INTEGRATION OF VECTOR MAGNETOMETER MODULE ON BOARD OF SMALL UAV

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The aim of this contribution is a proposal of vector magnetometer module implementation on board of small Unmanned Aerial Vehicle (UAV) also with proposal of software integration of magnetometer information and other inertial measurements. This contribution also include proposal of printed circuit boards of modular IMU. The results of solved issue represent the fundamental concept of simple navigation and stabilization algorithms in form of inertial measurement unit and program solution. Results based on these ideas and realizations are in graphical form explained at the end of contribution, focusing on examples of heading angle and Kalman filter estimation.

K e y w o r d s: Unmanned aerial vehicle, navigation, Kalman filter, complementary filter, integration algorithms

1 INTRODUCTION

Area of integration solutions and their subsequent implementation in a wide range of aerial applications are among the still relevant objects of interest. Development of on-board navigation algorithms passed over the last few decades of rapid growth, the accuracy and performance of these systems is still determining variable in an actual development of aerial vehicles. Topicality of the issue is contingent on a long-term trend of increasing the accuracy of systems, requirements increase the speed of data processing and new technology in the processing and integration of information. This contribution is divided into two parts. For meeting of these objectives was required the proposal of theoretical analysis and design, choice of target mechanical arrangement and the choice of components also with sensors. The issue of algorithms required to achieve the objectives in the form of filter analysis, estimation algorithms and transformation methods that lead to the overall design of information processing by using vector magnetometer. Given the intention to propose a widely applicable system and create a platform for programming basis of simple navigation and stabilization algorithms, where Kalman filter is used.

2 PROPOSAL OF INERTAL MEASUREMENT UNIT

Proposal of an inertial measurement unit capable for required navigation within the expected navigation tasks is an important step of quality, which has a global impact on composition and navigational skills of object in which the unit will be applied. IMU used in aerospace applications are complex, and due their size and economic demands unusable for "low - cost" systems, where a simple UAV also belongs. One of the objectives of this work is to design printed circuit board for the IMU usable on board UAVs, which combines the basic properties of the measuring unit and miniaturizes dimensions, weight and power requirements, while its performance is comparable to commercially available IMU. The following figure is an example of the basic concept of the IMU, which is designed taking into account the above assumptions.

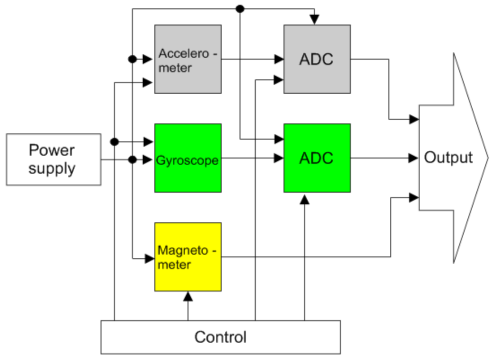

Figure 1. Proposed Inertial Measurement Unit for UAV

The goal of the concept is to create an arrangement of sensors that will not cause mutual interference of elements, while the proposed concept is focused to the dimensional requirement of miniaturization. In this case, the basis of the IMU has three modular parts, in which the individual accelerometers and gyroscopes are arranged to form the desired functional three-axis system. The following table summarizes the used sensors and their selected characteristics [1][2].

Tab. 1. Overview of sensor parameters

	ADXL335	HMC5983	L3G462A
Power supply [V]	1,8 – 3,6	2,16 – 3,6	3
Nonlinearity [%] FS	± 0,3	± 0,1	± 0.5
Range	± 3 g	± 8 gauss	± 625 dps
Temperature range [°C]	-40 to 85	-40 to 85	-40 to 85
Frequency range [Hz]	X, Y: 1600 Z: 550	0,75 - 220	140
Sensitivity	270 – 380 mV/g	270 – 1370 LSB/gauss	2 mV/dps

Due to the requirement of accuracy and rapid processing of data converters was chosen simultaneous sampling with parallel connected inputs, so the effort is the reduction of error signal processing in progressive sampling. Simultaneous access to information and results of inertial measurement reduces errors and time shift between the measurements that are considered in subsequent calculations at the same time. A / D converter AD 7606-6 from Analog Devices with a resolution of 16 bits and a six inputs was chosen as the best and most accessible in terms of design and ability of simultaneous sampling. Following properties are important for whole proposal and UAV application [6].

