Improvement of the GNSS Solution for Advanced RPAS Applications Utilizing PPP, RTK or Sensor Integration

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ABSTRACT

Navigation parameters like position, velocity and attitude are essential for many RPAS (Remotely Piloted Aircraft System) applications. However, the requirements for the navigation sensors are very high. They have to be cheap, small, and light-weighted. The actual RPAS laws in several European countries even raise the requirements regarding accuracy and reliability of the navigation solution to improve the safety of RPAS applications. Nevertheless, the standard solution for the position determination of RPAS is the so-called GNSS SPP (Single Point Positioning) method which enables a limited accuracy of a few metres only and cannot provide attitude parameters.

For many advanced RPAS applications, more accurate and reliable navigation parameters are needed. This paper shows quite simple ways to improve the accuracy of the SPP solution for real-time applications utilizing GNSS receivers which are capable of providing single-frequency raw-data. Furthermore, the potential of sensor integration to improve the reliability of the solution on the one hand and to enable the estimation of attitude parameters on the other hand is shown. The sensor integration is realised by combining a GNSS sensor with inertial sensors and a three-axis magnetometer.

1 INTRODUCTION

RPAS (Remotely Piloted Aircraft Systems, see Figure 1) are a current issue for very different applications like earth observations, aerial photography, rescue operations, etc. For these systems, important parameters like the position, velocity, and attitude are provided by navigation or autopilot systems. However, the particular requirements for the navigation sensors are very high. RPAS only offer a limited transport capacity concerning volume as well as weight, hence, there are also exact requirements for the size and weight of the sensors. Furthermore, to offer cheap RPAS flights for civil applications, only low-cost sensors are eligible. Nevertheless, the system requirements for some applications are quite high, especially when thinking about non-line-of-sight operations.

Fig. 1: Example of an RPAS (©Institute of Geodesy, TU Graz)

The position of RPAS is often provided by GNSS (Global Navigation Satellite Systems) sensors. To minimize the costs, usually low-cost, code-based, single-frequency GNSS receivers are used together with SPP (Single Point Positioning). However, this just enables a limited position accuracy of several metres, which might not be sufficient for some applications. This paper shows quite simple and cost-effective ways to improve the accuracy of GNSS solutions for RPAS operations by utilizing either the RTK (real-time kinematic) approach where a continuous data link to the RPAS is required or by utilizing predicted PPP (Precise Point Positioning) products (no data link is required). For both approaches, one may use the open-source and platform-independent software package RTKlib, which make these algorithms even more attractive for RPAS operators.

Beside the position, several RPAS applications also need other navigation parameters like velocity and attitude (e.g., for direct georeferencing of aerial images [1]). To yield these additional parameters as well as to improve the reliability of the navigation solution, it is appropriate to integrate different sensors like GNSS, inertial sensors, and magnetometers. This paper shows the advantages of sensor integration with respect to GNSS-only solutions.

This paper is structured as followed. Within chapter 2, the different real-time GNSS techniques are shortly described, chapter 3 explains the principles of sensor integration, chapter 4 shows exemplary results and chapter 5 concludes this

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paper.

2 GNSS ALGORITHMS

2.1 *Single Point Positioning (SPP)*

SPP (Single Point Positioning) is the standard method to determine the position by GNSS. It uses code-measurements in combination with broadcast ephemeris and ionospheric parameters provided by the navigation messages of the satellites. It is the simplest and cheapest method to determine the position in real-time with a limited accuracy of a few metres. The big advantage of this method is that this method is implemented in every kind of GNSS receiver and that the position determination can be done autonomously.

Many GNSS receivers, even in the low-cost segment, support SBAS (Satellite-Based Augmentation Systems) signals (e.g., EGNOS, WAAS, MSAS). These signals provide a slight improvement of the SPP position accuracy due to broadcasted range corrections and an improved ionosphere model. For instance the company u-blox specifies the achievable accuracy of the horizontal SPP solution to be 2.5 metres, the accuracy including SBAS signals to be 2 metres. The limitation using EGNOS in northern and central European countries is that the geostationary satellites are not always visible. The visibility gets even worse for a mountainous environment like in Austria.

