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Artikel: Development of an RTK-GPS system for the direct georeferencing of UAVs

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Development of an RTK-GPS system for the direct georeferencing of UAVs

Unmanned aerial vehicles (UAVs) are increasingly used as platforms in remote sensing applications. Generally, for these applications a georeferencing of the collected data is required. In this article a direct georeferencing system for lightweight UAVs based on RTK-GPS is presented. The implemented RTK-GPS algorithms and results of a flight test are briefly discussed.

UAVs (unmanned aerial vehicles) werden immer häufiger als Plattformen für Fernerkundungsanwendungen verwendet. Für die damit verbundenen Aufgaben spielt die Georeferenzierung häufig eine wichtige Rolle. In diesem Beitrag stellen wir ein System auf Grundlage von RTK-GPS für die direkte Georeferenzierung leichter UAVs vor. Neben den implementierten RTK-GPS Algorithmen werden Ergebnisse eines Testflugs präsentiert.

Les UAV (unmanned aerial vehicles) sont utilisés de plus en plus comme plateforme pour des tâches de télédétection. A cet effet le géoréférencement joue souvent un rôle important. Dans cet article nous présentons un système basé sur RTK-GPS pour le géoréférencement d'UAV légers. En plus de la mise en oeuvre d'algorithmes RTK-GPS les résultats d'un vol d'essai sont présentés.

Gli UAVs (unmanned aerial vehicles) sono utilizzati sempre più spesso come piattaforma per le applicazioni di telerilevamento. La georeferenziazione svolge un compito sempre più rilevante per le mansioni annesse e connesse. In quest'articolo presentiamo un sistema basato su RTK-PGS per la georeferenziazione diretta degli UAV più leggeri. Oltre agli algoritmi RTK-GPS implementati si presentano anche i risultati di un volo di prova.

Ch. Eling, L. Klingbeil, H. Kuhlmann

1. Introduction

In recent years, micro- and mini-sized unmanned aerial vehicles (UAVs), which can be characterized by a weight limit of 5 kg and a size limit of 1.5 m (EISENBEIß 2009), 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. For these applications mostly a georeferencing of the collected data is required. This georeferencing can be done indirectly using ground control points (d'Oleire-Oltmanns et al. 2012) or directly using an onboard sensor system (Nagai et al. 2009). Since the indirect georeferencing is time-consuming and not real-time capable, the development of an onboard georeferencing system for UAVs is currently in great demand (Bláha et al. 2011).

In this contribution a new direct georeferencing system for lightweight UAVs is presented. This system is not only designed to enable a georeferencing of remote sensing data, but also to allow for an autonomous navigation of the UAV platform. For this purpose, the georeferencing needs to be processed in real-time. Generally, the georeferencing system should have the following characteristics: (a) The weight of the system has to be less than 500 g so that the system is applicable on micro- and mini-sized UAVs. (b) The system has to be real-time capable. (c) Gaps of single sensors should be bridgeable by other sensors. (d) The system is intended to provide accurate positions (σ_{pos} < 5cm) and attitudes (σ_{att} < 1 deg). (e) The system is designed to allow for the integration of data from additional sensors, such as cameras or laserscanners.

All the software that is running on the georeferencing system is in-house developed. To give an example for the software development, this paper is focused on the implemented RTK-GPS (real-time kinematic GPS) algorithms, which enable a cm-accurate positioning of the UAV in real-time.

2. The direct georeferencing system

2.1 Design of the direct georeferencing system

The main sensors of the georeferencing system are a geodetic grade dual-frequency GPS receiver (Novatel OEM 615), a tactical grade MEMS IMU (Analog devices ADIS 16488) and a single frequency GPS chip (Ublox LEA6T). These sensors are directly connected to a real-time processing unit (National Instruments sbRIO 9606). This link is realized by an in-house designed 6-layer printed circuit board (PCB). The reason for choosing the sbRIO as processing unit is that it consists of a FPGA and a 400 MHz processor on one board so that the FPGA can be used to realize the interfaces to the onboard sensors and the 400 MHz processor can be used to compute the positions, velocities and attitudes of the UAV in real-time.

The whole system is named the *PO*-box (position and orientation box). To allow for the determination of RTK-GPS positions on the *PO*-box, the GPS raw observations from a master station have to be transmitted to the onboard system. The link to the GPS master station is realized by XBee Pro 868 long-range radio frequency modules.

