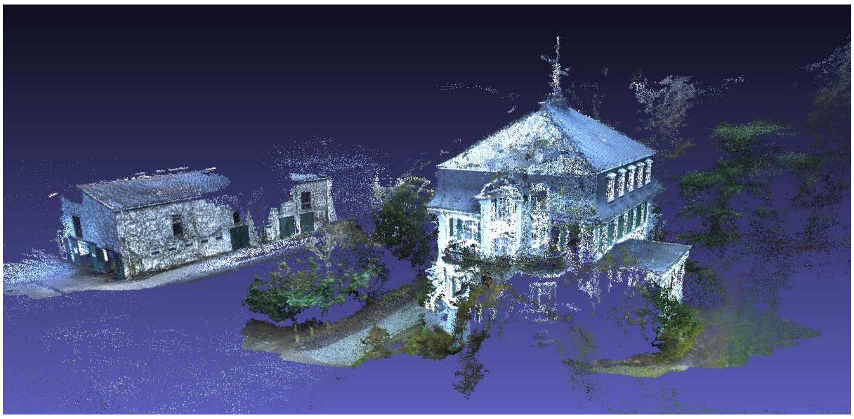

Fig. 5: A scene with four non-rectified point clouds, which result from georeferenced images collected during four independent MAV flights.

4.2 Agriculture applications

Another example for the use of the direct georeferencing system and the generation of georeferenced point clouds with an MAV is shown in Fig. 6. In this case georeferenced images were taken during a flight over a wheat field. The same process was repeated after two weeks. The difference of the respective point clouds, which were determined using the software Photoscan by the company Agisoft, reveals the plant growth at an interval of two weeks. These results show, that the determination of plant growth rates, which usually result from time-consuming field work, can be done easily and with high resolution using MAVs. With the use of a direct georeferencing system this process is getting even more efficiently, since the deployment of ground control points can be omitted.

4.3 Development of a directly georeferenced portable laser scanning system

Even if the presented direct georeferencing system is mainly intended to be used on MAVs, its small and lightweight design also offers several other opportunities for various applications. One example is the use of the direct georeferencing system in combination with a small, lightweight and low-cost laser scanner.

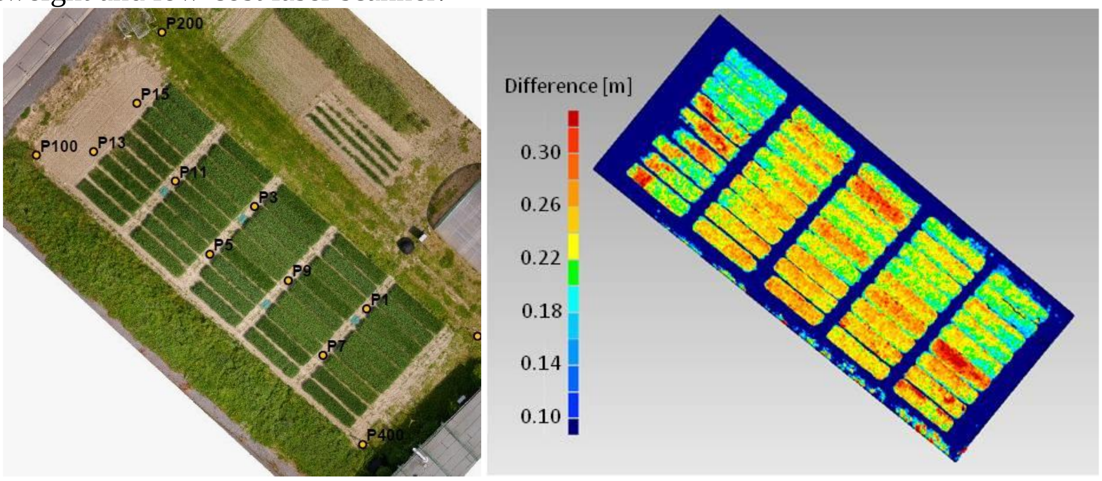

Fig. 6: Orthophoto of a wheat field (left) and the difference of the vegetation height, determined from the results of two MAV flights at an interval of two weeks (right).

In recent years terrestrial laser scanning has become an established technology for the 3D data acquisition in the surveying and mapping, since laser scanners provide high resolution data with high accuracies at high speed. However, for the measurement of a complex scene the laser scanner generally has to be moved to different viewpoints and all measured scenes have to be registered and georeferenced, which leads to a significant increase of the effort. In contrast, with a directly georeferenced kinematic laser scanning system also complex scenes can be measured with little effort.
Fig. 7 shows a portable laser scanning system we developed for kinematic laser scanning. It is a combination of the direct georeferencing system with a Hokuyo UTM-30LX-EW low cost and lightweight 2D time-of-flight laser scanner. The laser scanner is used here as an external

sensor on the direct georeferencing system (see Fig. 3). Thus, the time synchronization and the point cloud calculation are directly realized on this unit.