- modularity
- power supply
- filtration
- simultaneous sampling
- microcontroller

Modular approach allowed, at the expense of the size of the resulting proposal, to use multiple sensors of the same type and orientation, which increases the quality of statistical processing of measured data. The mechanical arrangement of the elements and the overall design choice had a significant impact on minimizing the ratio of random noises that degrade inertial measurement. The particular arrangement and number of sensors allowed us to reduce the noise, but also allowed the application of various other algorithms to improve the signal – noise ratio at the input to the computing units.

In the following figures are given PCB of proposed modular IMU unit that are designed taking into account the above requirements.

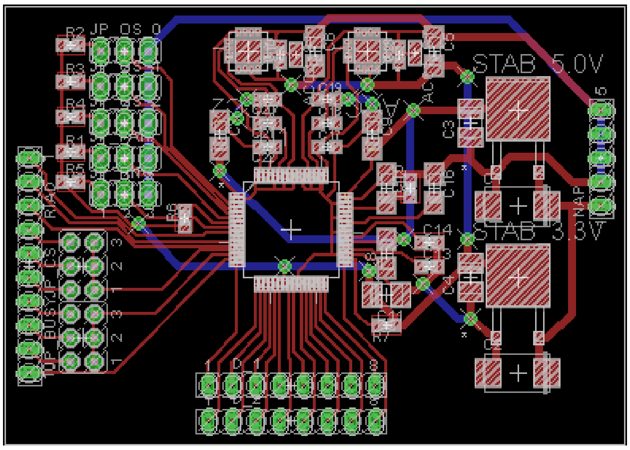

Figure 2. Printed circuit board of accelerometer module

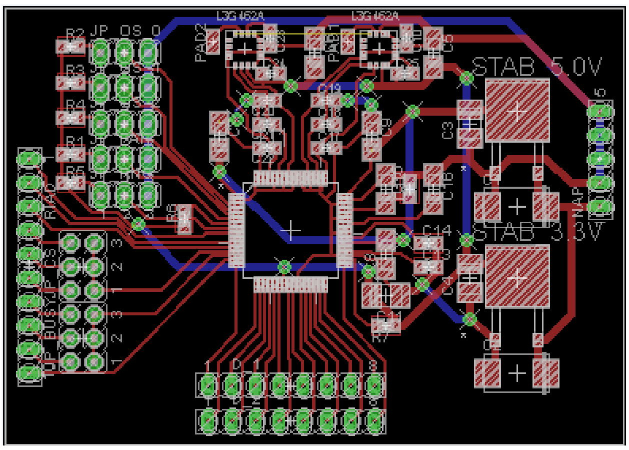

Figure 3. Printed circuit board of gyroscope module

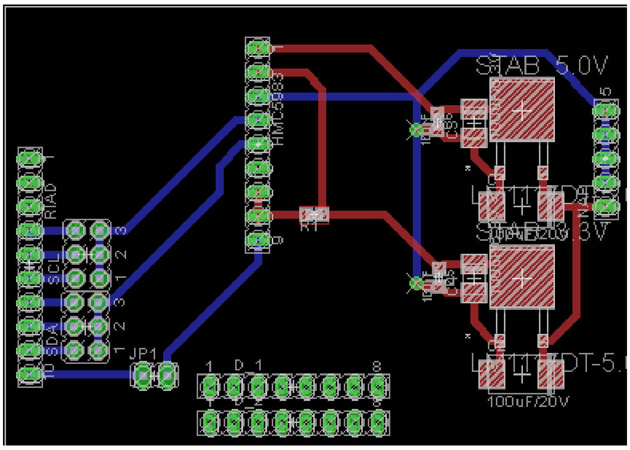

Figure 4. Printed circuit board of magnetometer module

In the case of accelerometer and gyroscope module are used analog outputs. The signal from the output of these sensors is fed into the corresponding A / D converter, the internal characteristics are set according to the requirements of the particular application. Application of converter AD7606 - 6 ensures desired simultaneous sampling. In case of magnetometer is used sensor with digital output according to availability and price of sensors in this category. Scheme design of individual modules include, in case of accelerometer and gyroscope, two for each case. This option is contingent on efforts to suppress noise by averaging the outputs of the two sensors. The real application based on these proposals would also contain a software backup solution in case of failure of one of the pair of sensors that would be considered as primary. Another advantage in terms of analysis of the characteristics of an inertial measurement unit is possibility of modules creation with different sensors of a particular type and their rapid implementation on board. More economical use is also breakout form, which is used in the design of the magnetometer module [7][8].

3 PROPOSAL OF IMPLEMENTATION ALGORITHMS

Program proposal of inertial measurements and magnetometer data processing was dependent on the premise application for which program was constructed. Due to the requirement of further use of the program for the stabilization problem of small UAVs was the software solution designed to calculate and estimate parameters that are important in this issue. With availability of inertial and magnetometer information, there were many variants of integration processes that lead to the desired goal in the form of the calculated or estimated parameters. Level of complexity, the requirements on the ability of the proposal to cover the