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An integrated GPS/MEMS-IMU navigation system for an autonomous helicopter ☆

Ein integriertes GPS/MEMS-IMU Navigationssystem für einen autonomen Helikopter

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Abstract

During the last years, there is an increasing demand for cheap and easy to operate platforms for surveillance and reconnaissance purposes. Therefore, the development of micro aerial vehicles is receiving an increasing attention. However, VTOL-MAVs often show an inherent instability that makes at least an automatic stabilization necessary, because otherwise the operator would not be able to keep these vehicles airborne. This requires the availability of navigation information, especially the vehicle's attitude has to be known.

This paper addresses the development of an integrated navigation system based on MEMS inertial sensors and GPS for a VTOL-MAV. Special attention is paid to the handling of GPS outages. While usually periods without GPS aiding can be bridged using the unaided strapdown solution, the poor quality of the MEMS inertial sensors prohibits this approach here. Therefore, during GPS outages the accelerometer data is interpreted as approximate measurements of the local gravity vector. Additionally, the usage of a magnetometer providing measurements of the Earth's magnetic field is motivated and discussed. Finally, flight test results illustrate the performance of the resulting system, proving that the achieved attitude accuracy is sufficient for the automatic control of the MAV. This holds in situations with permanent GPS loss and dynamic maneuvering, too.

Zusammenfassung

In den letzten Jahren ist das Interesse an kleinen, kostengünstigen, leicht zu bedienenden Fluggeräten für Überwachungs- und Aufklärungsaufgaben stetig gestiegen. Gerade schwebeflugfähige MAVs sind jedoch inherent instabil, so dass zumindest eine automatische Lageregelung notwendig ist. Dies ist nur möglich, wenn entsprechende Navigationsinformationen zu Verfügung stehen, insbesondere die Lage des Fluggeräts muss bekannt sein.

Dieser Beitrag beschäftigt sich mit der Entwicklung eines integrierten Navigationssystems für ein VTOL MAV, das auf MEMS Inertialsensoren und einem GPS Empfänger basiert. Normalerweise werden in einem GPS/INS System GPS Ausfälle mit Hilfe des Inertialnavigationssystems überbrückt. Aufgrund der geringen Güte der MEMS Inertialsensoren ist dieser Ansatz hier nicht anwendbar. Stattdessen wird ausgenutzt, dass die Beschleunigungsmesserdaten von der Schwerebeschleunigung dominiert sind. Das erlaubt die Stützung von Roll- und Pitchwinkel während eines GPS Ausfalls. Ferner wird der Einsatz eines Magnetometers beschrieben, der zur Sicherstellung der Beobachtbarkeit des Yaw-Winkels notwendig ist. Die Ergebnisse von Flugversuchen zeigen, dass die Qualität der so gewonnenen Lageinformationen auch bei permanenten GPS-Ausfällen und dynamischen Flugmanövern zur Stabilisierung des MAVs ausreicht.

Keywords: UAV; GPS/INS integration; Kalman filter; Magnetometer

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1. Introduction

The interest in micro aerial vehicles (MAV) for surveillance and reconnaissance purposes is growing constantly. For many mission scenarios, vertical take-off and landing, as well as the ability to hover are desired. This is offered by MAVs of helicopter-type. However, while fixed-wing MAVs often show an inherent stability, the helicopter attitude requires permanent control. The key to such an attitude control is reliable, accurate, and especially continuously available attitude information.

In principal, attitude information can be obtained from a multi-antenna GPS system. Due to the availability of low-cost, light-weight GPS receivers, this is an interesting option for a variety of applications. Concerning a MAV, the possible baselines are very short, which has a negative influence on the attitude accuracy that can be achieved. Additionally, this technique works only if the carrier phase integer ambiguities can be estimated, which is not a trivial task, especially with single-frequency receivers. As attitude information is required in situations without any GPS signals available, a multi-antenna GPS system is not an option for the VTOL-MAV considered here.