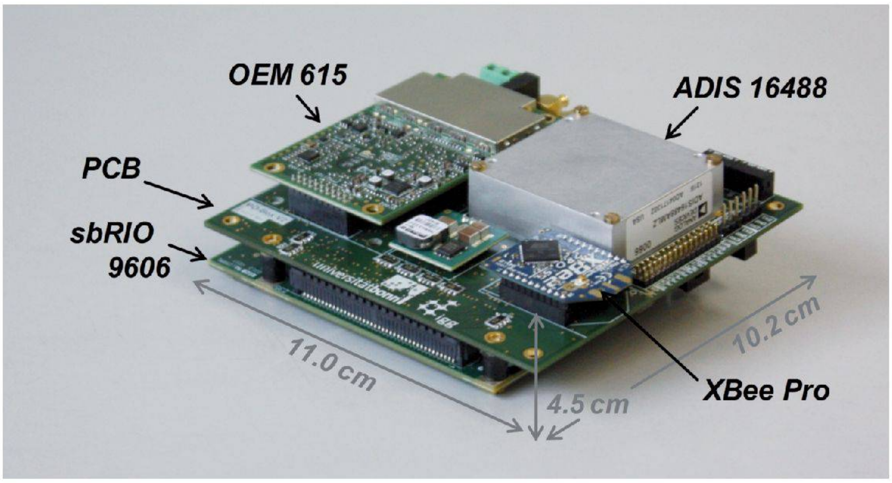

Fig. 1: The *PO*-box seen from the top.

In addition to the RTK-GPS processing the observations from the Novatel receiver are also intended to be used for the attitude determination. For this purpose the *PO*-box contains the second GPS receiver (LEA6T). The two GPS antennas (NavExperience 3G+C, Ublox ANN-MS) form a short baseline on the UAV serving as a GPS compass.

The realization of the *PO*-box is shown in figure 1. Together with both GPS antennas the total hardware costs of the direct georeferencing system are approximately 13 000 € of which more than 50% are due to the dual-frequency GPS receiver. The weight of the unit is approximately 390 g.

2.2 Software development

The FPGA and the 400 MHz processor are primarily programmed using LabView™, which is well suited for the development and administration of parallel real time tasks. The RTK-GPS and the attitude determination algorithms are written in C++. The import of this software into the visual programming environment of LabView™ has been realized using dynamic link libraries (dll-files).

2.3 The UAV platform

The UAV platform is based on the construction kit Mikrokopter Okto XL (HI-Systems 2013). In order to be able to place the georeferencing sensors on the UAV, to stabilize the system and to reduce the influence of vibrations, some modifications were necessary, such as the coaxial motor configuration (see figure 2).

Additionally to the direct georeferencing system, the UAV is also equipped with two stereo camera systems (iDS uEye UI-1221LE, 10Hz), one 5 Mpixel camera (iDS uEye UI-2280SE, 1Hz), one computer (i7-quadcore) and a Wi-Fi module. The stereo cameras will be used for obstacle detection and visual odometry in further developments. The 5 Mpixel camera is intended to act as mapping sensor and the computer is used for the image processing and data storage. The total weight of the UAV platform is 4.8 kg.

3. The RTK-GPS algorithms

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: (a) The final goal of the algorithm development is a tightly-coupled GPS processing 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 system the implemented software has to meet the requirements of the operating system that is running on the real-time processing unit.

3.1 The parameter estimation

The key to RTK-GPS positioning is the ambiguity resolution which is performed in the usual three steps: (1) float solution, (2) integer ambiguity estimation and (3) fixed solution.

The float solution is realized in an extended Kalman filter (EKF). Beside the rover position $r_R = [r_{R,x}, r_{R,y}, r_{R,z}]^T$ the EKF state vector x_{SD} also contains single-difference (SD) ambiguities N^j_{RM} on both frequencies:

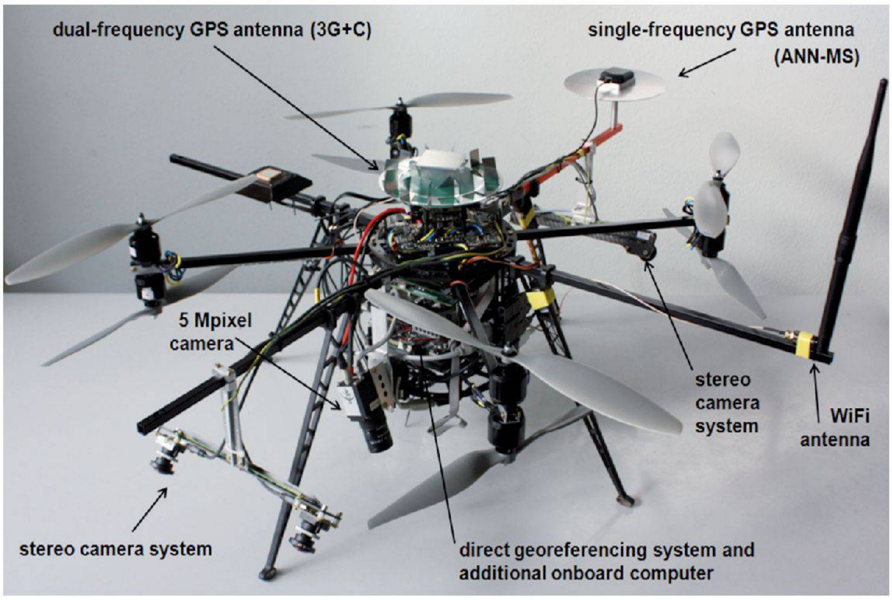

Fig. 2: The modified UAV with all sensor and processing components.