While SPP is implemented in every kind of GNSS receiver, the following enhanced methods require receivers being capable of raw-data output. Examples of such low-cost receivers are uBlox 6T, uBlox M8T, or NVS NV08C-CSM.

2.2 *Real-Time Kinematics (RTK)*

Many applications require very accurate positions which cannot be achieved by SPP. For this reason, the RTK (Real-Time Kinematics) algorithm was developed. RTK is based on simultaneous phase-measurements between two GNSS receivers, usually a static base station with known coordinates and a kinematic rover. The position of the rover is determined relative to the known coordinates of the base station by computing differences between the measurements. As a result of this approach, many systematic errors (satellite orbit and clock errors, atmospheric delays, etc.) are cancelled or are at least reduced dramatically. Therefore, with RTK an accuracy of several centimetres can be achieved.

The major disadvantage of RTK is the need of a continuous communication link between base station and rover resulting in much bigger effort and much higher costs contrary to the SPP algorithm. A second GNSS receiver on a known position and a communication module between this base station and the rover (RPAS) is required, or an access to a fee-based RTK provider is needed.

Of course, there are companies which offer all-in-one RTK receivers, but they are usually very expensive (several thousand dollars each). One low-cost realization is the system Piksi by Swift Navigation which only costs 995$ for a set of two receivers. Nevertheless, it might be too expensive for some applications. As a result, the relatively new technique called PPP may be suitable for RPAS applications.

2.3 *Precise Point Positioning (PPP)*

Precise Point Positioning can be seen as an enhanced method to determine the position without the need for a base station. The idea is to use code and phase measurements on the one hand, and precise orbit and clock data as well as more precise ionospheric maps on the other hand. With this approach, an accuracy of several decimetres or better can be achieved even in real-time applications. PPP can be performed using real-time streams or by downloading precise predicted products. For the sake of simplicity, in RPAS applications, the second approach is preferred, where no additional data link is required.

In this paper, four different types of files are used to generate an accurate PPP solution by using predicted PPP corrections only to enable real-time capability.

Actual ultra-rapid PPP ephemeris in sp3-format contain precise ephemeris which are predicted four times a day. They are just valid for a limited timespan and their accuracy decreases with time, hence, they should be downloaded directly before flight to get the best possible PPP solution.

Very important for single-frequency PPP solutions is precise ionosphere information, like predicted VTEC (Vertical Total Electronic Content) maps in the ionex-format. These VTEC rasters are used to correct the ionospheric delays of the measured signals and are predicted for one, two, or five days in advance. When using a high-cost dual-frequency GNSS receiver, the influence of the ionosphere on the measurements can be eliminated (see [2]), but when using low-cost single-frequency GNSS receivers these files are absolutely essential in order to get the highest accuracy with PPP.

To make the different types of measurements consistent (the measurements on different frequencies as well as the code- to the phase-measurements), differential code biases (DCB) shall be included as dcb-files. These dcb-files get updated regularly, e.g., once a month by CODE (Center for Orbit Determination in Europe).

An antenna correction file (in antex-format) contains calibration parameters for satellite and receiver antennas. This file has to be updated for new satellites or receiver antennas.

All of these files needed for PPP can be downloaded for free, e.g., from the ftp-server of CODE before a flight and improve the quality of the determined positions for several hours, hence, they are suitable for typical RPAS applications. Additionally, these PPP corrections can be used in combination with the open source software package RTKlib, so no additional costs and just very little additional effort is required in comparison to the SPP solution. Nevertheless, the accuracy is increased considerably by using a PPP algorithm instead of a SPP algorithm.

2.4 Comparison of the GNSS algorithms

Table 1 gives a short summary of this section. It outlines that all three algorithms are appropriate for real-time applications and are supported by the open source software RTKlib.

