

An universal Autopilot Hardware and its Attitude Estimation for all kinds of MAVs

Heinrich Warmers, Oliver Riesener, Arthur Neumann, Andreas Dei

Hochschule Bremen, Institute for Aerospace Technology, Flughafenallee 10, 28199 Bremen, Germany, phone: +49-(0)421-5905-2407, fax: +49-(0)421 5905 2400, web : <http://www.iat.hs-bremen.de>, email: hwarmers@hs-bremen.de

Abstract: This paper addresses the hard- and software design of a new universal education autopilot system for MAVs. In contrast to other solutions the hardware consists of sensors and the software of attitude estimations algorithms to fly VTO aircrafts as well as normal plane aircrafts. A low cost Inertial Measurement System with signals from MEMS gyros, MEMS acceleration sensors, MEMS pressure sensors for altitude and speed measurements and a three axis magnetometer analogue converted with 16 bit and 24 bit (altitude) resolution gives the input for the attitude estimations and flight control algorithms in combination with a GPS receiver. Different attitude estimations algorithms (Kalman- and Complementary- Filters) were developed, simulated and tested by practical flight experiments to overcome sensor errors like drifts, offsets, noise and vibrations generated by the motors and propellers. A new developed brushless controller and its control algorithms give up to 10 % more flight time compared with an industrial solution. A quadrocopter especially designed to take photos and videos with a normal 200g digital camera was developed and used the new autopilot and brushless controller with good performance.

1 Introduction

In the last years many MAVs and autopilots where developed and tested successfully. At Akaflieg and Hochschule Bremen plane MAVs (Busca400, 230g, Lerche400 195g, both wingspan 400mm [1]) and VTO MAVs (quadrocopters [2]) have been developed and constructed since 2008. The results (autopilots and software) of the Paparazzi project (ENAC Toulouse) were used for the first plane aircrafts. The position is measured with the GPS, the attitude with IR sensors. For our quadrocopters the software and the new autopilot hardware "HB-Autopilot" was developed in Bremen. Since we develop both VTO (quadrocopters) and normal plane micro aircrafts we want to design one hardware autopilot and attitude estimation software for all kind's of MAVs. The different sensors: magnetometer for VTO aircrafts and difference pressure sensor to estimate the true airspeed for normal plane configurations need only low mass, volume and costs.

The new autopilot therefore can be used for micro aircrafts without disadvantages. The sources of the hardware documentation and software are free for everyone since the General Public License is applied for both projects (free download: http://paparazzi.enac.fr/wiki/Main_Page <http://www.akaflieg.hs-bremen.de/>).

In the past same MAVs were successfully used for meteorologic measurements [3],[4],[5]. Based on this experience a cost action ES0802 was started and works currently with members of many EU countries. The new autopilot was designed for MAV for metrological measure flights by the compatibility with mass storage and free 16 bit A/D channels and all weather compatibility.

1.1 The IR-attitude measure system

For an automatic flight of aircrafts a system to measure the roll and pitch angle is necessary. Paparazzi uses therefore an IR-measurement-

system as the first version of the diy drones project [6] for normal plane configurations. The IR-sensors sense the temperature radiation in a wavelength from 5-14 μ m. Four sensors are used to measure the position angle. Two pairs are used and each pair is arranged to look to the opposite direction. They are connected in a way, that the temperature difference is measured. Since we have a large temperature difference between the sky and the ground the pitch and roll angle can be calculated with this information. The difference signal is amplified by a factor of 1000 before it is given to analogue inputs of the micro controller. A second contrast sensor with tow IR-sensors is used for automatic gain control.

This system works well under visual flight condition at day and night. In towns with high buildings, fog, clouds and inversion weather conditions in the tropics the IR attitude estimation system fail. The dynamics of the IR sensors is too slow for fixed wing aircraft below 0.4m wingspan and quadcopters. By practical flight tests in the north of Germany we were not able to fly in about 10% of our attempts.

To overcome this problem, an other measurement system (magnetic- rate- and acceleration-sensor based) is necessary. The common way is to use the integration of three gyro signals to get the pitch raw and yaw angle. Since there is a sensor bias for the rate signals the error of the angle will grow fast over the time. The bias has to be compensated by fusion of different sensor signals. Three methods were taken into account, implemented and tested:

1. Applying an Extended Kalman filter with 7 state variables
2. Applying a Complementary filter
3. Applying a DCM algorithm with a feed-back control system (proportional integral) for bias correction

Before practical tests are possible the requirements for the autopilot, the sensors and electronics have to be defined and the development process of the hardware has to be finished.

