ADVANCED GPS/INS INTEGRATION FOR AUTONOMOUS MINI AND MICRO AERIAL VEHICLES AND SCIENTIFIC PAYLOAD APPLICATIONS

A. Heindorf[1], T. Martin[1], M. Buschmann[2], P. Voersmann[1]
1) Institute of Aerospace Systems, Technical University of Braunschweig, D-38108 Braunschweig, Germany
2) Mavionics GmbH, D-38108 Braunschweig, Germany

OVERVIEW

The current paper describes an improved method of GPS/INS integration for autonomous Mini and Micro Aerial Vehicles (MAVs). Therefore, a recently developed, highly integrated autopilot system is described at first with a focus on the applied inertial sensors and their calibration. Along with a low-cost GPS receiver, the inertial sensors provide the input data for a tightly-coupled Kalman Filter based on time-differenced carrier phases instead of the typically used delta-ranges. Aiming at fast and precise attitude estimation, the capability of this method has been verified in flight test with a GN&C test platform, whose results will be shown in this paper. Besides the application of the filter for a MAV autopilot system, the same system is also used for a meteorological measurement system on-board a MAV, which provides high resolution data of the three-dimensional wind vector.

1. INTRODUCTION

Since 2001 autonomous Mini and Micro Aerial Vehicles (MAV) are one of the main topics of research at the Institute of Aerospace Systems (ILR) of the Technical University of Braunschweig, Germany. In cooperation with the company Mavionics GmbH, also located at the Research Airport in Braunschweig, a family of autonomous fixed wing MAVs has been developed with wingspans ranging from 50 cm to 330 cm. Equipped with an identical autopilot system, all these aircraft are capable of operating and navigating fully automatically including start and landing. A portable ground station unit with graphical user interface allows monitoring the MAV's status as well as real time changes of the mission, e.g. altering course and waypoints.

Currently a new highly integrated flight control system is being implemented based on an improved method of GPS/INS integration. For this purpose a tightly-coupled Kalman Filter is used, in which the typically applied delta-ranges have been replaced by time-differenced carrier phases enabling fast and precise attitude estimation without solving the integer ambiguity problem. This method is already in use at the ILR for a meteorological MAV (M^2AV), which measures i.a. the incident flow with a 9-hole-probe allowing a highly accurate determination of the three-dimensional wind vector in post processing.

The following chapters describe the sensor package with a focus on the inertial sensor calibration and the principle of the developed Kalman-Filter along with first results of flight tests. The paper then gives an outlook on the on-going work at the ILR towards the final development of a new autopilot system and its application.

2. GPS/INS HARDWARE

The essential hardware components of the GPS/INS system consist of a commercially available single-antenna, single-frequency stand-alone GPS receiver and a MEMS[1]-based Inertial Measurement Unit (IMU, six degrees of freedom) completely designed by ILR and Mavionics [1]. While the GPS receivers provides satellite raw data with an update rate of 1 Hz, IMU data acquisition is performed with 100 Hz, coevally the frequency of the navigation algorithm.

2.1. MEMS-based IMU (TrIMU)

Measuring only 40 x 40 x 15 mm³, the MEMS-based IMU is fully equipped with three orthogonal angular rate Sensors and two dual axis acceleration sensors covering the x-axis twice with different sensitivities (see TAB 1).

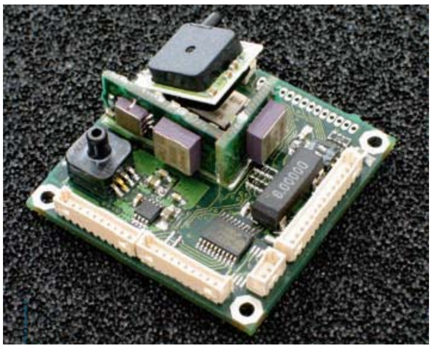

FIG 1. MEMS sensor system (TrIMU)

The denomination TrIMU refers to the three functions implemented on the circuit board: Inertial measurements, gauging of pressure sensors for static and dynamic pressure and the ability of controlling up to 12 servo channels. The additional functions of pressure measurement and servo controlling were implemented

[1] MEMS = Micro-electro-mechanical System

with regard to the application of the sensor board as a multi-functional component for an autopilot system. All sensors deliver an analogue output signal, which is converted by a 24 Bit Σ–Δ-A/D-converter (static pressure) and a 12 Bit SAR-A/D-converter (all other sensors) respectively. TAB.1 displays the main characteristics of the TrIMU system.