	SPP	RTK	PPP
Real-time	Yes	Yes	Yes
Meas.	Code	Phase (+Code)	Code+Phase
Ephemeris	Broadcast	Broadcast	Precise
Add. effort	-	Base	File-download
Comm. Link	No	Yes	No
Accuracy	Metres	Centimetres	Decimetres

Tab. 1: Comparison of the GNSS algorithms

The difference of the introduced approaches lies in the differently used signals and ephemeris as well as in the different additional effort with respect to SPP and the achievable accuracy.

3 SENSOR INTEGRATION

The requirements concerning reliability are very high for RPAS, especially during non-line-of-sight operations. On the other side, GNSS position accuracy suffers from shadowing effects, multipath effects, jamming, etc., which can tremendously decrease the quality of the GNSS position solution or even make GNSS positioning impossible. In addition, many applications require attitude information of the RPAS which cannot be derived from GNSS observations. It is possible to determine the COG (Course Over Ground = orientated direction of RPAS motion) with consecutive GNSS positions, but it is not possible to determine roll, pitch, and heading/yaw (direction of the major axis of the RPAS). In case of an RPAS, the COG may differ from the heading angle because of, e.g., air currents (see Figure 2).

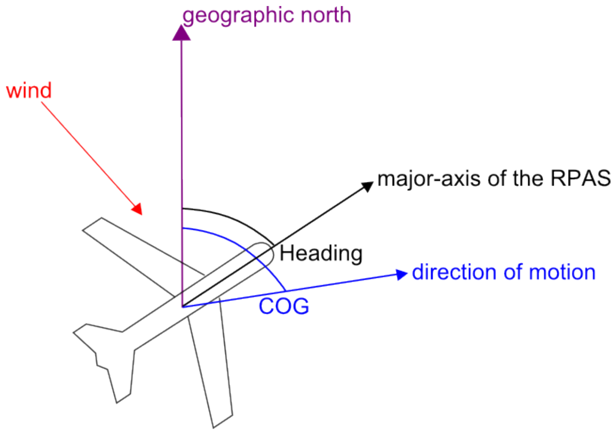

Fig. 2: Difference of Heading and COG

To overcome these problems, GNSS observations can be integrated with additional sensors. By adding low-cost MEMS inertial sensors (three accelerometers and three gyroscopes), it is possible to estimate the attitude parameters (orientation of the RPAS in terms of Euler angles, quaternions, or a rotation matrix). The heading estimation of the inertial sensors may be improved using a three-axis-magnetometer (see [3]) in addition. This is required, especially in long periods of low or no motion, where the gyroscope drift cannot be compensated. In general, magnetometers have to be calibrated to counteract the influence of magnetic distortions from ferrous objects in the surrounding area of the RPAS. Additionally, the magnetic declination has to be taken into account (for local applications as a constant offset in the magnetometer heading). Taking these facts into account, accuracies of a few degrees can be obtained.

The sensor integration is usually done by implementing a Kalman-Filter (for details see [4], [5] or [6]) to optimally fuse the different signals. Additional information about the system dynamics can be added into the dynamic model to make the solution even more reliable and robust.

Most integrated navigation systems, above a few thousand dollars, have all the mentioned sensors integrated in a small and effective shape (e.g. MTi-G-700 by xSens) and even provide a small controller on-board which already integrates all the measurement data in a Kalman Filter to estimate position, velocity, and attitude. For the sensor integration, no open-source software is known to the authors. The presented results are based on self-implemented software routines.

4 RESULTS

4.1 Data

The results refer to a test drive with a car in the south of Graz (see Figure 3). The reason for using a test drive instead of a RPAS-flight is that it is much easier to verify the achieved results with a car by transporting additional high-accurate sensors which cannot be transported with RPAS because of their size and weight. All in all, three different types of results were produced for this paper.