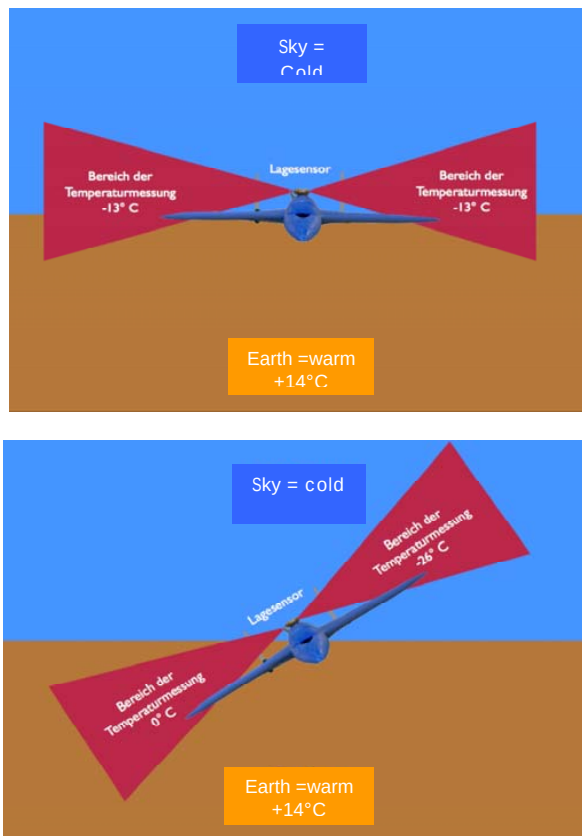


Figure 1: Principle of the angle measurement system

2 Requirements for an universal autopilot and data acquisition system

At the design start we want to perform the following requirements:

- all weather and all kind of MAV compatibility by using an Inertial Measurement Unit (IMU) to estimate the attitude; acceleration up to 5g max. rate 300°/s; 10 servo outputs; 5V i2c bus for brush less controllers of quadcopters
- Resolution of the altitude estimation 5cm by pressure measurement by use of a temperature compensated MEMs sensor and 24 bit ADC with more than 10 samples/s
- true airspeed measurement with pitot tube
- magnetometer with 3 axis; yaw error < 1°
- temperature sensor -55...125°C
- analogue inputs for sensor signals converted by 16 bit ADCs, 6 free channels for a data acquisition system
- low cost < 500 Euro, low mass < 30g, low dimensions < 41mm x 57mm x 27mm
- two PCBs, one controller PCB called MCU micro controller unit (figure 4), one sensor PCB called IMU (figure 3)
- compatibility of the sensor (IMU) PCB to all micro controller with SPI interface and 4 free I/Os
- first, use of the LPC2148 ARM7 32 bit micro controller,
- use of µblox LEA4 and LEA5 GPS receivers with 4Hz update rate and typically 1,5..5m position error in outer city regions

- low noise 5V and 3.3V analogue supply voltages, 3.3V and 5V (2,5A) digital supply voltages
- Paparazzi software compatible, JTAG test interface, 2 power switches, one buzzer output
- interfaces: 2 i2c one with 5V, 2 SPI one for SD mass storage (2GB), USB, 2 UART, GPS reset time pulse input, reset input,
- only use of free development tools (LINUX, GCC, OCAMEL), all software sources, all documentation all constructions files free to use for everyone by using the GPL and free download.

3 HB-Autopilot and its application for quadcopters

To full fill the requirements the following solutions were chosen.

3.1 MEMS (*Micro-Electro-Mechanical Systems*) sensors

Three **alternative Gyroscopes** from different suppliers with different vibrancy frequencies can be applied by the use of small rate sensor PCBs (figure 2):

1. **ADXRS610** (Analog Device) very good temperature drift, best linearity, expensive, difficult to solder (22kHz)
2. **LISY300AL** (ST Microelectronics) cheap, has problems with vibration generated by the drive train not possible to use with quadcopters (5KHz)
3. **MLX90609-R2**, (Melexis) easy to solder, large housing (>20KHz)

Two acceleration sensors **ADXL330** 3-axis $\pm 3g$, or **ADXL323** 2 axis $\pm 3g$ and **ADXL320** 2-axis $\pm 5g$, (to measure the gravitation force



Figure 2: Sensors PCBs with rate sensors

and estimate a correction signal for the angle). For the estimation of the gravity force a 2g range is advisable. If acrobatic flight manoeuvres are applied a 5g range is required for the z sensor. By the use of different sensors both requirements are solved. We found out that the acceleration sensors have huge gain and bias errors. Under zero gain condition we measured a bias of 0,2g and for 1.0g we measured 0.83g for the ADXL330. A special calibration process is necessary to use such sensors for attitude correction. The sensor uses difference capacitance and generate much noise.