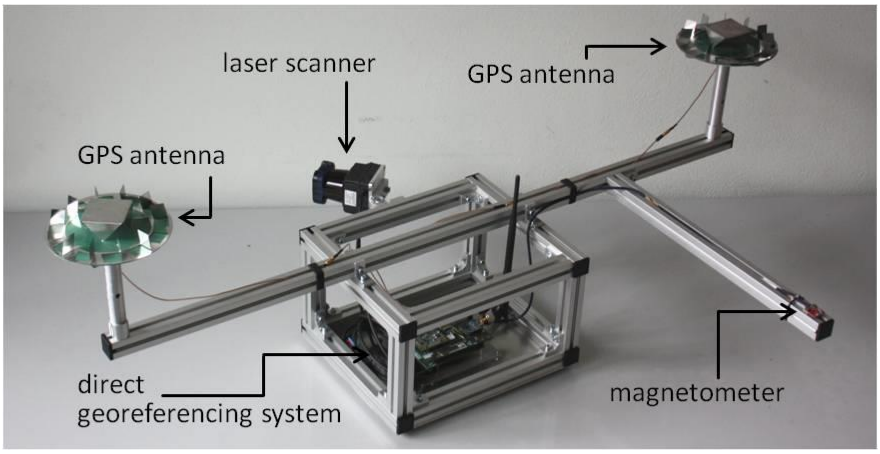

Fig. 7: A directly georeferenced portable laser scanning system for kinematic 3D mapping.

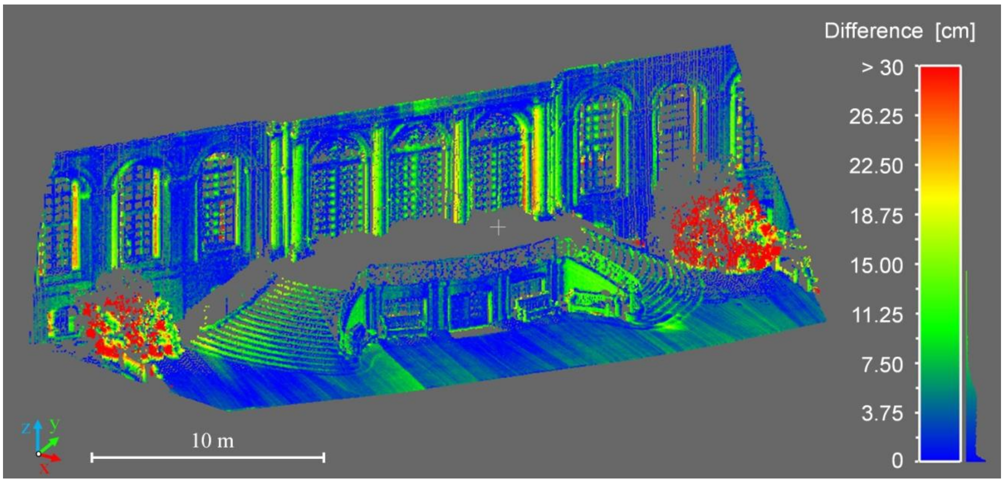

Fig. 8: Difference between the results of the directly georeferenced portable laser scanning system and the results of a terrestrial laser scan, which act as reference solution here.

In Fig. 8 differences between a directly georeferenced point cloud, measured by the portable laser scanning system, and a terrestrial laser scanning point cloud, which was indirectly georeferenced using ground control points, are shown. Although there are some systematic errors visible, the differences are mostly less than 7.5 cm. The larger differences in the foreground (red) are a result of growing vegetation in the period between both scans. The systematic errors result from the system calibration between the laser scanner and the direct georeferencing system. Currently, the authors are working on an improvement of these calibration methods.

5. CONCLUSIONS

In this paper a direct georeferencing system was presented, which is mainly intended to be used for the real-time position and attitude determination of lightweight UAVs. Summarizing, the system has the following characteristics:

- The weight of the system is 240 g, without the GPS antennas.
- The system is real-time capable.
- All sensors are synchronized and/or hardware triggered and outages of single sensors can be bridged by other sensors.
- The system provides high accuracies for the positions ($\sigma_{pos} < 5$ cm) and attitudes ($\sigma_{att} <$ 1 deg) during flights.
- The integration of additional sensors, such as cameras or laser scanners, is possible.

As sensors for the position and attitude determination the presented direct georeferencing system consists of a dual-frequency GPS receiver, a single-frequency GPS receiver, a tactical grade IMU and an additional magnetometer. All the algorithms that are running on the system are in-house developed, such as the RTK GPS algorithms, the GPS attitude determination algorithms and the GPS/IMU integration. In this way adaptations are possible to meet the requirements of various applications.

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