sensors	**measurement range**
angular rates (x,y,z)	±300 °/s
lin. acceleration (x1,y)	±1.5 g
lin. acceleration (x2,z)	±8.2 g
static pressure	15 to 105 kPa
impact pressure	0 to 1.250 Pa
derived air data[2]	**measurement range**
barometric altitude	0 to 13 km
air speed	0 to 45 m/s (h = 0 km)
additional functionality	
actuator control (PWM[3])	12 ch., 100 Hz
remote control input	1 channel, time-muxed

TAB 1. TrIMU characteristics

Being extremely small, light-weight and low-cost, the MEMS-sensors perfectly match the requirements in terms of an application on an MAV autopilot system, but they are generally less accurate compared to conventional inertial sensors, i.e. mechanical gyroscopes or fibre-optical gyroscopes [2]. Especially their temperature dependence can, for instance, lead to sensitivity errors in the range of ±10% FS (gyros) or bias variation of ±100 mg (acceleration sensors). Another crucial source of measurement errors arises from the finite precision during the manual TrIMU fabrication leading to misalignments of the sensor axes of several degrees. Hence, it was necessary to develop a calibration process and setup in order to characterize each TrIMU individually.

2.2. TrIMU calibration

To overcome the mentioned sources of MEMS sensor inaccuracy, every TrIMU is subjected to a calibration process to determine the temperature dependence of each sensor's bias and sensitivity as well as the misalignment errors. Calibration results are stored to the non-volatile memory of the TrIMU microcontroller enabling the output of both raw measurement data and calibrated inertial measurement data.

The calibration set-up contains of a precision turn table and a thermo-electrically driven thermal chamber, which can be mounted onto the turn table. Both devices are controlled via individual serial links to a PC, also monitoring TrIMU measurement data. A high-precision holder allows the alignment of the TrIMU in six different attitudes with each of the tree orthogonal TrIMU axes up or down and an additional diagonal attitude, where all sensors are equally subjected to earth's gravity and the angular rate vector.

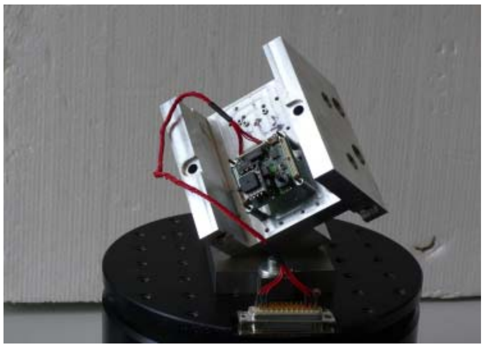

FIG 2. Calibration set-up (thermal chamber not shown)

2.2.1. Temperature calibration

In the first step of the TrIMU calibration, the temperature dependence of each sensor's bias b_i and scale factor k_i are determined. As each angular rate sensor contains an individual temperature sensor, it stands to reason to use these sensor output values $\theta_{x,y,z}$ as temperature reference for the angular rate sensors' scale factors $k_{\omega x,\omega y,\omega z}$ and bias values $b_{\omega x,\omega y,\omega z}$. Concerning the acceleration sensors' scale factors $k_{ax1,ax2,ay,az}$ and bias values $b_{ax1,ax2,ay,az}$ the temperature sensor of the geometrically closest angular rate sensor is applied as reference.

During the temperature calibration process of the acceleration sensors, the TrIMU was aligned in the six different attitudes, where the orthogonal sensor axes x, y, and z were directed once in the positive direction of the earth gravity vector and once in the negative direction. As a result each acceleration sensor was excited with +1 g, 0g and –1 g. In contrast to the necessary manual change of attitude during the accelerometer sensors' calibration, the temperature calibration of the angular rate sensors could be conducted only utilising the diagonal attitude, where all three sensors are equally excited by the angular rate ω_t of the turn table[4]. For the calibration angular rates from -400 °/s to +400 °/s in steps of 50 °/s were used.

As a compromise between accuracy and expenditure of time, the temperature calibration was carried out between 0 °C and +50 °C in steps of 10 °C. The availability of measurements for six different temperatures leads to a best fit of the temperature dependence of bias and scale factor for all sensors with a fifth-grade polynomial. Due to the desired temperature range of -20 °C to +70 °C the polynomial, now only valid for the measured temperature range, was supplemented by linear interpolation to meet the desired range.

[2] according to ICAO standard atmosphere
[3] PWM = Pulse Width Modulation

[4] Due to the diagonal attitude the excitation per sensor is (ω_t)^1/3.