A high-accurate reference solution was computed in post-processing by integrating a high-precision IMU (Inertial Measurement Unit) including ring-laser gyroscopes (iMAR iNav RQH) with a geodetic dual-frequency GPS/GLONASS receiver (Javad Sigma TRE-G3TH). A tightly-coupled integration (see [7]) was carried out with the commercial software Inertial Explorer to achieve a reference trajectory of centimetre accuracy. The disadvantage is that the complete system is too large and heavy for RPAS (10 kg, 29x20x18 cm).

The GNSS signals for the GPS-only solutions were collected from a low-cost single-frequency GPS receiver (u-blox 6T). The different types of solutions (SPP, PPP and RTK) were performed by the open-source software RTKlib. For the RTK solution, an own static base station (Novatel DLV-3, short baseline < 5 [km]) was used.

For generating an integrated solution, the raw inertial and

Fig. 3: Trajectory in the south of Graz (©Google Earth)

magnetometer measurements of an integrated system (MTi-G by xSens) were used in addition to the mentioned GPS receiver (u-blox 6T). After magnetometer calibration, the different signals were combined within a self-implemented loosely-coupled Extended Kalman Filter algorithm.

The arrangement of the different sensors on the car is shown in Figure 4, where a low-cost AeroAntenna AT575-142 antenna has collected the GPS signals for the u-blox receiver.

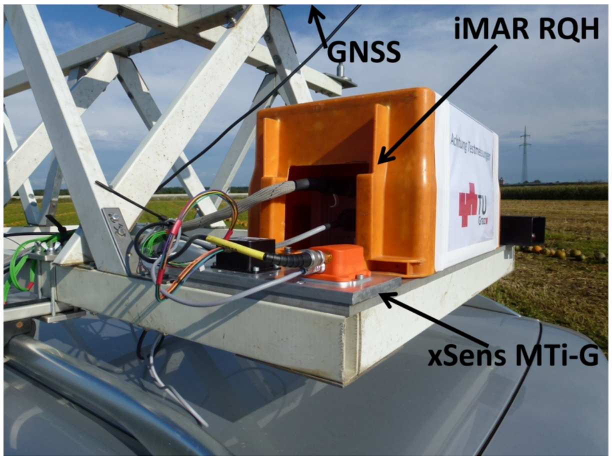

Fig. 4: Arrangement of the sensors

4.2 GNSS Solutions

Figures 5 and 6 show the coordinate differences of the GPS-only solutions with respect to the reference solution. Table 2 and 3 show the corresponding statistical values. On the one hand, the median of the deviations with respect to the reference solution is shown, on the other hand, the empirical standard deviation is shown. In this case, the median describes a systematic offset of the solution. The empirical standard deviation, otherwise, represents the noise (random errors).