Two pressure sensors from Freescale are used the **MPXH6115A6U/6T1** 0..115kPa to estimate the altitude and the **MPXV7002** difference pressure 20kPa to measure the true air speed. To use the GPS altitude is not advisable since the typical error is in the range of 9..15m. The absolute pressure sensors give in combination with the 24 bit delta sigma ADC LTC2440 from Linear Technologies a resolution in the cm range. The sensor has a silicone pill to shield the die. By hard acceleration this silicone generates forces to the membrane, which is measured as altitude change. They are also light sensitive.

3.2 Magnetometer

To achieve a high quality magnetometer three KMZ51 magnetic field sensors (NPX) to measure all three Cartesian vector components of the magnetic earth's field, are used. In combination with the 16 bit ADCs this gives a yaw angle error lower than 1° . To estimate the yaw angle influences with ferromagnetic material and the attitude is considered. SMD resistors and capacitance contain nickel. In a post start calibration process all possible attitudes of the aircraft are applied and the

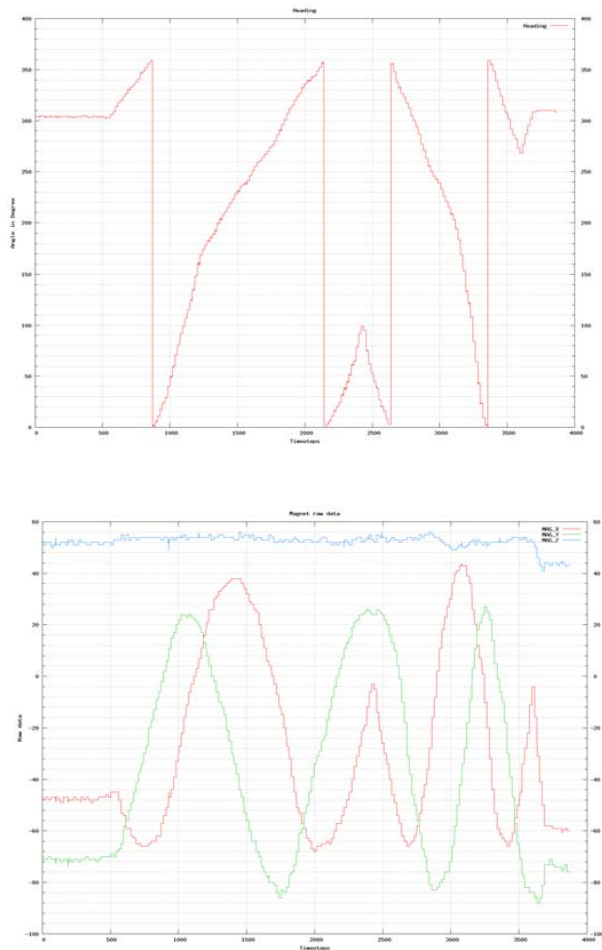


Figure 3: calculated heading and sensor raw data

maximum and minimum fields for each axis are stored. An unsolved problem even in small MAVs is the influence of magnetic fields generated from the electric drive train. We use twisted power wires and keep the wires more than 5cm away from the sensors (see figure 6). For the batteries we noticed no influence. Another problem especially with the use of quadcopters in vicinity of buildings and iron concentration like bridges is the deviation. A solution to this problem is to correct the derivation with a free RC channel by the safety pilot. If the aircraft has speed over ground the speed vector estimated with the GPS system can be used to correct the yaw drift.

As temperature sensor the MAX6605 (MAXIM) in the range from -55°C ... $+125^{\circ}\text{C}$ is applied. For all ADCs the SPI interface is used. Two 16 bit 8 channel ADCs MAX1168 with in 200k samples/s minimized the required number of pins and give higher accuracy compared with the 10 bit ADCs of the LPC2148.



Figure 3: IMU printed circuit board



Figure 4: MCU printed circuit board



Figure 5: Finished autopilot

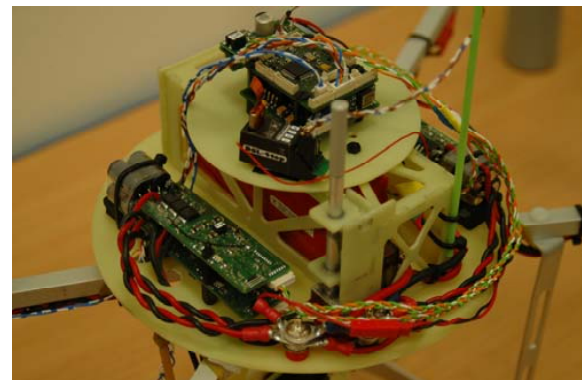


Figure 6: HB-Autopilot and new brushless controllers applied for a developed photo copter



Figure 7: Photo copter with 200g digital camera

3.3 Application for quadcopters

The block diagram of HB-Autopilot for quadcopters is shown in figure 8.