To provide IMU output with a relatively high frequency of 100 Hz, it is not possible for the microcontroller to compute every sensor's bias and scale factor with a fifth grade polynomial, also keeping in mind that is has to be decided first, if the fifth grade polynomial or the linear interpolation have to be used for the measured temperature. Therefore, the polynomial for the bias values and scale factors are converted into vectors and are stored inside the microcontroller's non-volatile memory. Every vector contains 128 values and is directly addressed by the value of the geometrically nearest temperature sensor.

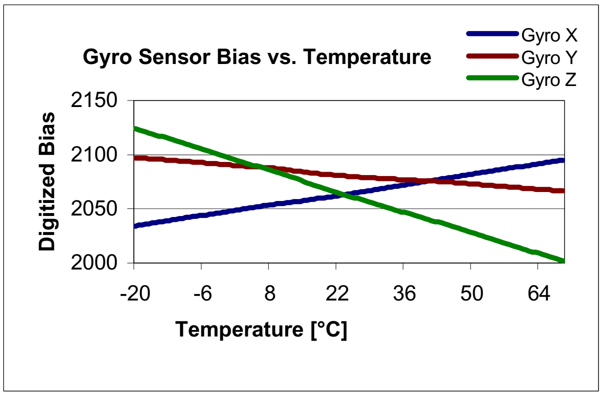

FIG 3. Angular rate sensor bias vs. temperature

As an example for a typical MEMS-sensor temperature dependence FIG 3 shows the bias values of the three angular rate sensors versus temperature. The ideal value for all sensors would be 2048, with respect to the resolution of 12 Bits. But as it can be seen in the figure, all bias values are clearly temperature dependent, with slopes varying in magnitude and sign. For the depicted z-gyro the bias deviation corresponds to a deviation of the uncompensated signal of 30 °/s. This behaviour is typical for MEMS-based inertial sensors and will always lead to the demand of an individual calibration of each single sensor.

2.2.2. Calibration of misalignment errors

As already described, it can not be assumed that the sensors' sensitive axes form an orthogonal system. For each sensor i there exist two misalignment angles e_{i1} and e_{i2}, which describe the deviation of the sensor's axis towards the other two Cartesian axes of the reference coordinate system. The determination of the misalignment angles is done using a set of measurement data at constant temperature for six different attitudes[5] for the acceleration sensors and three different attitudes once with a positive angular rate $+\omega$ and once with the same rate but negative sign $-\omega$. Let k_i be the sensor's scale factor, b_i the bias value and ε_{i1} and ε_{i2} the misalignment angles, there exist four unknown variables per sensor. With the six measurements at well-known excitations, a calibration model containing six equations can be set up with only these four unknown variables, so that the variables can be computed numerically. Typical misalignment angles for the TrIMU's acceleration sensors (A) and angular rate sensors (G) are shown in TAB 2. As an example the following section describes the determination of the calibrated angular rates.

Sensor	ε_1 [°]	ε_2 [°]
A_{X2}	-1,16	-0,03
A_{Y2}	-1,01	-4,06
A_{Z10}	-1,29	-0,64
A_{X10}	-1,09	-1,20
G_x	-0,07	0,20
Gy	-1,36	0,55
G_z	0	0,28

TAB 2. Typical misalignment angles of a TrIMU

The set of measurement values of the angular rate sensors forms an own coordinate system with

$$\overline{\omega_s} = (\omega_{x,S}, \omega_{y,S}, \omega_{z,S}) \tag{1}$$

in the sensor-fixed coordinate system (index S). In case of misalignment, the axes x, y and z do not form an orthogonal coordinate system. To obtain the desired angular rate vector

$$\overline{\omega_g} = (\omega_{x,g}, \omega_{y,g}, \omega_{z,g}) \tag{2}$$

in the geometric or IMU-fixed coordinate system (index g, do not confuse with the geodetic system) a transformation of the vector $\overline{\omega_s}$ using a transformation matrix $\underline{\underline{M}}$ is applied:

$$\overline{\omega_g} = \underline{\underline{M(\theta)}} \cdot \left(\overline{\omega_s} - \overline{b(\theta)}\right) \quad . \tag{3}$$

