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SENSORIC SUBSYSTEM DESIGN FOR SMALL MODEL OF HELICOPTER

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ABSTRACT

The paper deals with hardware design for sensoric subsystem of a small helicopter model and in real time generates data about helicopter state variables during helicopter flight. The main unit for data processing presents an embedded computer built on a mini-ITX motherboard with processor Intel i3. As the helicopter presents a system with six degrees of freedom and in the fact, during the flight, there is not any fixed point that would enable to calibre the sensors placed on the helicopter board, for processing of sensor data Kalman filter is necessary.

Keywords: *Kalman filters, ADIS16405, navigation, sensoric system, helicopter*

1. INTRODUCTION

Navigation presents a very old art which has become a complex science. It is essentially about finding the right way of a body from one place to another and there exist many possibilities to achieve this objective.

The operation of inertial navigation systems depends upon laws of classical mechanics as were formulated by Sir Isaac Newton. For example, if given the ability to measure acceleration, it would be possible to calculate the change in velocity and position by performing successive mathematical integration of the acceleration with respect to time. In many sensoric subsystems the inertial sensors are mounted on a stable platform and are mechanically isolated from the rotational motion of the vehicle. Modern sensoric subsystems have removed most of the mechanical complexity of platform systems by attaching the sensors rigidly, or "strapped down" to the body of the vehicle. The potential benefits of this approach are lower cost, reduced size and greater reliability. The major disadvantage consists in increase of computing complexity. At present the tasks of strapdown inertial navigation [1] are used in modern robotics systems.

Current development of considerably cheap MEMS sensors [2] and powerful processors enable to implement techniques of inertial navigation [3, 4] into a light-weight and powerful equipment. One of new promising way is based on utilization of small commercial mini-ITX boards with the Intel processors that allow to install an arbitrary operational system and to utilize its advantages for data processing.

In the contribution we describe development of a sensoric system hardware placed on board of a real helicopter model (Fig. 1) enabling to process and evaluate flight data. Based on input vector and sensed output vector components it is possible to derive a fuzzy model of the system. Computing the state vector based on data collected from various sensors is performed in real-time. This solution was chosen due to a possible implementation of the sensoric system into a real-time control system what we are going to perform in next step of our research.

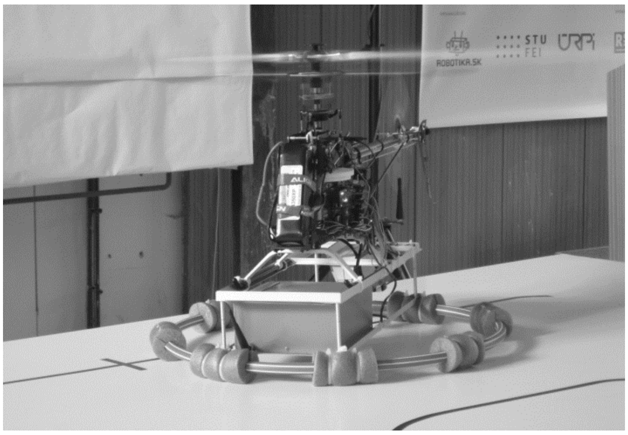

Fig. 1 Small model of a helicopter T-REX 600

The debugged program is based on the Linux operational system, utilization of the GNU Scientific Library [5], and subsystems utilizing powerful 32-bit processors with the cores ARM7 and Cortex-M3 [6].

2. EQUATIONS FOR STRAPDOWN INERTIAL NAVIGATION

As it is mentioned above the inertial navigation is based on Newton differential vector equations that can be expresses in the form (Eq. 1-4)

$$\dot{P}_e = T_{BE}^{-1}(\Phi,\theta,\psi)V_b = T_{BE}^{-1}(\alpha_e)V_b, \tag{1}$$

$$\dot{V}_b = M_b^{-1}\left[F_{cg} - \omega_b \times (mV_b)\right], \tag{2}$$

$$\dot{\omega}_b = I_n^{-1}\left[M_{cg} - \omega_b \times (I_n\omega_b)\right], \tag{3}$$

$$\dot{\alpha}_e = E^{-1}(\Phi,\theta)\omega_b = E^{-1}(\alpha_e)\omega_b. \tag{4}$$

where:

T_{BE} – matrix of transformation from the earth frame to the body frame
P_e – position vector in regard to earth frame
V_b – vector linear velocities regarding to the body frame (u, v, w)
ω_b – vector of angular speeds regarding to the body frame (p, q, r)
α_e – vector of body orientation regarding to the earth frame, components Euler's angles (Φ, Θ, ψ)
E – transformation matrix of angular speeds
M_b – diagonal matrix of dimension 3x3, where the elements are created by total mass of the body
I_n – matrix 3x3 representing distribution of the mass along particular axes: its elements consist of moments of inertia relative to particular axes
F_{cg} –vector of resultant forces reduced to the centre of gravity of the body
M_{cg} –vector of resultant torques reduced to the centre of gravity of the body

These equations are valid for an arbitrary body with 6 degrees of freedom situated in the space. The vector α presents the body orientation in respect of our reference coordinate system that is identical with the Earth coordinate system. Resultant forces F_{cg} and resultant torques M_{cg} presents external forces/torques created by the forces and torques generated by actuator of mechatronics system. In our case it is by the main rotor and tail rotor of the helicopter. The most important vector for navigation is the vector P_e presenting the position of the body in the environment.