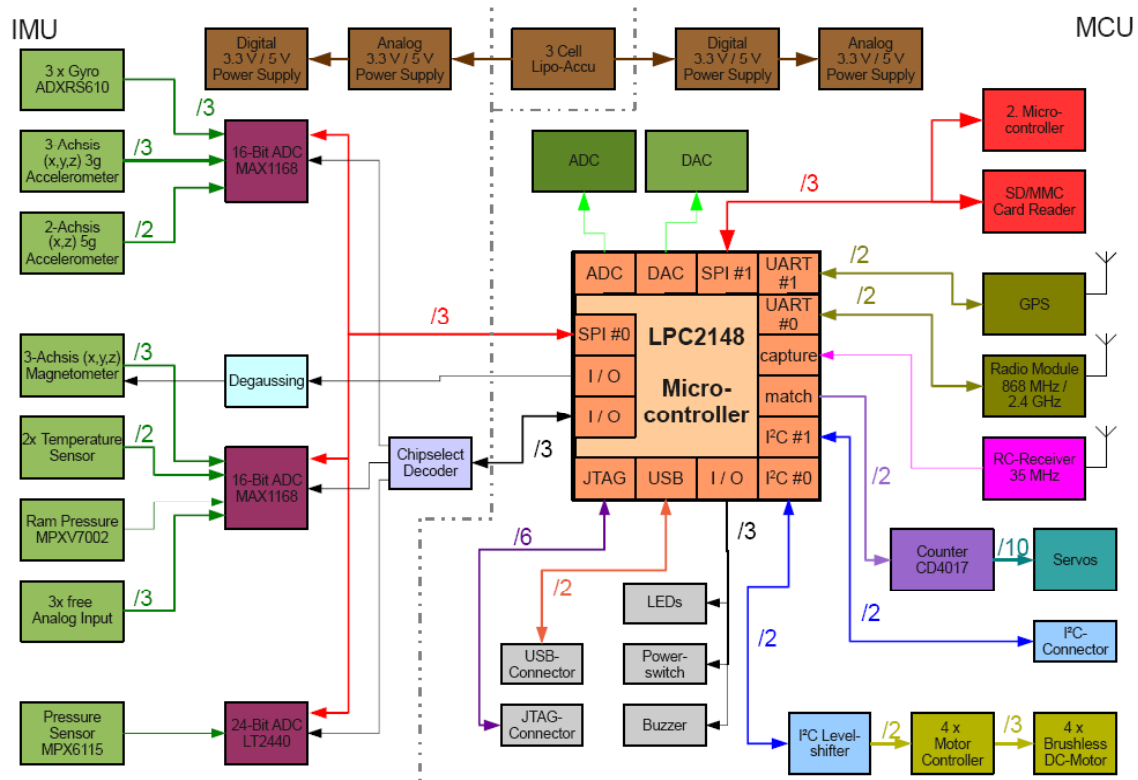


Figure 8: Block diagram

On the left hand side the components of the IMU are shown. The dashed line is the border between the two units. By the use of the SPI bus between the micro controller and the ADCs the account of wires between the two PCBs is low and many I/O lines of the micro controller are saved for other interfaces. The JTAG connectors give the chance to use debugger like the GDB for software development and test. Up to 6 lines can be used for additional measurement signals with 10 bits by using the internal ADCs of the micro controller. These lines can also be used for future extensions. By the use of the USB connection between the PC and the target the flash time is only 2-3 sec and the turn around time is low. The buzzer gives alarm messages

for low battery and RC-lost situations. To get the system working for an automatic flying camera quadcopter the GPS receiver, bi-directional telemetry modem, the RC receiver to obtain commands from the safety pilots, a decimal counter CD4017 to serve the impulses for standard servos, the four brushless controllers and motors and the battery are necessary. The servos are used to stabilize the camera viewpoint by the attitude information's and to activate the camera-tipping device. For the use of the system in normal plane aircrafts the account of the motors and brushless controller are normally reduced to one. The rudders are operated by servos.