Currently, the usage of computer vision for navigation purposes is receiving considerable interest. Different approaches are investigated [6,7,10,11], including the usage of image processing as the main aiding source for an inertial navigator. However, there are several problems connected to computer vision that are not easily overcome. Image processing requires a significant processing power, which may not be available on board of a MAV. If the image processing is performed on a ground station, the continuous availability of an appropriate radio link has to be assured. Additionally, besides the possible scaling problem associated with image processing, there is often a sensitivity to lighting conditions and contrast.

A well-known and widely used technique to obtain attitude information is the combination of GPS with inertial navigation. The continuous availability of the navigation solution, together with a high data rate, is assured by the inertial navigation system (INS), while the INS drift is compensated using the GPS measurements. Furthermore, the GPS measurements can be used to calibrate the inertial measurement unit (IMU), which improves the inertial navigation performance during GPS outages. Some systems use several GPS receivers in order to increase the availability of GPS measurements during dynamic maneuvering. Examples of GPS/INS systems applied to unmanned aerial vehicles (UAV) can be found in [2,3,12].

However, while the attitude accuracy offered by a GPS/INS system is impressive when GPS aiding is available, the usage of MEMS inertial sensors with significant scalefactor nonlinearities, misalignment, noise, and temperature-varying biases, is a problem during GPS outages: Without aiding information available, a sufficient attitude accuracy can be maintained for a short time only. Therefore, for MAV and UAV applications, an integration strategy has become popular that is significantly different from the usual GPS/INS integration known from missile and aircraft applications. Hereby, the GPS measurements are used to calculate the acceleration of the vehicle. Using the estimated attitude, this trajectory-caused acceleration can be removed from the accelerometer measurements, leading to an approximate measurement of the gravitational acceleration in body frame coordinates. Using this measurement of the local gravity vector, the roll and pitch angle estimates can be corrected. Finally, for fixed-wing MAVs, the yaw-angle estimate is corrected by exploiting assumptions on the vehicles aerodynamics, or a magnetometer can be used. Examples for this approach can be found in [1,5]. The advantage of this approach is the insensitivity to GPS loss. Without GPS measurements available, the acceleration caused by the trajectory dynamics cannot be removed, which leads to a reduced attitude accuracy, but a growth of attitude errors without bounds is still prevented. Unfortunately, when GPS measurements are available, they are used in a sub-optimal way, as the accelerometer biases cannot be estimated. Uncompensated accelerometer biases directly lead to systematic errors in the attitude estimates.

This paper describes the design of an integrated navigation system for a small four rotor helicopter, which comprises a MEMS IMU and a small, light-weight GPS-receiver. Additionally, a baro-altimeter and a magnetometer are included. The basic idea of this system is to assure an optimal usage of the GPS measurements while also achieving robustness in case of GPS loss by a switching between two operating modes: When GPS information is available, the first mode is selected. A sixteen-state Kalman filter estimates the errors of a strapdown calculation which are corrected subsequently, assuring hereby the long-term accuracy of the navigation solution. Additionally, the accelerometer and gyroscope biases are estimated and corrected. When GPS is lost, the second mode is selected. In this mode, the assumption is made that the accelerometer measurements are dominated by the local gravity vector, therefore indicating the down direction. The measured angular rates are integrated in order to extrapolate the current attitude estimate. A six-state Kalman filter processes the accelerometer and magnetometer measurements, providing an estimate of the current attitude errors and gyroscope biases, which are corrected subsequently. In this mode, the accelerometer biases cannot be estimated, so that the bias estimates obtained during GPS availability by the Kalman filter of the first mode have to be used to correct the accelerometer measurements.

In the next section, a brief description of the airframe is given. In Section 3 the integrated navigation system is described, including some remarks concerning the usage of the magnetometer measurements. In Section 4 simulation results are given, which illustrate the robustness of the attitude solution to GPS outages. In Section 5, the simulation results are confirmed by an offline-processing of navigation sensor data that was collected in a flight test. Finally, conclusions are drawn.