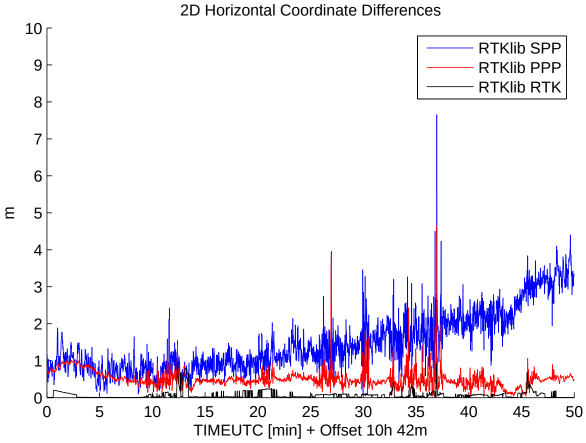

Fig. 5: Comparison of the horizontal GNSS coordinates

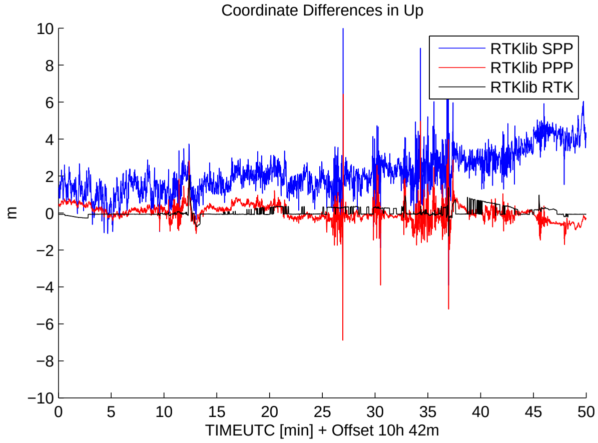

Fig. 6: Comparison of the GNSS heights

The SPP result has a large systematic error (Median between 1 and 2 metres, see Table 2 and 3), which is mainly caused by atmospheric / ionospheric effects for single-frequency solutions. This systematic error can be decreased for single-frequency GNSS receivers by using VTEC maps for better ionosphere modelling. The noise of the PPP solution is also more than halved from 0.8 to 0.2 metres for horizontal coordinates (see Table 2) and from 1.2 to 0.5 metres for vertical coordinates (see Table 3) due to the use of phase measurements.

The processing of a RTK algorithm leads to a further improvement of the accuracy with respect to the PPP solution. With this algorithm, an empirical standard deviation of about 10 centimetres for the horizontal and of 24 centimetres for the vertical position can be achieved (see Table 2 and 3).

	Median [m]	emp. Std. [m]
SPP	1.244	0.828
PPP	0.481	0.238
RTK	0.022	0.106

Tab. 2: Statistical results of the horizontal GNSS coordinates

	Median [m]	emp. Std. [m]
SPP	1.997	1.193
PPP	0.012	0.537
RTK	-0.060	0.241

Tab. 3: Statistical results of the GNSS heights

4.3 Sensor Integration

This section compares the GPS-only SPP solution (see section 4.2) with an integrated solution. The SPP algorithm was selected instead of PPP or RTK to demonstrate the potential of sensor integration, because it is the most commonly used technique to provide RPAS positions. The integration is carried out with a self-implemented loosely-coupled Extended Kalman Filter which combines the SPP solution with inertial and magnetometer measurements from the low-cost MEMS IMU xSens MTi-G. To identify the systematic errors too, Figures 7 to 12 show the difference of these results with respect to the reference solution.

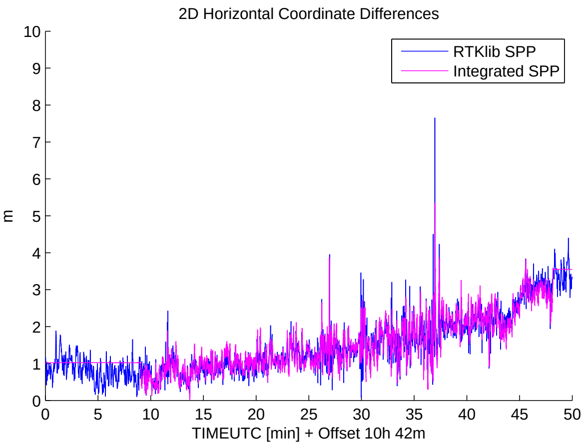

Fig. 7: Comparison of the SPP and the integrated horizontal position

The use of additional sensors in combination with a Kalman Filter has several advantages compared to the GPS-only solutions:

- It enables the estimation of attitude parameters (see Figures 10, 11, and 12).