4 Brushless Controller

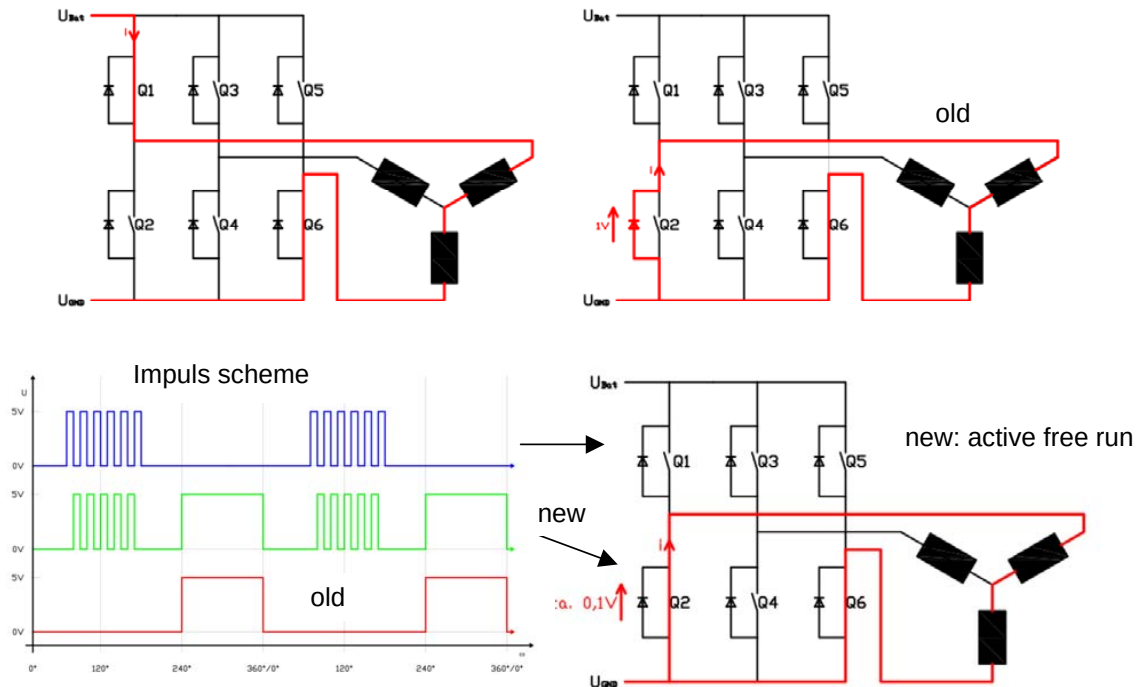


Figure 9: Improved Impulse scheme and voltage drops

For the first prototypes we used brushless controller designed and sold by the industry [7]. The efficiency of this and the output power was poor and we designed one with following performance [8]:

- Three interfaces I2C, PPM, UART for input signals
- Potential separation between interface and power part
- Up to 25A and 25V, special driver circuits for the power MOS-fets for fast switching, low resistance power mosfets
- Impulse scheme with active free run during PWM (part load)
- Two parallel connected filter electrolyte capacitor for safety reasons (we

noticed crashes by malfunction of the single capacitance of the industry controller)

The lack of much industry brush less controllers is the poor efficiency in part power situations. Normally half maximum power condition is the most time in which the quadcopter motors operate. To solve this problem a better impulse scheme is applied. Figure 9 shows the switching situation with the impulse scheme we found and the improved for active free run. To steer the motor in part load a pulse wide modulation is usually applied. The average voltage is proportional to the revolutions. In the first part one P-MOSFET (Q1) and one N-MOSFET (Q6) connect two wires of the motor with the battery. The switch Q1 is open in the second part. In the impulse scheme without free run the current is driven by the substrate diode of the switch Q2. A voltage drop in the range of 1V can be found. In the improved scheme the

switch Q2 is connecting again with a voltage drop of only 0.1V. After installation of the new brushless controller the flight time is increased typically by 10% .

5 Attitude Estimation

The attitudes estimation is done by the use of a body based coordinate system of the aircraft index b. The rate and acceleration MEMS sensors are arranged in the direction of the unit vectors of this system. The navigation is based on an earth coordinate system index g. The transformation can be based by the use of the direction cosine matrix (DCM) describing the transformation from the body to the navigation and Euler angles (compare figure 10.) The transformations are non-linear. The use of Euler angle is easy to understand but has the problem of some singularities and the intensive time consuming of transcendent functions. Therefore two of the methods we tested use representation with quaternions and avoided this disadvantages. Figure 10 shows the estimation of attitude and position with rate and acceleration signals:

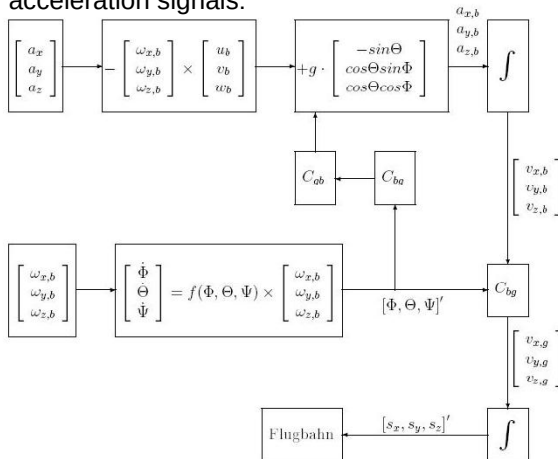


Figure 10: Strap down calculation with Euler angle

5.1 Basic principle

The basic principle of the estimation of the attitude angle is to trust most of the integrated rate signals and to correct errors by the use of fixed reference vectors. The gravitation

vector $\vec{g}_z$ is used to correct the pitch and roll angel. For the yaw angle two different referees can be used: 1. all three components of the magnetic earth field for VTO aircrafts or 2. the estimated ground speed from the GPS receiver for normal plane configurations.

A problem to estimation the corrections for the roll and pitch angle by the of the acceleration sensors is that they measure also centrifugal acceleration and translation acceleration generated by speed changes. The estimation of the centrifugal acceleration is easy by

$$\vec{a}_{centipital}^b = \vec{\omega}_{gyro} \times \vec{V}^e \quad (1)$$

The estimation of the translation acceleration is more difficult. A common method is to avoid the correction if the difference of the measured acceleration minis the centrifugal acceleration (1) has a greater norm than 9.81m/s^2 . To take into account that the translate acceleration take only short time periods and the long time values are most destined by the g force gives a approach in which a low pass filtered acceleration signal is added to a high pass filter integration of the rate signals. This structure is an application of a complementary filter. The second method for the sensor signal fusion is the use of an Extended Kalman Filter.

The errors which have to be compensated are:

- Bias and drift errors of the rate sensors,
- Noise,
- Vibration, we found out that for small quadcopters the vibration generated by the drive train coupled into the acceleration and rate signals reach up to 25% of the full range values (compare figures 12 to 14).

5.2 Extended Kalman Filter

The developed, simulated, practical tested filter is able to estimate the rate sensor bias and the quaternion components for attitude estimation. The effects of noise, vibration of the rate and acceleration sensors signals and the rate bias are eliminated. The system state consist of 7 components the quaternions q_0, q_1, q_2, q_3 and the roll_bias, pitch_bias and yaw_bias. The filter is based on the work in [9] in which all used equations are described more in detail. A schematic of the filter is shown in figure 11.

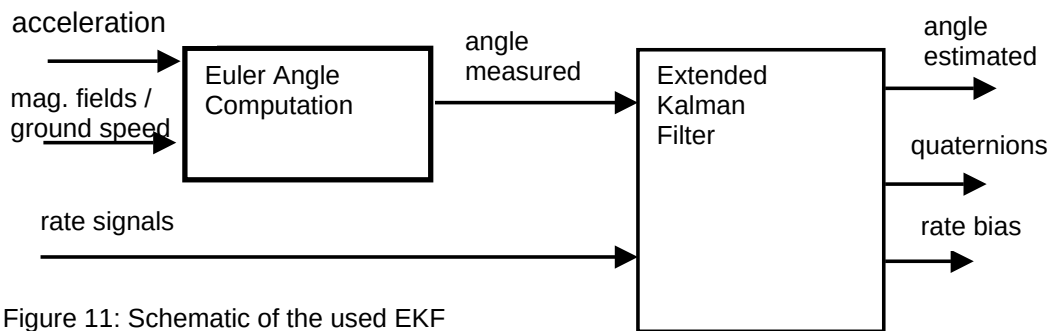


Figure 11: Schematic of the used EKF

After the implementation first in Matlab and second in C-code we made same simulations on real measured sensor signals and plotted the results of flight tests after the implementation of the C code.

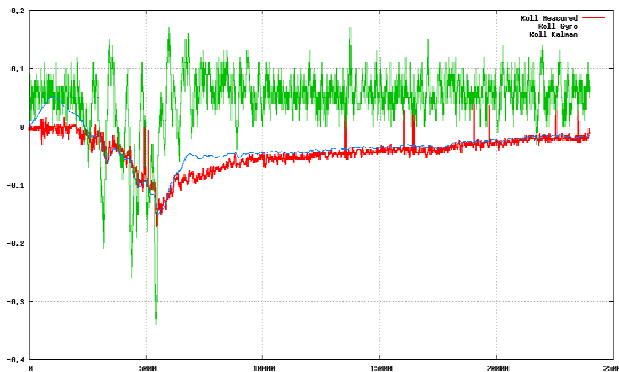


Figure 12: Estimated (blue) and measured (red) roll angle with the Matlab test bench with measured rate sensor signals of real flight