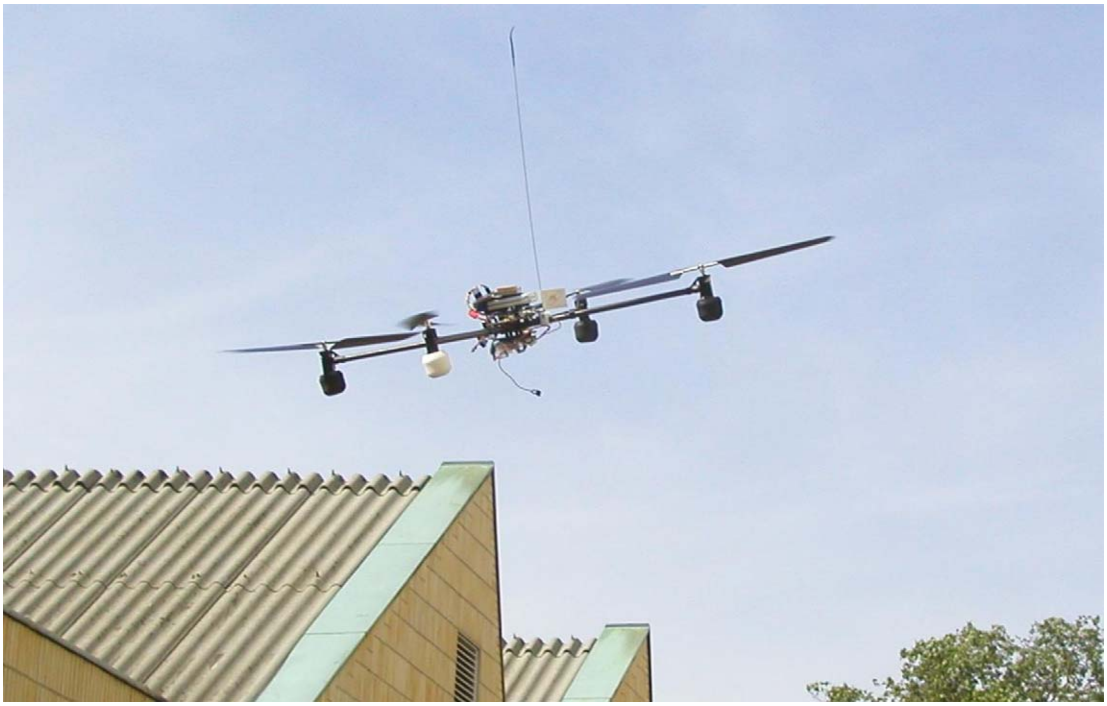

Fig. 1. VTOL-MAV in flight.

2. Principle of operation

This paper focuses on the type of VTOL-MAV shown in Fig. 1, although the integrated navigation system described in this paper can be applied to a variety of other vehicles, too, including fixed-wing MAVs. The MAV considered here is a four rotor helicopter, which is controlled by the speed of the rotors only. A major advantage of this design is the mechanical simplicity: All rotors are fixed-pitch rotors, complicated swashplate mechanics which are necessary for conventional helicopters are not required. Two opposite rotors are rotating clockwise, while the remaining two rotors are rotating counter-clockwise. Therefore, the torques acting on the frame cancel, if the rotors are running at identical speeds. In order to start a translational movement in forward direction, the speed of the front rotor is decreased, while the speed of the rear rotor is increased. The result is a non-zero pitch angle, which leads to a horizontal component of the thrust vector building up. In order to maintain a constant height during this maneuver, the overall thrust has to be increased, as the part of the thrust vector now causing the translational movement does not contribute to the lift force anymore. A rotation around the downward-pointing body-z-axis is achieved by increasing the speed of the rotors rotating clockwise while decreasing the speed of rotors rotating counter-clockwise, or vice versa. As the position, velocity and attitude of the MAV is controlled by the four rotor speeds, the MAV belongs to the class of under-actuated systems.

In a typical scenario, the MAV is operated based on the images provided by an on-board camera via a radio link. This requires that at least the vehicle's attitude is controlled automatically, as a manual attitude control based on camera images is impossible without excessive training. Obviously, an automatic attitude control is depending on the availability of attitude information. This attitude information is provided by the integrated GPS/INS navigation system described in the next section.