$$\mathbf{x}_{SD} = \left[r_{R,x}\ r_{R,y}\ r_{R,z}\ N^1_{RM,L1} \dots N^n_{RM,L1}\ N^1_{RM,L2} \dots N^n_{RM,L2} \right]^T \quad (1)$$

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 & Yasuda 2009).

To allow for an instantaneous ambiguity resolution the observation vector *l* consists of DD carrier phases $\Phi^{jk}_{RM}(t)$ and DD pseudoranges $P^{jk}_{RM}(t)$ on the GPS-L1 and the GPS-L2 frequency:

$$\mathbf{l} = \left[\Phi^{1k}_{RM,L1} \dots \Phi^{mk}_{RM,L1}\ \Phi^{1k}_{RM,L2} \dots \Phi^{mk}_{RM,L2}\ P^{1k}_{RM,L1} \dots P^{mk}_{RM,L1}\ P^{1k}_{RM,L2} \dots P^{mk}_{RM,L2} \right]^T \quad (2)$$

In the current state of the implementation a random walk model is assumed as dynamic model of the UAV in the EKF. Even if this is a simple model, it agrees sufficiently with the movement of the vehicle, when the process noise is chosen appropriately.

For the UAV applications the process noise of the position parameters is set to σ_{pos}=1m. This choice reflects the approximate dynamic capabilities of the UAV but doesn't smooth the positions too much. In contrast, the ambiguity parameters are assumed to be constant. Thus, their process noise could generally be set to zero. However, when slight variations of the ambiguity parameters are permitted, the parameters react better on changing satellite configurations. This is why the process noise for the ambiguity parameters is set to $\sigma_{amb} = 1 \cdot 10^{-4}$ cycles.

Since the pseudoranges are less accurate than the carrier phases, a distinction must be made between the carrier phase measurement noise σ_Φ and the pseudorange measurement noise σ_P. We do this assuming a constant factor of f = 100, and model the measurement noise at SD level as a function of satellite elevation *el* according to:

$$\sigma^2_\phi = 2 \cdot \left(a^2 + (b / \sin el)^2 \right) \quad \text{and} \quad \sigma^2_P = 2 \cdot \left(a^2 \cdot f^2 + (b / \sin el)^2 \cdot f^2 \right) \quad (3)$$

We found that a = 2 mm and b = 2 mm lead to good results for the receivers/antennas we have integrated on our UAV.

In step (2) the float solution and its covariance matrix are used to fix the ambiguities to integer values. We decided to use the MLAMBDA method (Chang et al. 2005) for the integer ambiguity estimation, since this method is, in comparison to the original LAMBDA method (Teunissen 1995), a little bit faster if many observations are available.

Finally, in the validation step a decision must be made, if the result of the ambiguity search can be accepted. This is done by the simple ratio test (Verhagen & Teunissen 2006). Once the ambiguity resolution has been successful, the fixed solution follows, where the final baseline parameters are estimated.

More details of the implemented RTK-GPS algorithms can be found in (ELING et al. 2014).

3.2 The task scheduling

The RTK-GPS processing is realized in two parallel tasks on the *PO*-box, the master task and the rover task (figure 3). The actual position determination is carried out in the rover task with a rate of 10 Hz. As already mentioned in section 2.1, the master observations have to be transmitted to the *PO*-box via radio, 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 (Mohino et al. 2005) are used for the position determination. The true master observations are only used to update the simulation error, which has to be applied to correct the simulation results in the rover task, assuming that the simulation error keeps constant over a short time.

4. Results of a test flight

In this section the RTK-GPS positions, determined on the *PO*-box in real-time during a UAV flight, will be evaluated comparing them to the results of additional GNSS software packages. To allow for this comparison, not only the real-time processed positions but also the GPS raw observations were logged on the *PO*-box during a UAV flight. Afterwards, the real-time positions of the *PO*-box, which will be abbreviated with IGG in the following, were compared to the results produced with two different GNSS software packages, namely RTKLIB (Takasu & Yasuda 2009) and Leica Geo Office (LGO) (Leica 2013). As shown in figure 4, the differences of the height components are always less than 2 cm, and mostly even less than 5 mm. Larger differences were found to be due to missing real master data which were not always available over the radio link in the real-time application. For postprocessing the master data were of course always available.

