

# Practical Aspects of Trirotor MAV Development

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## ABSTRACT

This paper outlines the mechanical architecture, hardware components, and software structure for an unmanned micro aerial vehicle (MAV) trirotor. It focuses on the practical approach to the design and assembly of an aerial platform with three rotors. Furthermore, an embedded microcontroller-based navigation and control system is proposed to provide efficient angular stabilization and stable hover during the different flight conditions. The design, analysis and the validation tests have been undertaken on the experimental aerial platform.

## 1 INTRODUCTION

Within the last years, rapid development of small and powerful microcontrollers, access to cheap and relatively accurate inertial sensors, reliable wireless links and finally efficient control systems allowed to advance some formerly existing aerodynamic configurations that were very difficult to control by human pilots only, like quadrotors. The most popular multi rotor configuration is undoubtedly quadrotor. It became widespread thanks to its mechanical simplicity and easily understandable dynamics. However, for some applications a quadrotor might be not particularly suitable due to relatively high mass caused by four motors, which reduces the power efficiency. Therefore, the purpose of this project was to design and assemble a vehicle with the number of motors reduced to three and capable of stable hover flight. This is an multidisciplinary problem with various requirements for mechanics, hardware and software. There are multiple publications on UAVs navigation and control [1],[2] based on commercially available platforms, there is also a number of papers focusing on theoretical considerations [3], [4]. These publications do not provide comprehensive overview of the UAV assembling from concept to flight.

The main goal was to design a simple, light and durable airframe carrying embedded measurement and control system, sufficient for first tests and flexible enough to adopt easily to future development without major changes. The main intention was to decrease the number of motors to three. It is obvious that such a modification introduces certain changes to the general system dynamics and require various modifications in the mechanical design. The issue that needs to be dealt with is the unbalanced torque acting on the trirotor caused by uneven number of motors. Alterations in the mechanical design proposed in this paper introduce a tilt mechanism for one of the motors. The tilt mechanism allows

adjusting orientation of one of the motors providing a method of compensation of excessive torque as well as control of the yaw angle. The trirotor flight principle can be explained following[5]:

$$(1.1) \quad = (f_2 - f_1)l_1$$

$$(1.2) \quad = f_3 l_2 \cos \theta - m_3 g l_2 + (f_2 + f_1)l_1 \sin \theta - 2m_{12}g \sin \theta$$

$$(1.3) \quad = f_3 l_2 \sin \theta$$

where:

$\phi, \theta, \psi$  – generalized moments

$f_1, f_2, f_3$  – forces generated by motors

$l_1$  – distance from the motors 1 and 2 to the x-axis

$l_2$  – distance from the motor 3 to the center of gravity

$\theta$  – tilt angle of the motor 3

$\psi$  – angle between side booms and axis y

$m_{12}, m_3$  – motors masses

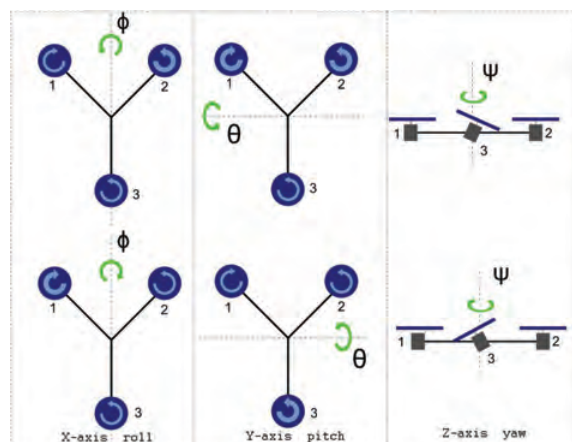


Figure 1: Principles of flight.

If all rotors are spinning with the same angular velocity, the total torque causes rotation along yaw axis. Therefore, the motors 3 is tilted which decomposes the generated thrust into lift force and a component acting in opposite direction to the unbalanced torque. The tilt angle can be adjusted resulting in rotation along yaw axis. Roll angle changes are achieved by generating unbalanced forces by motors 1 and 2. Rotation along y-axis is caused by unequal forces produced by motor 3 and sum of motors 1 and 2.