In detail:

$$\begin{pmatrix} \omega_{x,g} \\ \omega_{y,g} \\ \omega_{z,g} \end{pmatrix} = \begin{pmatrix} k_{x,x} & k_{y,x} & k_{z,x} \\ k_{x,y} & k_{y,y} & k_{z,y} \\ k_{x,z} & k_{y,z} & k_{z,z} \end{pmatrix} \cdot \begin{pmatrix} \omega_{x,s} & - & b_x \\ \omega_{y,s} & - & b_y \\ \omega_{z,s} & - & b_z \end{pmatrix} \tag{4}$$

The coefficients $k_{i,j}$ of the transformation matrix describe the contribution of the sensor i to the desired value along the geometric axis j. The coefficients $k_{i,j}$ contain not only the misalignment correction, but also the temperature-dependent scale-factor for each sensor. Besides this, the bias values b_i are also functions of the measured temperatures θ_i. As a result of the calibration process the correction of the sensors' temperature dependence and the geometrical misalignments can be done in two steps: The

[5] x-, y-, z-axis up- and downwards

first is the determination of the temperature-adressed vectors for bias and scale factor, the second contains the rather simple transformation (eq. (4)). Both tasks are unproblematically implemented in the microcontroller's code.

3. GPS/INS NAVIGATION

Indispensable for safe and reliable navigation, guidance and control of unmanned and unattended aircraft is a fast and precise determination of position, attitude and velocity. Therefore, the best suitable method had to be chosen from the variety of GPS/INS integration algorithms, generally divided into loosely-coupled, tightly-coupled and deeply-coupled[6] GPS/INS integration. With regard to the special receivers, that are required, the latter type had been excluded from the first. For the current MAV application a tightly-coupled method has been chosen. Compared to the loosely-coupled GPS/INS integration this method shows the advantage of aiding the INS data also with less than four SVs, which is of decisive importance aiming at high dynamically flight capabilities.

3.1. Navigation Filter

Regarding GPS data a tightly-coupled GPS/INS filter usually processes pseudoranges and delta-ranges. Here, the delta-ranges are replaced by time-differenced carrier phases, a method, which was introduced i.a. by Farrell [3] and provides the advantage that the integer ambiguities do not have to be solved. The key idea of this method is to improve the velocity aiding and, hence, the attitude estimate of the filter, which is the most important aircraft state in order to achieve good flight performances of autonomous MAV.

The discrete error state Kalman-Filter of state vector $\bar{x}$ provides estimates for the three position, three velocity and three attitude errors as well as the three errors in the gyro sensor signal bias estimates, the three errors in the accelerometer signal bias estimates, the error in the GPS receiver (RX) clock error and the error in the GPS RX clock drift (17 states):

$$\bar{x} = \begin{bmatrix} \delta\bar{r} & \ldots & position\_error \\ \delta\bar{v} & \ldots & velocity\_error \\ \delta\bar{\varphi} & \ldots & attitude\_error \\ \delta\bar{\omega} & \ldots & error\_of\_est.\_gyro\_signal\_bias \\ \delta\bar{a} & \ldots & error\_of\_est.\_acc.\_signal\_bias \\ \delta(c\Delta t) & \ldots & error\_of\_RX\_clock\_error \\ \delta\left(c\Delta\dot{t}\right) & \ldots & error\_of\_RX\_clock\_drift \end{bmatrix} \quad (5)$$

As aiding information, GPS raw data are used in order to closely meet the Kalman-Filter requirement of zero-mean and uncorrelated white noise. For one propagation step of this type of Kalman-Filter the microprocessor unit of the actual autopilot system requires approximately 1ms, easily matching the sensor and actuator update frequency of 100 Hz, while providing enough spare capability for the 1 Hz filter update, the flight controller and flight guidance.

[6] sometimes also referred to as ultra-tightly coupled

3.2. Flight test results

At the ILR a GN&C test platform was developed and manufactured containing of an unmanned aircraft with a wingspan of 2 m, 1.5 kg payload capacity and a maximum take-off weight of 6 kg. In addition to the described GPS/INS system the platform is equipped with a high-precision FOG-IMU. This FOG-IMU is a tactical grade sensor system and therefore serves as a reference for the low-cost system. The GN&C test platform is always operated by remote control.