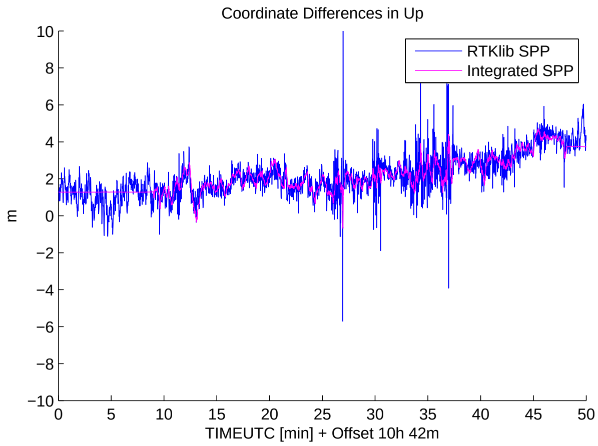

Fig. 8: Comparison of the SPP and the integrated height

- It smoothes the result, which improves the precision of the velocity and position information and allows to detect outliers (see Figures 7, 8, and 9).
- It usually enables a higher update rate of all parameters (because of the generally higher update rate of an IMU compared to GNSS).
- It helps to overcome data gaps during GNSS outages, which tremendously improves the reliability of the result.

Figures 7 and 8 show the differences in the horizontal coordinates and heights, respectively. The integrated solution is smoother than the GPS-only solution (see empirical standard deviation in Table 4). Nevertheless, the systematic offset of the SPP-solution (see Table 2 and 3) cannot be corrected by integrating those additional sensors, because they do not provide any information about the absolute position of the receiver.

	GPS		Integrated	
	Median	Emp. Std.	Median	Emp. Std.
2D-Pos [m]	1.244	0.828	1.197	0.776
Height [m]	1.997	1.193	1.983	0.939
Vel [m/s]	0.024	0.121	0.033	0.103
Roll [°]	n.a.	n.a.	0.039	0.197
Pitch [°]	n.a.	n.a.	-0.038	0.121
Heading [°]	n.a.	n.a.	-0.700	1.156

Tab. 4: Statistical results of integrated solution

The errors in the magnitude of the velocity are shown in Figure 9. The sensor integration again leads to a smoother, more accurate (see empirical standard deviation in Table 4) and more reliable solution.

Figures 10 to 12 show the attitude errors of the integrated solution with respect to the reference solution. These parame-