This paper presents a short overview of four stages of the practical implementation of a trirotor. The second chapter

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introduces mechanical design and dedicated flight computer. Measurement system including data filtering is described in the third chapter. Chapter 4 brings in the navigation equations and is followed by control system design in chapter 5. Tests results are presented in chapter 6.

## 2 MECHANICAL DESIGN

### 2.1 Airframe

The frame is the key element of an UAV. It should be possibly durable, stiff and light as well as affordable within project budget. Therefore, the materials selected to use were of the possibly finest quality limited only by price. A crucial factor for frame design is the material strength. However, the word “strength” have different meaning for different materials. For metals, strength means yield strength, for composites it is the tensile failure strength. The materials selection for the airframe was based on [6] which analyses their strength relative to cost and density. The materials chosen for the project were carbon fibre reinforced polymer (CFRP), aluminium, and polyamide PA 66. CFRP was used for side booms while the combination of aluminium and PA 66 were used for motors holders, tilt mechanism and central part. The airframe design in 3D CAD is shown in figure 2 and 3.

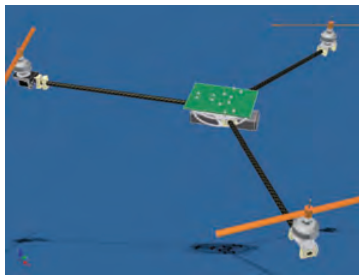


Figure 2: 3D tricopter design.

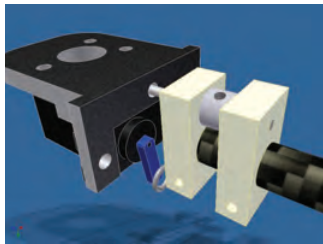


Figure 3: Tilt mechanism with analogue servo.



Figure 4: Assembled tricopter.

### 2.2 Components

The components used for assembly originate from RC models. Battery, servo, motors and propellers were adopted without changes. The brushless motors selected for the design require electronic speed controllers (ESC). These controllers are available to buy as RC models equipment, unfortunately, in this configuration they are not particularly useful for such a demanding task as stabilization of a rotorcraft. The main limitation is the standard RC model interface, so called pulse position modulation PPM, that operates with frequency as low as 50Hz. Therefore, a dedicated ESC with I2C or UART needs to be used in order to obtain a higher sample rate of the control signals. Some changes were made, so that the device after conversion could be controlled via I2C interface with up to 100kHz transmission frequency and is compatible with 2, 3 and 4-cell Li-Pol batteries (7,4V – 14,8V). The conversion process was performed according to the information from [7] where the new firmware originates from as well.

### 2.3 Hardware

A dedicated, microcontroller-based flight computer has been developed. The central unit of the flight computer is an Atmel ATmega 128 which performs data collection, solves navigation equations, reads and interprets orders from RC receiver, runs stabilization algorithms and controls the motors and servo. ATmega microprocessor was chosen due to number of available communication protocols (SPI, I2C, USART), low power consumption, and uncomplicated programming. The designed circuits and PCB can be used for both trirotor and quadrotor aerial platforms. It has four sockets for I2C bus and two PWM outputs. It's intended to work with ADIS16400 but due to flexible architecture can also communicate with other sensors types.

## 3 MEASUREMENT SYSTEM

### 3.1 Sensors array

Analog Devices ADIS16400 was selected as the main measurement unit. It is an integrated device containing triaxial MEMS gyroscope, triaxial MEMS accelerometer, triaxial magnetometer and auxiliary analog – digital converter. In the small (23 x 23 x 23 mm) and light, 16g, package there are also embedded temperature and voltage sensors allowing precise biasing of readings. Communication with the instrument is performed using SPI interface. The system provides fully autonomous operation and data collection after as little as 220ms start – up time and 4ms sleep mode recovery time. According to the datasheet, calibration of sensitivity, bias and axial alignment was performed for +25°C. The system provides also a Barlett-window FIR digital filtering.