The error of the roll angle, pitch angle and yaw angle of a 16 min test flight are shown in TAB 3. Altogether these results can be regarded as excellent and more than sufficient for the intended application. Further research of this type of navigation algorithms also include the consideration of vibration induced by the vehicle's engines [4].

	accuracy (1σ)
roll angle	0,54°
pitch angle	0.71°
yaw angle	1.22°

TAB 3. Attitude accuracy during flight tests

4. APPLICATIONS OF THE GPG/INS SYSTEM

Besides its obvious application within MAV and UAV navigation, the navigation system has already been implemented in a sophisticated meteorological measurement system, called the Meteorological MAV or M²AV [5]. The M²AV has been completely developed at the ILR and is based on a 2 m-wingspan MAV, similar to the GN&C test platform. As a meteorological sensor package the M²AV contains nose mounted sensors for temperature, relative humidity and three dimensional wind vector (9-hole-probe).

FIG 4. Meteorological sensors of the M²AV

Further elements of the sensor package are an own TrIMU and GPS receiver forming a navigation system, which is independent from the M²AV's autopilot system, allowing operation with or without the autopilot. Like the navigation algorithm also the meteorological data acquisition is performed with a frequency of 100 Hz, so that navigation data and meteorological data can directly be merged.

The M²AV has been intensively tested and built in small quantity. It is already in use in the context of national and international research campaigns, the most challenging one is the current research mission of two M²AVs at the British Antarctica research station Halley.

5. CONCLUSION AND OUTLOOK

At the Institute of Aerospace Systems a highly miniaturized GPS/INS navigation system has been developed and tested. Although based on low-cost components like inertial MEMS-sensors and a single-channel GPS receiver the applied navigation algorithm provides excellent results allowing an accurate and reliable use of the system in the context of MAV guidance, navigation and control. To meet this aim, the miniaturized IMU is extensively calibrated concerning temperature dependences and misalignment errors. Along with GPS raw data IMU data is provided to a discrete state Kalman-Filter, which uses time-differenced carrier phases instead of delta-ranges. This method especially matches the requirements of MAV application as it aid INS data also in case of less than four satellites visible. After validating filter results in drive and flight tests one of the first successful applications of the navigation system is the meteorological MAV (M²AV), where precise and high-frequent attitude information is essential especially for the three-dimensional wind vector determination.

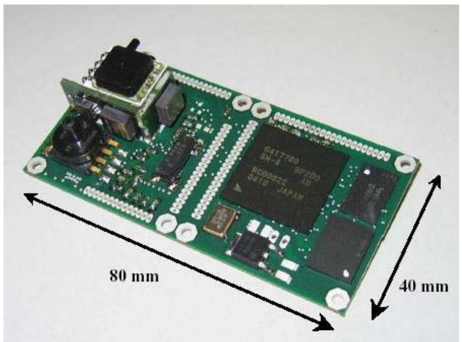

FIG 5. Highly integrated autopilot system MINC

The GPS/INS system is part of the development of a new autopilot system comprising of a TrIMU sensor package and a 64-Bit microprocessor module with floating point unit. Having implemented the navigation algorithm and also the flight control and navigation software the system is now ready for first flight test, whose results will be presented in short time.

ACKNOWLEDGEMENTS

The authors wish to thank the European Union for financing main parts of the research and development, whose results are presented in this paper.

LITERATURE

[1] **Buschmann, M.; Heindorf, A.; Vörsmann, P**. *MINC: A Miniature Integrated Guidance Navigation and Control System enables in-flight GPS/INS Data Fusion aboard a Micro Aerial Vehicle*. Proceedings of the 25th ICAS Congress (Hamburg, Germany, September 3-8, 2006).

[2] **Beeby, S.; Ensell, G.; Kraft, M.;White, N.** *MEMS – Mechanical Sensors*, Artech House Publishers, Boston, 2004, ISBN: 1-58053-536-4

[3] **Farrell, J. L.** *Carrier Phase Processing Without Integers,* Proceedings of the ION 57th Annual Meeting and CIGTF 20th Biennial Guidance Test Symposium (Albuquerque, NM, June 11-13, 2001). 2001,pp. 423–428

[4] **Martin, T.; Winkler, S.; Voersmann, P.**
GPS/INS Integration for Autonomous Mini and Micro Aerial Vehicle Navigation Considering Time Correlated Sensor Noise, Proceedings of the ION 63rd Annual Meeting (Cambridge, MA, USA, April 23-25 2007), 2007, pp. 710-716

[5] **Bange, J.; Kroonenberg, A. v. d.; Spiess, T.; Buschmann, M.; Krueger, L.; Heindorf, A.; Voersmann, P.**
Atmospheric Turbulence Measurements with the Automatic Mini UAV ‚M²AV Carolo', Joint Assembly of the American Geophysical Union (AGU, Acapulco, Mexico, 22-25 May 2007), 2007