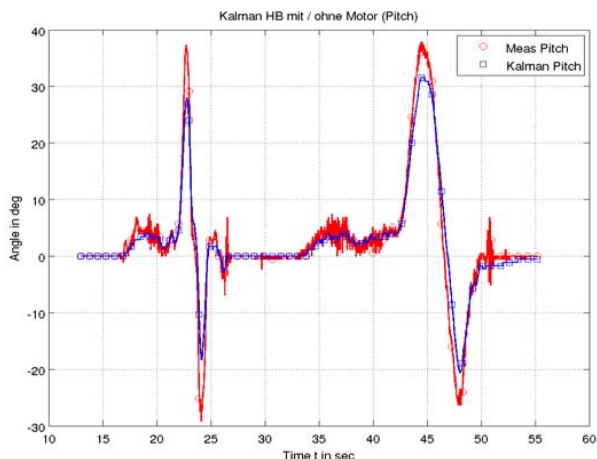


Figure 13: Pitch angle estimation (blue) on the quadcopter by hand movements and motor start after 30 seconds (c-code)

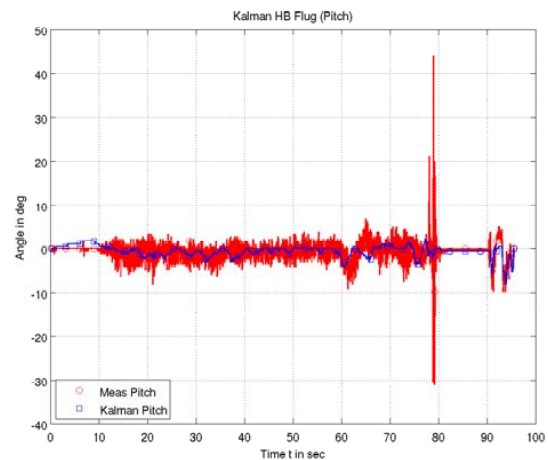


Figure 14: Estimated (blue) and measured (red) pitch angle of a flight with hard landing (80s).

The resume of this filter implementation is that it uses much computing power, an execute time of 7,5ms for each iteration and large RAM requirements and there for vibration and noise influence is fully filtered. In figure 14 is shown that even when large measured angle occur (80s) the estimated attitude is fully unaffected. After the landing the motors and the vibration are switched off. Before the filter was implemented we noticed jumps of the quadcopter by hard landings.

5.3 Complementary filter with correction by gravitation and magnetic field

Usually the application of a complementary filter for attitudes estimation needs less computer power

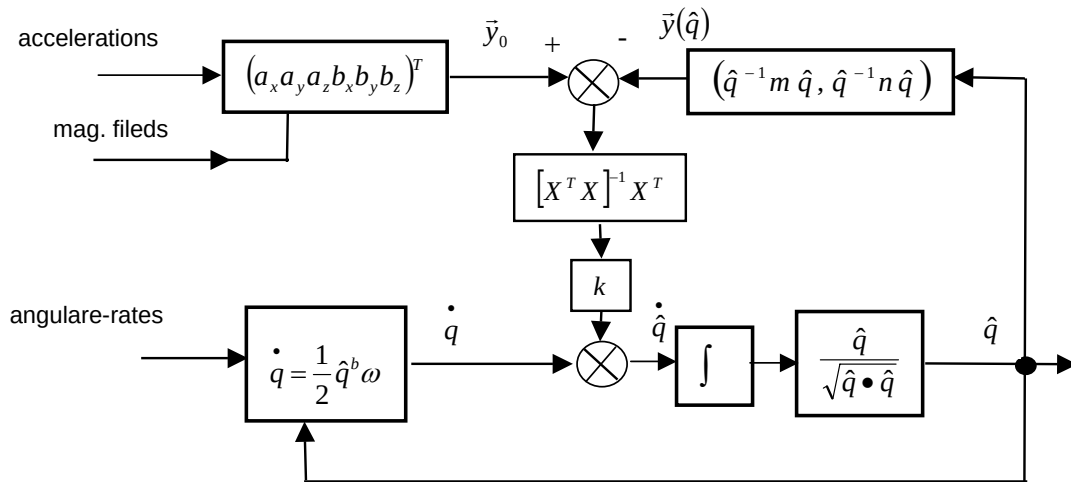


Figure 14: Structure of the complementary filter with the use of quaternions

compared with an Extended Kalman Filter. For our experiments we take an approach [11] which is based on quaternions and take the direct measured magnetic field and gravitation field components as rate signals into account. Also for this filter a Matlab test bench and a C-code for the autopilot were developed and tested. The structure of the filter is shown in figure 14 and same result data in figure 15.