### 3.2 Filtering

Due to the MEMS sensors nature, a noise in output signal is unavoidable. Additionally, running motors generate vibrations of wide spectrum. These two sources of noise can be modeled as white noise sequence. The white noise can be removed from sensors readings only by describing its statistical characteristics and applying appropriate filtering [8]. Digital linear, time-invariant (LTI) filters can be defined

by a difference equation of the following form:

$$(3.1) \quad \sum_{i=1}^M a_i y[n-i] = \sum_{j=1}^N b_j x[n-j]$$

where,

$a_i$  – feedback coefficients

$b_j$  – feed forward coefficients

The characteristics of input signals must be known to design a proper filter. The measurements, sampled at 200Hz, were collected from sensors placed on trirotor while motors were running to provide possibly close approximation of real flight conditions. A perfect overview of signals components was obtained using a high resolution PSD (Power Spectral Diagram) estimate[8].

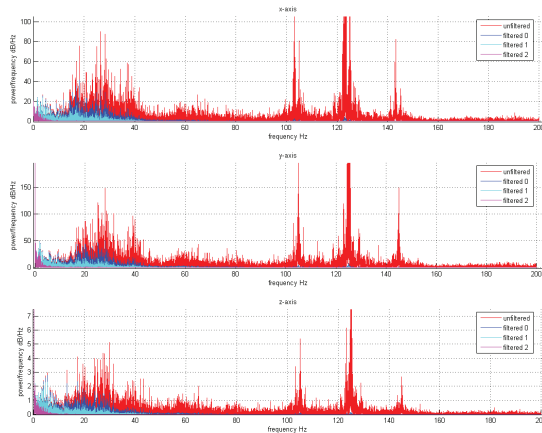


Figure 5: PSD estimate of gyroscopes outputs.

|   | FILTER 0<br>$\epsilon = 20\text{Hz}$ |        | FILTER 1<br>$\epsilon = 10\text{Hz}$ |        | FILTER 2<br>$\epsilon = 5\text{Hz}$ |        |
|---|--------------------------------------|--------|--------------------------------------|--------|-------------------------------------|--------|
|   | a                                    | b      | a                                    | b      | a                                   | b      |
| 1 | 1.0000                               | 0.1367 | 1.0000                               | 0.0730 | 1.0000                              | 0.0155 |
| 2 | -0.7265                              | 0.1367 | 0.0730                               | 0.0730 | -0.9691                             | 0.0155 |

Table 1: Filters cut-off frequencies and coefficients.

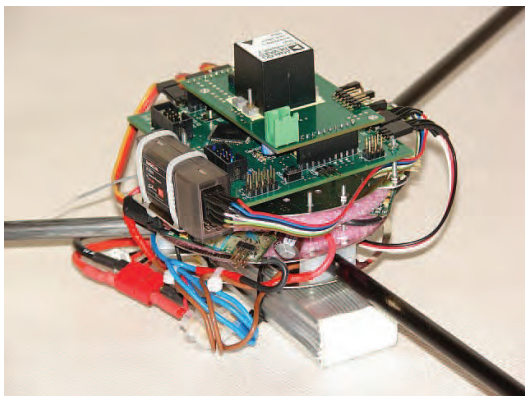


Figure 6: Central part of the trirotor with dedicated electronics, AHRS ADIS16400, RC receiver and battery.

Figure 5 shows PSD of measurements collected during the experiment. There are two main frequency intervals containing most of the noise components. The three peaks

between 100Hz and 150Hz are caused by vibrating three side booms, motors and propellers. The exact location of these peaks is dependent on motors rotational velocity. Noise in this frequency range is not particularly harmful for the navigation because it can be very easily filtered out by a low-pass filter of relatively high cut off frequency. The noise components located between 10Hz and 50Hz have much larger negative impact on the navigation system. Filtering performed with a low-pass filter of cut off frequency below 10Hz slows down the system significantly, on the other hand too high cut off frequency causes the navigation system collect remarkable noise, so the SNR (signal-to-noise ratio) decreases meaningfully.

Excessive tests of various filters determined that first order Butterworth IIR filters with cut-off frequency in range 10-20Hz are most suitable for the trirotor. They perfectly filter out the signal components of frequency 80-160Hz caused by rotating motors and significantly reduce low frequency noise appearing between 20Hz and 40Hz. What is important, the delay introduced by filters of these order is acceptable by navigation and control algorithms.

#### 4 NAVIGATION

During the research on INS, an efficient, novel algorithm for MARG system was found in [9]. It was a perfect solution due to very low computational load, quaternions internal implementation and high accuracy comparable with KF (Kalman Filter) solutions. The algorithm has been modified in order to provide higher usability and performance. During the first run the algorithm saves the initial orientation which will be a basis for further calculation.