3. Integrated GPS/INS system

Depending on the availability of aiding information, the integrated navigation system addressed in this paper switches between two modes. When GPS measurements are available, the first mode is selected. In this mode, the GPS measurements, the magnetometer measurements and the baro-altimeter measurements are processed in a sixteen state error state space Kalman filter. The state vector of this filter comprises three errors in position, three errors in velocity, three attitude errors, six errors of the inertial sensor bias estimates, as well as the error of the baro-altimeter bias estimate. The error state space formulation is widely used in GPS/INS integration: First, the error propagation equations of inertial navigation which form the dynamics part of the system model, can be represented very adequately as linear [4]. These error propagation equations can be found e.g. in [8]. Second, only three platform errors are required, whereas a total state space filter requires the four quaternion components to be included in the filter state vector. Obviously, a closed-loop formulation has to be chosen. Besides the fact that there are no advantages connected to an open-loop formulation, an open-loop formulation requires an inertial navigation performance able to keep the errors of the strapdown calculation within reasonable bounds during the mission, which is definitively not the case for the MEMS-based inertial navigator considered here.

The usage of a magnetometer is absolutely required for a VTOL-MAV: For any GPS/INS system that does not exploit assumptions on the vehicle dynamics, the yaw angle is observable only in presence of horizontal accelerations. Therefore, without a magnetometer, the yaw angle error would grow without bounds. As the direction cosine matrix enters the Kalman filter system model, such a yaw angle error would result in an erroneous propagation of the estimation error covariance matrix, which leads to a deterioration in accuracy, or even divergence. In principle, a magnetometer is able to continuously provide the required yaw angle information to avoid this scenario, without requiring external equipment. Unfortunately, the Earth's magnetic field can be disturbed, e.g., in proximity of large metal objects. The usage of this erroneous magnetometer measurements to aid the inertial navigator leads to attitude errors. Therefore, it was decided to use the magnetometer measurements to aid the yaw angle only: For the yaw angle, an error of e.g. twenty degrees may be tolerable. For roll and pitch, this is not acceptable.

The measurement equation for the processing of the magnetometer measurements can be derived as follows: First, as only the yaw angle is to be aided, the roll and pitch angles are assumed to be known perfectly. The measured magnetic field given in body frame coordinates, $\tilde{\vec{h}}^b$, is related to the Earth's magnetic field in navigation frame coordinates, $\vec{h}^n$, via

$$\tilde{\vec{h}}^b = C_b^{n,T} \vec{h}^n + \vec{v}_m, \tag{1}$$

where $\vec{v}_m$ denotes the magnetometer measurement noise. Hereby, $\mathbf{C}_b^n$ denotes the direction cosine matrix describing the transformation from the body to the navigation frame. The relationship between true and estimated ($\hat{}$) direction cosine matrix is given by

$$\hat{\mathbf{C}}_b^n = (\mathbf{I} + \mathbf{\Psi})\mathbf{C}_b^n \tag{2}$$

where $\mathbf{\Psi}$ denotes the skew symmetric matrix of the attitude errors. Rearranging Eq. (2) yields

$$\begin{aligned} \hat{\mathbf{C}}_b^n &= (\mathbf{I} + \mathbf{\Psi})\mathbf{C}_b^n, \\ (\mathbf{I} - \mathbf{\Psi})\hat{\mathbf{C}}_b^n &= \mathbf{C}_b^n, \\ \hat{\mathbf{C}}_b^{n,T} &= \hat{\mathbf{C}}_b^{n,T}(\mathbf{I} + \mathbf{\Psi}), \end{aligned} \tag{3}$$

and inserting Eq. (3) in Eq. (1) leads to

$$\begin{aligned} \tilde{\vec{h}}^b &= \hat{\mathbf{C}}_b^{n,T}(\mathbf{I} + \mathbf{\Psi})\vec{h}^n + \vec{v}_m, \\ \tilde{\vec{h}}^b - \hat{\mathbf{C}}_b^{n,T}\vec{h}^n &= -\hat{\mathbf{C}}_b^{n,T}\operatorname{skew}(\vec{h}^n)\vec{\Psi} + \vec{v}_m. \end{aligned} \tag{4}$$