In order to clarify that the larger differences really arise from the transmission time of the master data, the logged raw data were also processed using the IGG post processing software, which uses the same algorithms as the software on the *PO*-box. As shown in figure 5 the differences significantly exceeding 5 mm are no longer visible in the postprocessing results. The remaining differences of a few millimeters are correlated to the UAV height and are caused by different troposphere models (in the IGG software a modified Hopfield model (Goad & Goodman 1974) is used). The maximum differences of the North and East components did not exceed 1 mm. We concluded that the RTK-GPS positions determined by the PO-box are in accordance with the usual RTK-GPS accuracy.

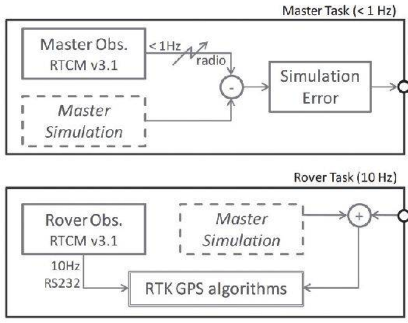

Fig. 3: The task scheduling of the RTK-GPS software on the PO-box.

5. Conclusion and outlook

In this contribution the current state of the development of a direct georeferencing system has been presented. In this

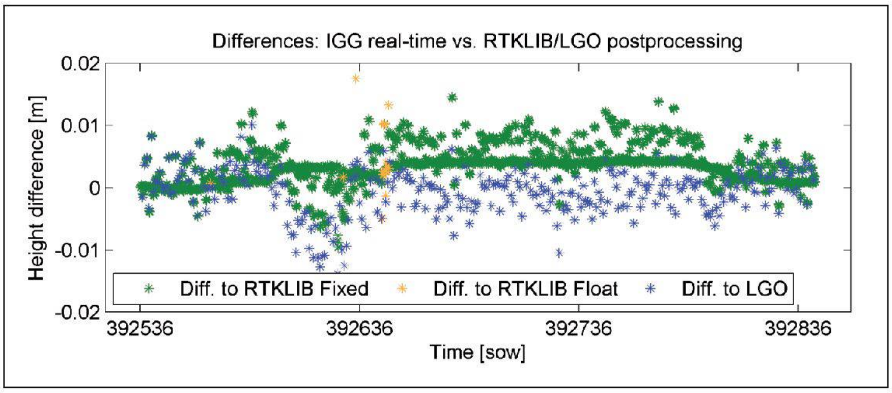

Fig. 4: Differences of the heights that were determined by the *PO*-box in real-time (IGG) and the heights that were determined in the post processing (RTK-LIB, LGO).

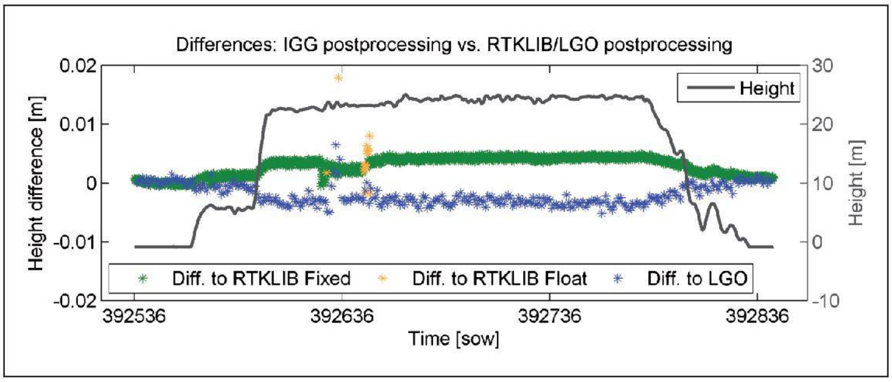

Fig. 5: Differences of the IGG postprocessing heights to the postprocessing results of RTKLIB and LGO as well as the UAV heights relative to the master station.

context the reasons for implementing an own RTK-GPS software as well as details to the first version of the RTK-GPS algorithm have been discussed. Results of a flight test have shown that the system is already applicable on lightweight UAVs. Thus, the fundament for further developments and improvements is laid. Planned developments are:

(a) The integration of IMU observations in the process model of the Kalman filter will improve the RTK-GPS float solution. The time to fix the ambiguities will decrease, and cycle slip detection will become more robust.

(b) The four cameras on the UAV and visual odometry (Schneider et al. 2013) will be integrated into the GPS algorithms and the final position determination.

(c) The RTK-GPS solution still will be evaluated using independent positioning systems. We plan to track the UAV using a lasertracker or a tachymeter during a flight.

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