##### 4.1 Orientation

The algorithm firstly calculates the orientation using gyroscopes readings -  ${}^S_E \mathbf{q}_{,k}$ . At this stage there is no correction for drift so the error is accumulating. At the second stage it calculates the orientation using vector measurements from accelerometers and magnetometers. The original algorithm from [9] uses a combination of accelerometers and magnetometers readings, however the modification introduced in this research assumes that a distinctive triple of measurements is provided for any orientation in space by both triaxial accelerometers and triaxial magnetometers. Therefore, the optimization problem from [9] can be extended eventually to:

$$(4.1) \quad {}^S_E \mathbf{q}_{(v,k+1)} = {}^S_E \mathbf{q}_k - k \frac{\nabla f({}^S_E \mathbf{q}, {}^E \mathbf{g}, {}^S \mathbf{a}, {}^E \mathbf{b}, {}^S \mathbf{m})}{\|\nabla f({}^S_E \mathbf{q}, {}^E \mathbf{g}, {}^S \mathbf{a}, {}^E \mathbf{b}, {}^S \mathbf{m})\|},$$

$$k = 0, 1, 2, \dots, n$$

where:

${}^S_E \mathbf{q}_{(v,k+1)}$  orientation calculated from vectors  
measurements  
 ${}^S_E \mathbf{q}_k$  last attitude estimation

S, E – sensor and Earth frame  
k – no. of iteration

and

$$(4.2) \quad f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E, \mathbf{b}^S, \mathbf{m}) = \left[ \frac{f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E)}{f(\mathbf{q}_E^S, \mathbf{b}^S, \mathbf{m})} \right]$$

where:

$$(4.3) \quad f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E) = \begin{bmatrix} 2g_x(\frac{1}{2} - q_3^2 - q_4^2) + \\ 2g_x(q_2q_3 - q_1q_4) + \\ 2g_x(q_1q_3 + q_2q_4) + \\ +2g_y(q_1q_4 + q_2q_3) + 2g_z(q_2q_4 - q_1q_3) - a_x \\ +2g_y(\frac{1}{2} - q_2^2 - q_4^2) + 2g_z(q_1q_2 + q_3q_4) - a_y \\ +2g_y(q_3q_4 - q_1q_2) + 2g_z(\frac{1}{2} - q_2^2 - q_3^2) - a_z \end{bmatrix}$$

$$(4.4) \quad f(\mathbf{q}_E^S, \mathbf{b}^S, \mathbf{m}) = \begin{bmatrix} 2b_x(\frac{1}{2} - q_3^2 - q_4^2) + \\ 2b_x(q_2q_3 - q_1q_4) + \\ 2b_x(q_1q_3 + q_2q_4) + \\ +2b_y(q_1q_4 + q_2q_3) + 2b_z(q_2q_4 - q_1q_3) - m_x \\ +2b_y(\frac{1}{2} - q_2^2 - q_4^2) + 2b_z(q_1q_2 + q_3q_4) - m_y \\ +2b_y(q_3q_4 - q_1q_2) + 2b_z(\frac{1}{2} - q_2^2 - q_3^2) - m_z \end{bmatrix}$$

where:

$\mathbf{a}^S = [0 \ a_x \ a_y \ a_z]^T$  accelerometers normalized readings

$\mathbf{m}^S = [0 \ m_x \ m_y \ m_z]^T$  magnetometers normalized readings

$\mathbf{g}^S = [0 \ g_x \ g_y \ g_z]^T$  gravity field initial orientation vector

$\mathbf{b}^S = [0 \ b_x \ b_y \ b_z]^T$  magnetic field initial orientation vector

which claims

$$(4.5) \quad \nabla f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E, \mathbf{b}^S, \mathbf{m}) = \\ = J^T(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E, \mathbf{b}^S, \mathbf{m}) f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E, \mathbf{b}^S, \mathbf{m}) = \\ = \begin{cases} J^T(\mathbf{q}_E^S, \mathbf{g}^S) f(\mathbf{q}_E^S, \mathbf{g}^S, \mathbf{a}^E) \\ J^T(\mathbf{q}_E^S, \mathbf{b}^S) f(\mathbf{q}_E^S, \mathbf{b}^S, \mathbf{m}) \end{cases}$$