As roll and pitch angle are assumed to be known perfectly, the vector of the attitude errors contains the yaw angle error γ only:

$$\vec{\Psi} = (0, 0, \gamma)^T. \tag{5}$$

This finally leads to

$$\tilde{\vec{h}}^b - \hat{\mathbf{C}}_b^{n,T}\vec{h}^n = -\hat{\mathbf{C}}_b^{n,T}(h^n_{\text{east}}, -h^n_{\text{north}}, 0)^T\gamma + \vec{v}_m, \tag{6}$$

the required Kalman filter measurement equation. It has to be noted that a magnetometer can provide information concerning the yaw angle only if roll and pitch angle errors are not too large. Otherwise, as the direction cosine matrix enters the measurement equation, the measurement matrix would be in error which can lead to filter divergence. In our case, the influence of roll and pitch angle on the magnetometer measurements is considered mathematically. A different approach would be to assure zero roll and pitch angles by using a gimbal-mounted magnetometer.

When GPS measurements have not been available for a certain period of time, e.g., one second for a receiver providing four measurements per second, the system switches to the second mode. In this mode, horizontal velocity and position information is not provided by the navigation system anymore. After an appropriate initialization of the state and the covariance matrix using data provided by the sixteen-state Kalman filter of the GPS/INS mode, the magnetometer data is now processed in the measurement step of a six-state Kalman filter. The state vector of this filter comprises the attitude errors and the gyroscope biases, therefore the system model of this filter is a subset of the system model of the GPS/INS Kalman filter used in the first mode.

Processing magnetometer measurements only never assures the complete observability of vehicle's attitude, as a rotation around the axis of the Earth's magnetic field cannot be detected. Therefore, it is assumed that the major source for the measured acceleration is the local gravity vector $\vec{g}_l$. With this assumption, the acceleration measurements can be used to assure the long-term stability of roll and pitch angle estimates by processing them in the filter estimation step, too. The influence of the trajectory dynamics on the accelerometer measurements is modeled as measurement noise $\vec{v}_a$. The variance assigned to the accelerometer measurements is increased based on the difference between the absolute values of the measured acceleration and the local gravity vector $\hat{g}_l$. It can be shown that, given that the vehicle is accelerating in forward direction at a constant height and the air friction can be neglected, the dynamics-induced acceleration and the gravitational acceleration just cancel for the body-x axis. The zero body-x accelerometer reading corresponds to a zero pitch angle – the aiding information processed in the filter is obviously wrong. However, the low weight assigned to the accelerometer measurements overcomes this problem, especially as the vehicle can not accelerate for long periods of time.

The measurement equation for the gravity vector based aiding can be derived as follows: The acceleration of the vehicle with respect to the Earth given in navigation frame coordinates, $\vec{a}^n_{eb}$, is related to the acceleration with respect to the inertial frame given in body frame coordinates, $\vec{a}^b_{ib}$, by

$$\vec{a}^n_{eb} = \mathbf{C}_b^n \vec{a}^b_{ib} + \vec{g}_l. \tag{7}$$

If the only source of acceleration is the local gravity vector, $\vec{a}^n_{eb}$ is zero. Therefore, Eq. (7) becomes

$$\begin{aligned} \vec{0} &= (\mathbf{I} - \mathbf{\Psi})\hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{g}_l + \vec{v}_a, \\ \hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{g}_l &= \mathbf{\Psi}\hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{v}_a, \\ \hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{g}_l &\approx -\mathbf{\Psi}\vec{g}_l + \vec{v}_a, \\ \hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{g}_l &= \operatorname{skew}(\vec{g}_l)\vec{\Psi} + \vec{v}_a. \end{aligned} \tag{8}$$

The upper two rows of Eq. (8) are of the form of a Kalman filter measurement equation, relating the 'measurement' $\hat{\mathbf{C}}_b^n \vec{a}^b_{ib} + \vec{g}_l$ to the roll and pitch attitude errors in a linear way.