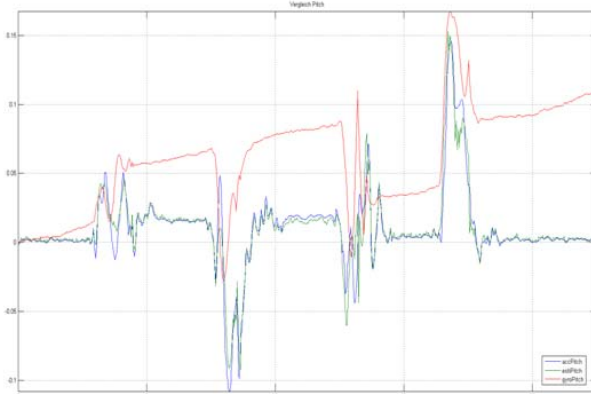


Figure 15: Results for pitch estimation

The gyro pitch signal was built with the integration of the rate signal. The bias results in a large error. The filter estimated signal is not drifting. We made same practical flight test and found out that there were no substance disadvantages compared to the Kalman Filter. When the magnet sensor data were used the estimated pitch and roll angle were a little more imprecise. The run time for the filter was 1.5ms.

5.4 DCM algorithm with a feed back control system (proportional integral) for bias correction

In [11] [12] [13] the use of a complementary filter with quaternion for attitude estimation and control of different MAVs is described. The authors of [14] developed from approach [11] to [13] a filter with following properties:

- The kinematics equations are integrated in a notation of the DCM 50 times per second.
- To save orthogonality of the DCM for every integration step a small adjustments of the matrix elements are applied.
- For bias and drift error correction a PI feedback controller is used. To estimate the errors the acceleration data and the GPS ground speed vector is used.

The structure of this filter is shown in figure 16.

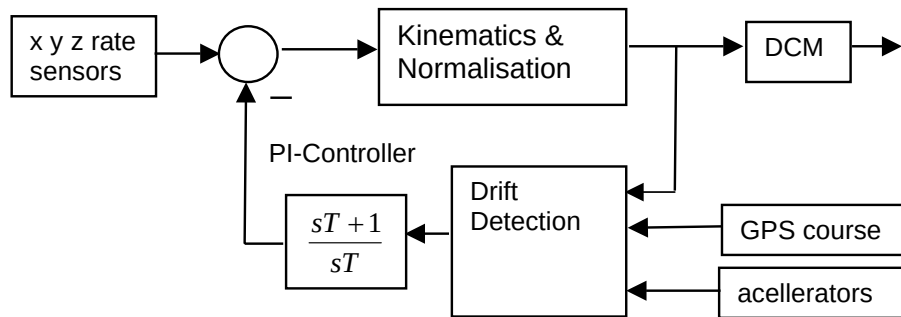


Figure 16: DCM based complementary filter with PI-Controller [14]

We take this filter for normal plane configurations and integrate it to the Paparazzi autopilot system (with tiny13 hardware) by the use of a small planar sensor pub with new MEMS rate sensors from STMicroelectronics LPR530AL (pitch and roll) the LY530ALH (yaw) and the ADX335 (Analog Device) acceleration sensor. The rate sensors have high vibration frequencies (over 20kHz) and a high vibration resistance. A test with the tiny autopilot mounted on a quadcopter and the Kalman were successful. After exact bias calibration of the sensors we found out that the DCM filter with PI-Controller is very robust by low computer cost. The run time is only 0,59ms for the LPC2148 ARM7 micro controller running at 60 MHz. The only small disadvantage is that the controller after power up needs about one minute to stabilize on zero pitch and roll angle (figure 16). We made automatic flights with a 400mm and 800mm span with delta. Compared with the old IR-sensors attitude estimation these solutions give all weather compatibility and a better performance in flight dynamics. The future work to do is to make a Matlab test bench and to compare the simulation results with the other filter performances. A practical test with quadcopters has also to be made.



Figure 17: Stabilization of rolls and pitch angel after power up.

6 Conclusion

This paper describes the hard- and software design of a new universal education autopilot system for MAVs. In contrast to other solutions the hardware consists of sensors and the software of attitude estimations algorithms to fly VTO aircrafts as well as normal plane aircrafts. Three different attitude estimation algorithms were developed, simulated and tested by practical flight experiments. The Extended Klamman Filter and the DCM-filter with the PI-Controller show good results in practical flight tests. The new tested planar rate sensors gives the change to lower weights and dimensions for autopilots. Currently a single PCB autopilot is under development with this sensors.

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