where:

$$(4.6) \quad J^T(\mathbf{q}_E^S, \mathbf{g}^S) = \\ = \begin{bmatrix} 2g_yq_4 - 2g_zq_3 & 2g_yq_3 + 2g_zq_4 \\ -2g_xq_4 + 2g_zq_2 & 2g_xq_3 - 4g_yq_2 + 2g_zq_1 \\ 2g_xq_3 - 2g_yq_2 & 2g_xq_4 - 4g_zq_2 - 2g_yq_1 \\ -4g_xq_3 + 2g_yq_2 - 2g_zq_1 & -4g_xq_4 + 2g_yq_1 + 2g_zq_2 \\ 2g_zq_4 + 2g_xq_2 & -4g_yq_4 + 2g_zq_3 - 2g_xq_1 \\ 2g_yq_4 - 4g_zq_3 + 2g_xq_1 & 2g_yq_3 + 2g_xq_2 \end{bmatrix}$$

and

$$(4.7) \quad J^T(\mathbf{q}_E^S, \mathbf{b}^S) = \\ = \begin{bmatrix} 2b_yq_4 - 2b_zq_3 & 2b_yq_3 + 2b_zq_4 \\ -2b_xq_4 + 2b_zq_2 & 2b_xq_3 - 4b_yq_2 + 2b_zq_1 \\ 2b_xq_3 - 2b_yq_2 & 2b_xq_4 - 4b_zq_2 - 2b_yq_1 \\ -4b_xq_3 + 2b_yq_2 - 2b_zq_1 & -4b_xq_4 + 2b_yq_1 + 2b_zq_2 \\ 2b_zq_4 + 2b_xq_2 & -4b_yq_4 + 2b_zq_3 - 2b_xq_1 \\ 2b_yq_4 - 4b_zq_3 + 2b_xq_1 & 2b_yq_3 + 2b_xq_2 \end{bmatrix}$$

The orientations resulting from accelerometers and magnetometers readings are averaged and denoted as  $\mathbf{q}_{v,k}^S$ .

#### 4.2 Fusion

There are two independent sources of updates for new attitude estimation:  $\mathbf{q}_{v,k}^S$  and  $\mathbf{q}_{v,k}^S$ . Fusion of the two estimates was performed by a complementary filter:

$$(4.8) \quad \mathbf{q}_k^S = (1 - \beta) \mathbf{q}_{(v,k)}^S + \beta \mathbf{q}_{(v,k)}^S, 0 \leq \beta \leq 1$$

The complementary filter after derivation performed in [9] has a following form:

$$(4.9) \quad \mathbf{q}_k^S = \mathbf{q}_{(v,k)}^S - \frac{\nabla f}{\|\nabla f\|}$$

Which is equal to:

$$(4.10) \quad \mathbf{q}_k^S = \mathbf{q}_{(v,k)}^S - \frac{\nabla f}{\|\nabla f\|}$$

And leads to:

$$(4.11) \quad \mathbf{q}_k^S = \mathbf{q}_{(k-1)}^S + \mathbf{q}_k^S \Delta t$$

The parameter  $\beta$  was found during the experiments, providing fast algorithm reaction for rapid changes along with good drift correction in long run.

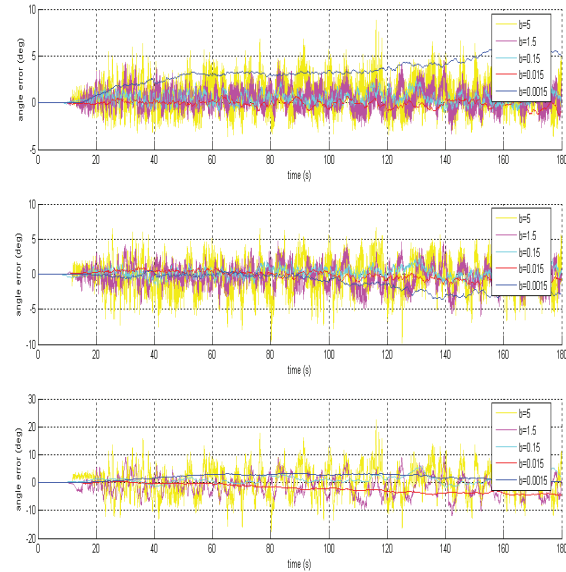


Figure 7: Influence of parameter  $\beta$  on performance of navigation algorithm.