dynamic properties of the target object and accuracy are important attributes in the actual program proposal. During program proposal was necessary to pay attention for real possibilities of using the program, this is why C++ program environment was used for this proposal. This in many ways corresponds to the platforms that use today available microcontrollers. Proposed program script, for which it is necessary to incorporate the ability to work with real data at the required processing speed, must be able to exhibit some variability associated with the transcription to the selected microcontroller. At the level of this work, completed program proposal also included text source files with inertial and magnetic field data. In the following figure is shown a block diagram of the proposed integration algorithm, which uses all information sources for achievement of desired results.

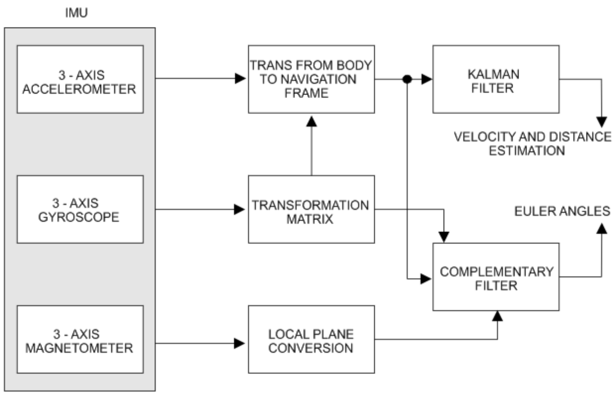

Figure 5. Block diagram of integration algorithm

Block diagram in Fig. 5. uses all sources of inertial information. Using of complementary filter was chosen for calculation of position angles, and this represents the filter element allowing data fusion. Heading angle evaluation is based on fusion of magnetometer and gyroscope data, other attitude angles are based on fusion of accelerometer and gyroscope output information. Estimate of distance was provided by two - state Kalman filter, these parameters are determined in each axis using a special filter. In terms of navigation application of the algorithm described in Fig. 5 on board of the UAV was also necessary to clarify the issue of coordinate systems. All sources of measured values, which are further processed by the algorithm, are measured on board of aerial vehicle. In terms of theoretical knowledge, we assume that these information are measured in the body coordinate system. For estimation and calculation of various parameters, it was necessary to express the system in which they can be evaluated by an observer. Therefore, as the observer system was selected navigation coordinate system. The angular rate and acceleration between transformation systems represent the input for filters. This procedure was rewritten into a coherent program code that can work within the scope of this process with defined sequence of measurement results from the text file, or specific arrangements are used for the application in microcontrollers. Attention was focused on the output of the complementary filter, particularly on the results of the heading angle evaluation process. This parameter was selected as a priority in terms of fulfilling one of the basic ideas of this contribution. In this case was also described the projection of the particular measurements to the horizontal plane of the magnetometer. For appropriate evaluation of heading angle was necessary to suppress other angles effect and achieve value of heading in horizontal plane.