In parallel to the six-state Kalman filter, another Kalman filter is running which processes the baro-altimeter measurements and an estimate of the acceleration in down-direction, calculated from the accelerometer measurements and the attitude estimates. This filter provides height and velocity in down direction, the baro-altimeter bias estimated during the availability of GPS measurements allows to relate the baro-altimeter indicated height to the true height above the WGS-84 ellipsoid. In this way, an automatic control of attitude and height of the vehicle is possible even in case of permanent GPS loss.

Prior to the development of the switching approach described here, a navigation system which is robust with respect to GPS outages was designed based on one single Kalman filter [9]. The focus for this system was on providing attitude information only. Concerning the GPS measurements, only the velocity information was used, resulting in a twelve state filter. However, an extension of this one-filter-based approach to the processing of GPS position information and baro-altimeter measurements led to undesired artifacts, which was the motivation for the filter switching described in this paper.

4. Performance assessment using simulated data

The performance of the developed navigation system was assessed in numerical simulations. A block diagram of the simulation program structure is shown in Fig. 2. First, the true angular rates and accelerations of the vehicle are integrated to obtain the vehicle state, which is later used as a reference to calculate the errors of the estimated navigation solution. Next, GPS, baro-altimeter, magnetometer and inertial sensor data is generated based on this truth reference and typical sensor error characteristics. For the generation of the inertial sensor data, the sensor inherent noise as well as the vibration environment is taken into account. Then, the generated sensor data is processed by the developed navigation system. The estimated navigation solution as well as a desired trajectory is handed over to the flight controller, which generates the inputs to a simulation of the motor and rotor characteristics. This way, for each rotor the lift forces are obtained. From the lift forces and the resulting torques, a simulation of the VTOL MAV dynamics finally calculates the vehicle accelerations and angular rates, and the simulation loop starts over again. The reason for including flight control and MAV dynamics in a simulation that aims to assess the performance of the navigation system only, is to achieve the most realistic trajectories possible, because the trajectory dynamics has an influence on the navigation system performance, too. The attitude accuracy achieved by the developed navigation system, averaged over twenty-five simulation runs, is shown in Figs. 3 and 4. For these simulations, a GPS outage was assumed, starting at the 120 second point and lasting for sixty seconds. Obviously, the attitude accuracy is worse during the GPS outage. However, the switching to the six-state filter which assumes that the accelerometer measurements are dominated by the local gravity vector assures an attitude accuracy which is sufficient to stabilize the MAV. After the GPS outages, the navigation system switches back to the sixteen-state GPS/INS filter without any artifacts, and the attitude accuracy increases again. For comparison, the attitude accuracy obtained by a navigation system, which does not use the gravity-vector based aiding during GPS outages, is shown. For this system, roll and pitch angle errors grow with time as expected, according to the performance of the inertial navigator. However, it has to be noted that during the GPS outage, magnetometer and baro-altimeter measurements have to be used very carefully, as otherwise an immediate filter divergence can occur. Especially, the processing of the magnetometer measurements is critical. The measurement matrix required to process the magnetometer measurements contains entries of the direction cosine matrix. With roll and pitch angle errors growing, this direction cosine matrix is increasingly in error, which leads to a misinterpretation of the magnetometer measurements. As a result, for a

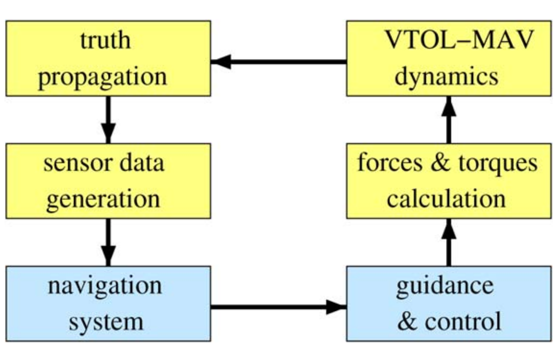

Fig. 2. Simulation program block diagram.