Tests were performed while ADIS16400 was mounted on trirotor frame, motors were running and filtering was applied. The measure used to evaluate algorithm performance was root mean square error (RMSE). It was calculated over the interval 0-180s for each axis separately. Eventually, the arithmetic mean of these values was computed and was presented in the table 2:

|               | RMSE    |        |         |         |
|---------------|---------|--------|---------|---------|
|               | x-axis  | y-axis | z-axis  | mean    |
| <b>0.0015</b> | 12.5147 | 2.5062 | 4.6179  | 6.5463  |
| <b>0.015</b>  | 0.1301  | 0.3954 | 6.2707  | 2.2654  |
| <b>0.15</b>   | 0.6223  | 0.4473 | 2.6729  | 1.2475  |
| <b>1.5</b>    | 1.3319  | 2.3426 | 12.1701 | 5.2815  |
| <b>5</b>      | 3.0773  | 4.5904 | 25.1942 | 10.9540 |

Table 2: RMSE of navigation algorithm with various values of parameter  $\beta$ .

The parameter  $\beta$  determines how big is the influence of vector measurements on the final result. For small values of  $\beta$ , the navigation performance was affected by gyros drift that could not be compensated by absolute vector measurements. For large values of  $\beta$ , the drift correction overshoots the exact solution causing the optimization algorithm operate far from the optimal solution. The tests have shown that the value of  $\beta$  should be close to 0,15 in order to provide highest navigation system performance.

## 5 CONTROL SYSTEM

System state is estimated according to the measurements obtained from a MARG sensors array. As it was already shown, ADIS16400 provides information about current angular velocity, linear acceleration and magnetic field orientation, with sample rate up to 819,2Hz. The raw readings are processed by a navigation algorithm which outputs the information about current UAV orientation.

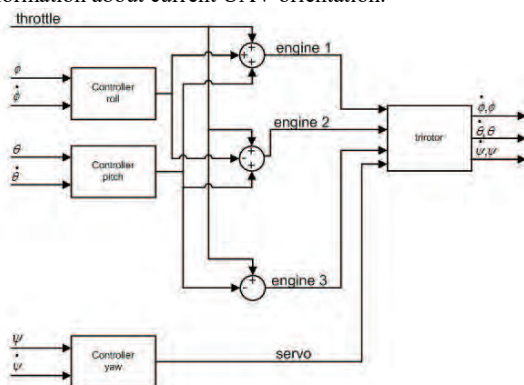


Figure 8: General system structure.

It is important to note, that the raw measurements, especially angular velocities, are of much faster dynamics than the attitude orientation returned by navigation algorithm. The reason is that they are measured directly by sensors, while the navigation algorithm introduces some extra dynamics.

The objective of the control algorithm for trirotor was stabilization of angles, in other words, ability to track and maintain given roll, pitch and yaw angles. The control system was decoupled and as a result each of the axes has a separate control algorithm. Three control algorithms return separate inputs for three motors and servomechanism which need to be combined together with throttle signal in a mixer. The general system structure is presented in the figure 8.

According to the research on existing control systems for UAVs and investigation of measurements characteristics a PID cascade was chosen for realization of trirotor control algorithm. An example of the control system of roll angle is presented in the figure 9.

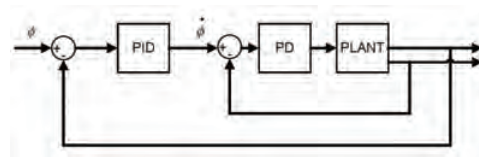


Figure 9: Control schema for roll stabilization.