As mentioned in previous chapters, all values of observed variables are measured in the body coordinate system. In addition to these data, for transformation between two selected coordinate system is also necessary to consider the rotation issue of coordinate systems. Due to process of transformation and quantification of parameters in the selected navigation coordinate system, it is necessary to establish the transformation matrix. The relationship between these systems is defined by the Euler matrix of a particular mathematical expression. Transformation at this level, however, due to the motion of an object in space is not sufficient. Maneuvering object in space causes a change in the relative positions of the considered systems respectively. The aim of the solution was to find the derivative transformation matrix, which generally leads to solutions with anti - symmetric matrix. For transformations, which are based on the matrix of the Euler angles, is the evaluation procedure different. Detailed derivation and clarifying issues dealing with numerous publications. The solution is based on the creation of so-called temporary coordinate system, which after subsequent adjustments leads to the following relationship [1]:

$$\omega_{nb}^{n} = \begin{bmatrix} \omega_{nb}^{nx} \\ \omega_{nb}^{ny} \\ \omega_{nb}^{nz} \end{bmatrix} = \begin{bmatrix} 1 & s(\phi)t(\theta) & c(\phi)t(\theta) \\ 0 & c(\phi) & -s(\phi) \\ 0 & \dfrac{s(\phi)}{c(\theta)} & \dfrac{c(\phi)}{c(\theta)} \end{bmatrix} \begin{bmatrix} \omega_{nb}^{bx} \\ \omega_{nb}^{by} \\ \omega_{nb}^{bz} \end{bmatrix} \quad (1)$$

Following picture summarizes steps of program implementation, where the result of evaluation is Euler matrix necessary for transformation of accelerations from body to navigation coordinate frame.

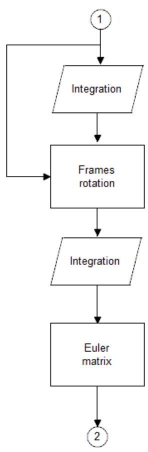

Figure 6. Euler matrix solution steps

The procedure summarized in Fig. 6 is the program implementation, which calculated Euler matrix from available data necessary for further operations. In this illustration is the input to the sub-1 algorithm angular velocity vector measured on board of the object, while output 2 is already mentioned Euler matrix. Such modified acceleration values, which were governed by the angular position of the object in space, entering the Kalman filter. This mathematical tool was used to estimate values of acceleration, which result was the estimate of the distance and speed of the object relative to the starting point of the measurement. The model of the Kalman filter is as follows [2][3].

$$x_k = \begin{bmatrix} p_k \\ v_k \end{bmatrix} = \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p_{k-1} \\ v_{k-1} \end{bmatrix} + \begin{bmatrix} t^2/2 \\ t \end{bmatrix} a_k + \begin{bmatrix} t^2/2 \\ t \end{bmatrix} w_{k-1} \qquad (2)$$

$$z_k = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p_{k-1} \\ v_{k-1} \end{bmatrix} + v_k \qquad (3)$$

Determination of the Q and R matrices is based on knowledge of the noise, i.e. standard deviation of the measured acceleration in each axis. For determination of these covariance matrices is necessary to calculate the noise characteristics of sensor for each iteration.

Another part of the program proposal is a branch of complementary filter. Due to the availability of three outputs, it was necessary to choose which information is source for one of used filters. In this case, the complementary filter was the object of sensor fusion for the purpose of desired output information clarification. In this case, the input information was represented by attitude angles. In terms of design and knowledge of mathematical tools used in case of transformations of coordinate frames, there were a lot of practice solutions. For solution of sensor fusion are in this case used following relationships [4][5]:

$$\theta_{(k)} = \left(k\left(\theta_{(k-1)} + \left(\omega_{y(k)}\,T\right)\right)\right) + \left((1-k)\,\theta_{ACC(k)}\right) \qquad (4)$$

$$\phi_{(k)} = \left(k\left(\phi_{(k-1)} + \left(\omega_{x(k)}\,T\right)\right)\right) + \left((1-k)\,\phi_{ACC(k)}\right) \qquad (5)$$

$$\psi_{(k)} = \left(k\left(\psi_{(k-1)} + \left(\omega_{z(k)}\,T\right)\right)\right) + \left((1-k)\,\psi_{MAG(k)}\right) \qquad (6)$$