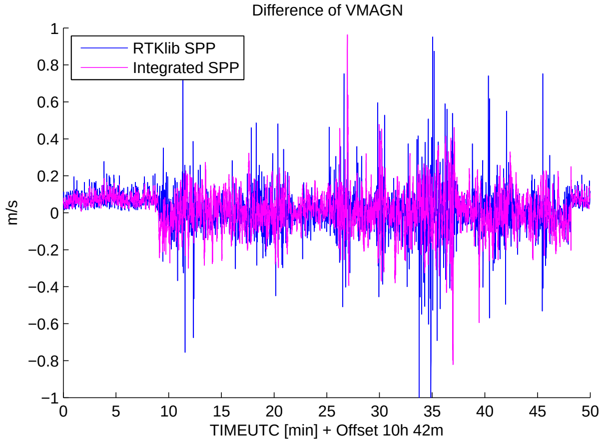

Fig. 9: Comparison of the SPP and the integrated velocity

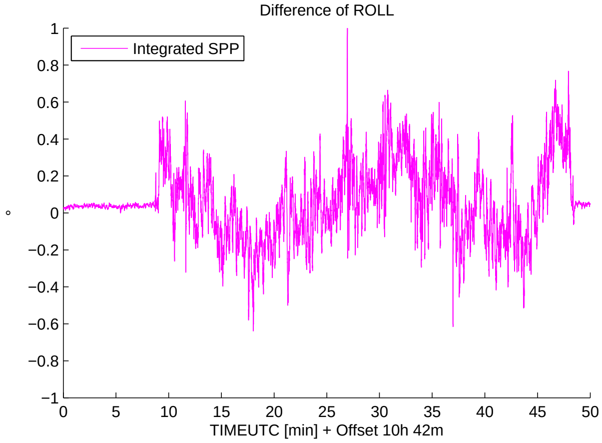

Fig. 10: Integrated roll angle

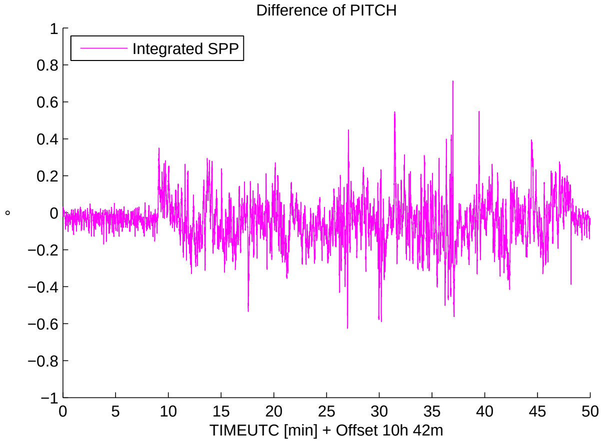

Fig. 11: Integrated pitch angle

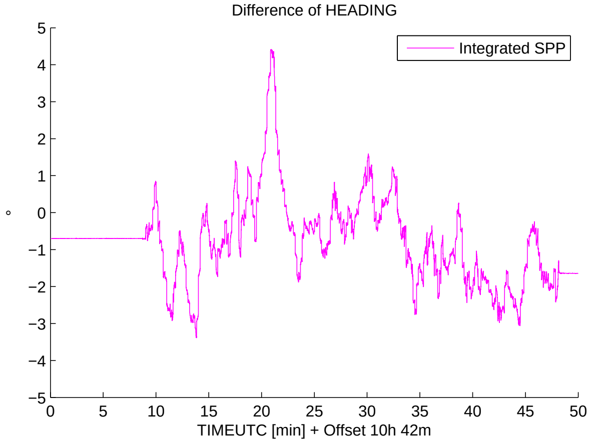

Fig. 12: Integrated heading angle

ters cannot be provided using GNSS sensors exclusively. The parameters roll and pitch can be determined very well (empirical standard deviation $< 0.2°$), due to the strong correlation to the well determined horizontal velocity of the vehicle. By contrast, the heading is only very slightly correlated with the other parameters and, hence, it is mainly determined by gyroscope and magnetometer measurements. Because of the errors in these measurements, the accuracy of the heading is worse compared to roll and pitch (see Table 4). The systematic effects in the heading are mainly a result of magnetic distortions in the magnetometer measurements caused by other cars, street signs, etc. Depending on the RPAS application and operating field, the operator can decide whether or not to use the magnetometer for heading determination. In many cases, the field of operation of RPAS applications is expected to be better than street environments, hence, the results are expected to be better. For this paper, the magnetometer heading is used to show that even for bad conditions (many magnetic distortions) a well integrated heading with a standard deviation of about 1.2 degrees (see Table 4) can be determined.

5 CONCLUSION

The most commonly used method for RPAS navigation is the so-called GNSS SPP, but for many applications the quality of this method may not be sufficient. To improve the accuracy as well as the reliability and to enable the estimation of attitude parameters, this paper presented the advanced, real-time GNSS algorithms PPP and RTK and showed the potential of sensor integration. The benefits of the presented approaches are shown with measurement data of a test drive with a car.

The accuracy of the position solutions can be improved from about 1 meter (SPP) to some decimeters (PPP) or even to about 10 centimeters (RTK). Additionally, these advanced GNSS algorithms can nearly eliminate the systematic errors of the SPP algorithm, which are mainly caused by not considered ionospheric delays in the GNSS signals.

By integrating the GNSS solution with inertial sensors and magnetometers, the quality of the results can further be increased. Especially, the reliability is improved compared to the GNSS-only solution, because short GNSS data gaps of some seconds can be compensated by sensor integration. A further advantage is that attitude parameters can be estimated using these additional sensors. The roll and pitch angle can be estimated with an accuracy of about 0.1 degrees. In contrast, the calculated heading has a reduced accuracy of about 1 degree.

Summarizing, all of the presented algorithms improve the quality of the navigation solution with respect to the commonly used GNSS SPP method and can be used for RPAS applications in real-time. Depending on the required accuracy and reliability as well as on the needed parameters (e.g., attitude parameters) and the maximum effort, one can choose between PPP, RTK, or sensor integration.

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