The structure of controller chosen for the internal loop is of type B with filtered derivative [10]. The type B structure was selected in order to avoid undesired overreactions on changes in setpoint. Moreover, a filter in the derivative term provides additional control quality improvement. This loop guarantees quick reaction on disturbances in the system and eases tuning of the inherently unstable system. The outer loop, similarly to the inner one, is of type B with filtered derivative, however, there are some modifications introduced. The first modification concerns the way the setpoint changes are applied to the system. The main concern behind it is to reduce the overshoot when the setpoint varies rapidly. One method to avoid this problem would be to use type C PID controller. Although it removes the overshoot, it might be too slow for aerial vehicle, because the desired value is being tracked only by the integral term. The method that was implemented in the trirotor algorithm is a low-pass filter which reduces the speed of change of the setpoint to 10deg/s which is slow enough to avoid peak reaction of proportional term, and on the other hand, fast enough to provide high UAV performance. The second algorithm enhancement is a double anti-windup protection system. It limits the maximal value of error that supplies the integral part and defines lower and upper bound for the integral term value. The third enhancement of the algorithm is a filter in derivative term.

## 6 TESTS RESULTS

The tests were performed in order to examine whether all components are working properly and stabilization of trirotor attitude is possible. The ability to maintain a given setpoint for at least 60 seconds was tested for each axis separately using a specialized stand that limited the number of degrees of freedom to one. The tuning process followed cascade systems tuning rules i.e. the inner loop was tuned to have possibly high proportional and derivative gain. These setting provided good rejection of disturbances appearing in the inner loop.

Secondly, the outer loop having slower dynamics was tuned so, that the trirotor was able to maintain a given setpoint. Tests results were satisfactory, the trirotor was able to hold a given setpoint for unlimited time. The tests results are shown in figure 10.

Once the trirotor was capable of maintaining a given, constant setpoint it was tested against step changes in setpoints. The gains required slight modifications in order to prevent a overshoot to occur and provide damping of oscillations. The tests have proven that the trirotor is properly tracking changes in setpoints in all axes. The results are presented in the figure 11.

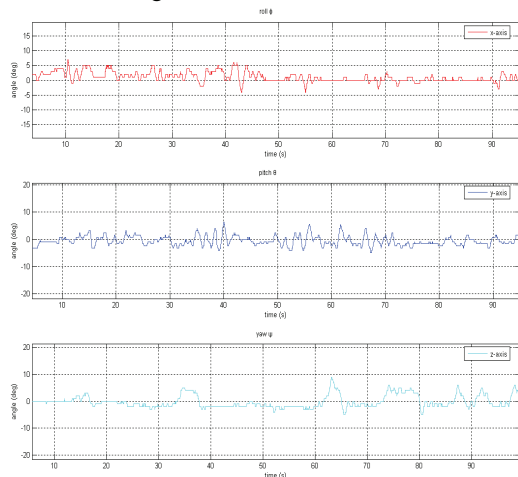


Figure 10: Euler angles during the hover flight.

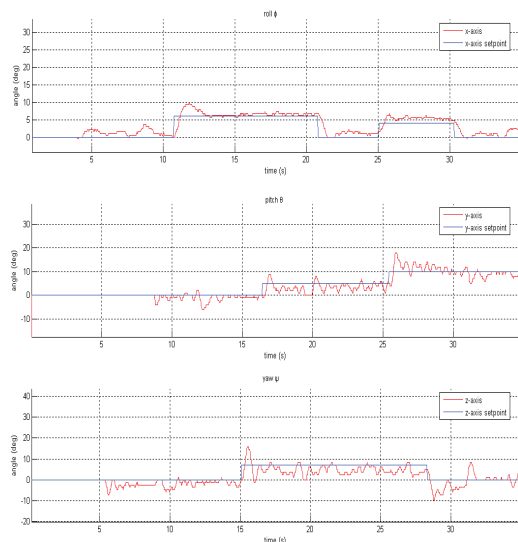


Figure 11: Tracking of the Euler angles desired values.

## 7 CONCLUSIONS

In this paper we have presented the whole trirotor system, beginning with the mechanical construction and then through the electronics till the control algorithm implementation at the last stage. The trirotor aerial robot can make possible of plenty of potential applications for unmanned aerial vehicles.

An approach to hardware implementation of the navigation algorithm, as well as control algorithm has been described. The navigation algorithm based on accelerometers, gyroscopes and magnetometers combined with the cascade control structure provides good stabilization during the different flight conditions. The trirotor is able to maintain given orientation as well as track the changes of the Euler angles. The practical realization of the attitude stabilization system is an important step in the development process of more advanced functionality of the autonomous flying vehicles. First attempts to outdoor flights were very promising and achieved results are satisfactory.

## ACKNOWLEDGEMENTS

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