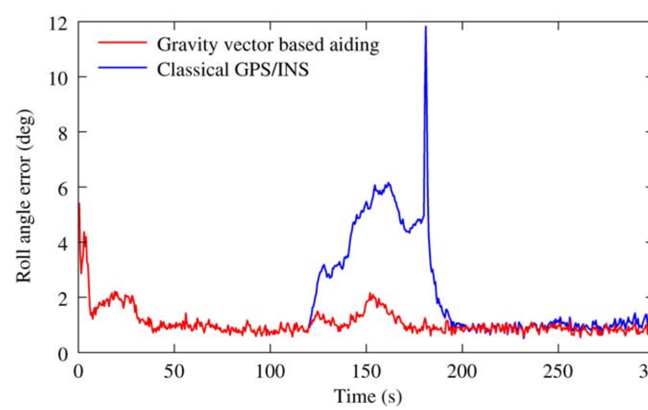

Fig. 3. Roll angle error, GPS outage from 120 s until 180 s.

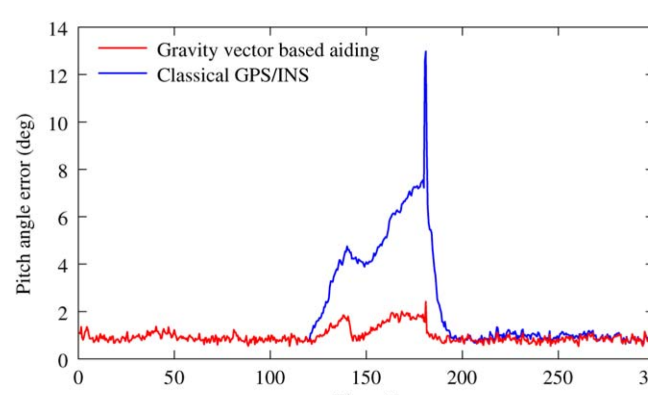

Fig. 4. Pitch angle error, GPS outage from 120 s until 180 s.

permanent GPS outage not only the roll and pitch angle accuracy deteriorates, it is also impossible to prevent the growth of the yaw angle error, despite that fact that magnetometer measurements are available. In opposite to that, the gravity-vector based aiding during GPS outages does not only assure a sufficient roll and pitch angle accuracy, it is also the key to maintain a reasonable yaw angle accuracy by allowing to calculate the magnetometer measurement matrix correctly. Furthermore, large attitude errors can be a serious problem when the first GPS measurements are available after a GPS outage: Without any workarounds, a slow filter convergence, or even divergence can be the result.

5. Performance assessment using flight test data

Finally, the simulation results were confirmed using flight test data. In this flight test, the MAV was flown using the gravity vector based aiding only, thereby demonstrating that the stabilization of the MAV is possible without GPS measurements at all. During the flight test, all sensor data were recorded on a 64 MB flash card. In order to investigate the performance of the gravity vector based aiding, a navigation solution was calculated based on all available sensor data including GPS, which was used as an approximate truth reference. Afterwards, an artificial GPS outage was introduced in the sensor data from 400 seconds until 450 seconds. This modified sensor data was processed offline by the developed navigation system using the gravity-vector based aiding, as well as by a navigation system that bridges a GPS outage without such a specialized aiding technique. The two navigation solutions obtained this way were compared to the approximate truth reference, the attitude errors obtained from this comparison are shown in Figs. 5 and 6. The flight trajectory is shown in Fig. 7, illustrating a considerable amount of maneuvering taking place.

Obviously, without the gravity vector based aiding during GPS outages, the attitude errors soon become unacceptably large. As the GPS/INS solution – which contains attitude errors as well – was taken as the reference, Figs. 5 and 6 do not show the true absolute attitude errors, but the deterioration of attitude accuracy when GPS is lost. Of course, without GPS a reasonable position and velocity accuracy cannot be maintained: Due to the poor quality of the MEMS sensors the position errors approximately grow up to thirty meters or more during the first ten seconds of a GPS outage. As predicted from the numerical simulations, a sufficient yaw angle accuracy can be maintained, too, as the approximate knowledge of roll and pitch angle allows to process the magnetometer measurements correctly, while a processing of magnetometer data in presence of large roll and pitch angle errors corrupts the yaw angle estimate. This completely confirms the results obtained in the previous section.