In relations (4) - (6) is used combination of two types of information, which led to desired evaluation of angle information. For determination of the rate ψ was chosen combination of values from the gyroscope and magnetometer, where the first source was considered as high-frequency source and second as the low-frequency source. In the case of determining the pitch θ and roll Φ was used the combination of data from accelerometer and gyroscope, where accelerometer acted as a source of low frequency information. In relations performs filter coefficient k, the angular velocity about the axis ω, sampling period T and angles $\psi_{MAG\,(k)}$, $\Phi_{ACC\,(k)}$ and $\theta_{ACC\,(k)}$ calculated from the low-frequency sources. These angles can be relatively easily determined using the selected function. Program implementation required conversion of these angles in each iteration based on the available information in the form of low-frequency acceleration or magnetic field strength.

$$\psi_{MAG(k)} = \left(atan2\left(\frac{H_y}{H_x}\right) * \left(\frac{180}{\pi}\right)\right) \qquad (7)$$

$$\theta_{ACC(k)} = \left(atan2\left(\frac{a_x}{a_z}\right) * \left(\frac{180}{\pi}\right)\right) \qquad (8)$$

$$\phi_{ACC(k)} = \left(atan2\left(\frac{a_y}{a_z}\right) * \left(\frac{180}{\pi}\right)\right) \qquad (9)$$

The above relations (7) - (9) represent the method of calculating of the angles from sources of low-frequency information supplied to the complementary filter itself, represented by Equation (4) - (6). The term H in relation (7) performs magnetic field strength in the individual axes, corresponding accelerations in each axis are used to calculate the pitch and roll. Graphical explanation of this numerical procedure is as follows.

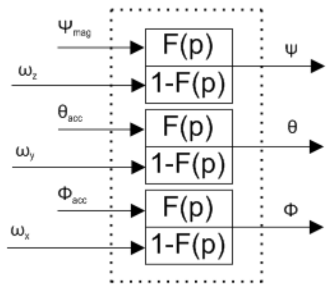

Figure 7. Complementary filter for attitude angles

In Fig. 7. is shown the basic concept of complementary filtering also with transfer functions. Individual low and high frequency information were entering this filter through these transfer functions, and the result is evaluation of each angle based on sensor fusion.

4 VERIFYING OF PROPOSED ALGORITHM AND GRAPHICAL RESULTS

The block of transformations is shown in Fig. 5 and algorithmic approach of the solution in Fig. 6. To verify the function of this block were performed measurements, where user moved with IMU successively in the directions x, y and z. Then followed the same sequence of rotation about all three axes. This section shows the transformation of acceleration in the direction of the x axis from aircraft to navigation coordinate system. The following illustration shows the acceleration values before and after the transformation.

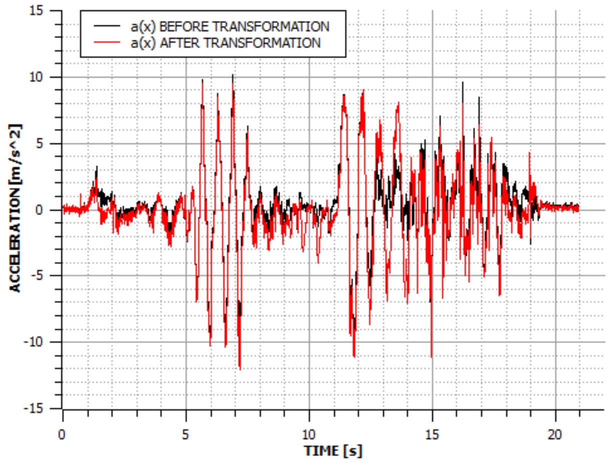

Figure 8. Transformation of "x" acceleration

For verification of the complementary filters performance was used inertial measurement unit IMU 9DOF. Measurements to verify the correctness of determining angles were held separately. IMU rotation around the selected axis was recorded in a text file. Valuable inputs in the form of a text file were given into the program to the corresponding complementary filter. The following figure shows the output of the complementary filter for measuring the course.