6. Conclusion

In this paper, the development of an integrated GPS/INS navigation system for a VTOL-MAV was addressed, where the focus was on assuring an attitude accuracy sufficient for an automatic stabilization of the MAV under all operating conditions, including permanent loss of GPS. Due to constraints in size, weight and cost, MEMS inertial sensors of very poor quality had to be used. In order to avoid a growth of attitude errors during GPS outages, the navigation system switches – triggered by the availability of GPS measurements – between a sixteen-state GPS/INS filter and a six-state magnetometer/INS filter. Numerical simulation and flight test results illustrate a sufficient attitude accuracy during GPS outages, while in opposite to other approaches, the GPS measurements are used to full capacity when available. Interestingly, an approximate knowledge

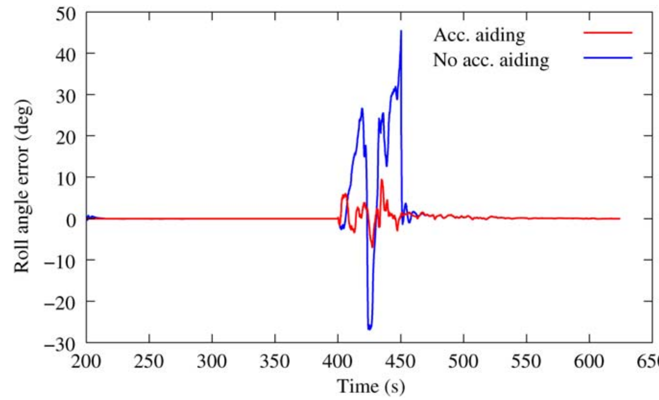

Fig. 5. Simulation using flight test data: Roll angle error with respect to the GPS/INS solution.

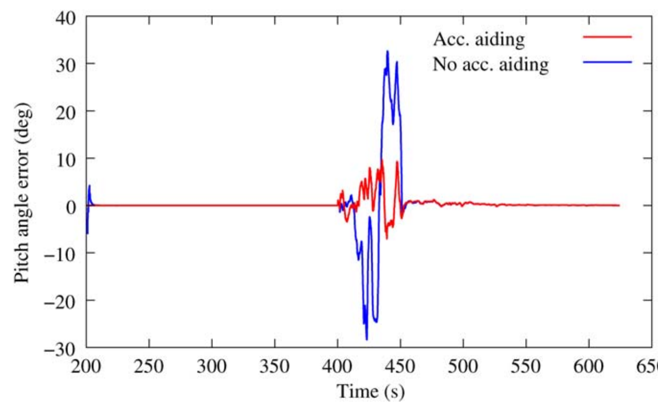

Fig. 6. Simulation using flight test data: Pitch angle error with respect to the GPS/INS solution.

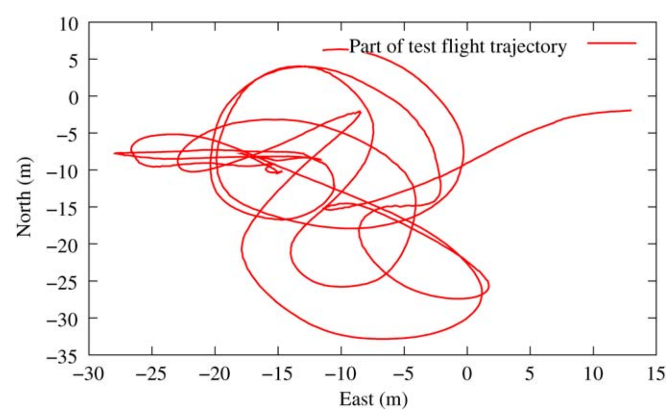

Fig. 7. Flight test trajectory.

of roll and pitch angle is crucial with respect to the processing of magnetometer measurements, too, as components of the direction cosine matrix enter the magnetometer measurement matrix. Although the navigation system described in this paper was designed for a VTOL-MAV, the developed switching approach can be easily applied to a variety of other systems, as long as the assumption holds that the accelerometer measurements are dominated by the local gravity vector.

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