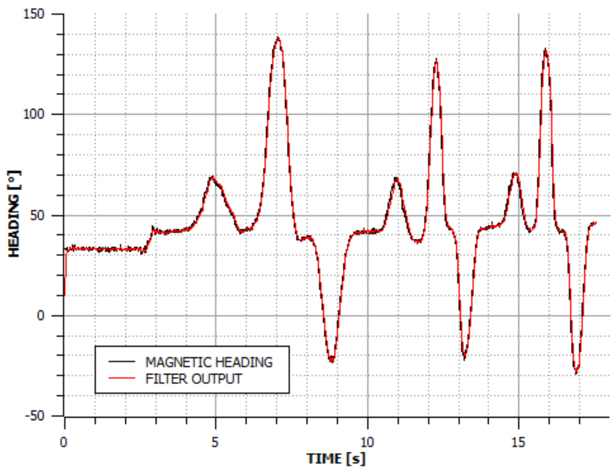

Figure 9. Evaluation of heading angle

Verification of Kalman filter function based on this model was also provided by using of IMU 9 DOF unit. Following pictures represent the estimation of the distance and velocity of object in *x* – direction of movement.

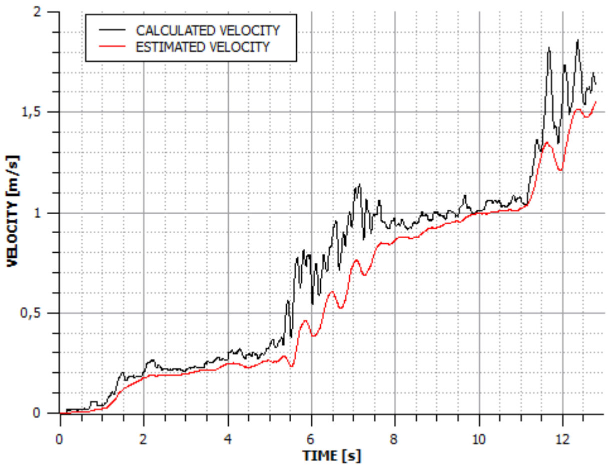

Figure 10. Estimation of velocity in x – direction

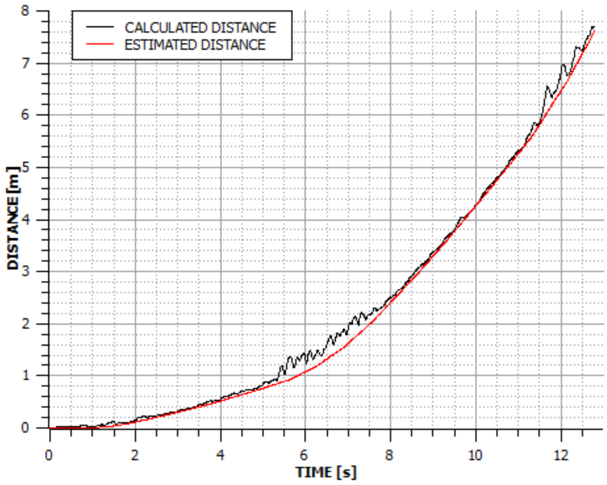

Figure 11. Estimation of distance in x – direction

5 CONCLUSION

The content of this contribution is the design of the inertial measurement unit with program processing of the vector magnetometer information, which would be applicable on board UAVs. Implementation is based on schematic design of an inertial unit and program proposal, which uses the available inertial and magnetic field data for the purpose of calculating selected parameters and their refinement through the proposed sensor fusion. The results of this program solution are also listed in this contribution in graphical form. Proposed measuring unit, as well as proposal of algorithm is useful as a basic building block for a follow-up measurement algorithms and applications usable on small UAVs. Significant results are schematic design of the IMU, which meets several characteristics of today's demands for this type of measuring device. Similarly software solution that uses all available sources of information, achieved the expected results and also demonstrates the idea of sensor fusion.

ACKNOWLEDGEMENT

This work has been supported by the grant agencies of Slovak Republic under the grants KEGA 028TUKE-4/2013, VEGA 1/0286/13 and APVV-0266-10.

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