3. HARDWARE DESIGN

The main computing unit is created by a small embedded computer based on a motherboard mini-ITX with the processor Intel i3. Advantage of the motherboard consists in integrating the supply unit with the board, so to supply the motherboard it is enough to connect a stabilized voltage 19 V with the tolerance of ±10 %. The supply source consists of five Li-pol accumulators. The control computer communicates with other subsystems through USB interfaces that are converted into the RS422 bus. To eliminate vibrations during flight, the motherboard is fixed by small shock absorber blocks (Fig. 2).

Fig. 3 shows the block interconnection of particular subsystems and control computer. Four printed boards with electronics that fulfil individual tasks are connected to the motherboard.

The main board presents a communication, supply, and control node. Embedded linear stabilizers ensure supply of servomotors for cyclic control of the helicopter; further they ensure supply of components of the board itself and they also supply other parts of the sensoric system. To the board there are connected USB busses from the control computer that are converted into the signals of the RS422 form.

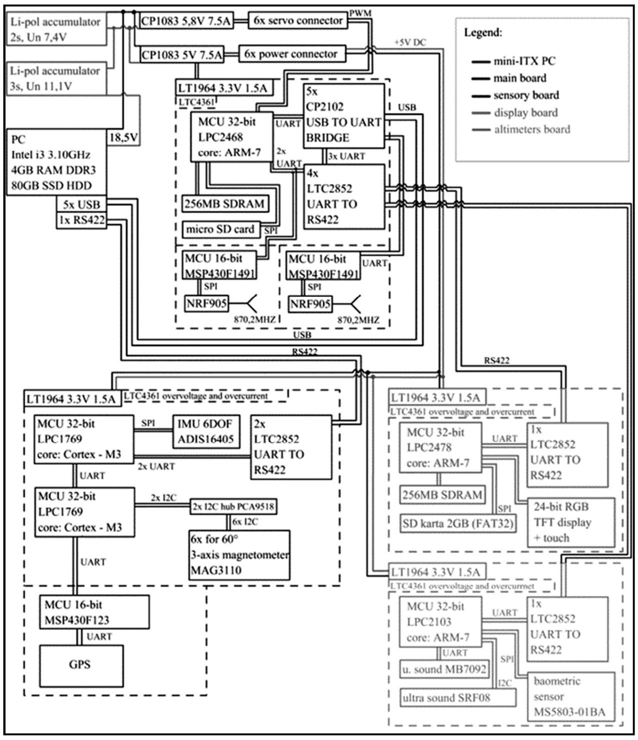

Fig. 3 Interconnection of subsystems in the control system

Communication with the operator is ensured by small high-frequency transceivers NRF905 embedded on small of printed circuit boards that are connected to the main board by connectors (Fig. 4).

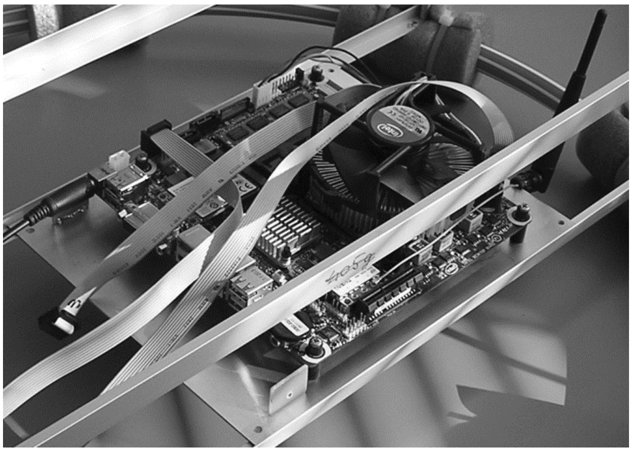

Fig. 2 Fixing the motherboard to the helicopter frame

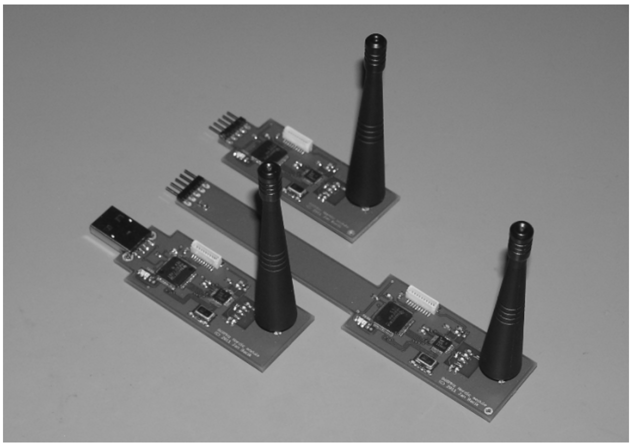

Fig. 4 Communication modules (high-frequency transceivers)

The processor accepts control signals from the operator and then it generates the control signals for the servomotors of cyclical control.

A small 24-bit TFT display embedded by a resistant touch panel creates graphical user interface (GUI). Observing it the operator sees basic data the about helicopter state and he is able to set up file name and storage site for collected data during the helicopter flight.

Among important subsystems for model identification based on experimental data there are two boards: a board of artificial horizon and board of altimeter. The main sensor of the altimeter horizon board is the sensor ADIS16405, that presents a complete inertial systems including triaxal magnetometer, triaxial accelerometer, and triaxal gyroscope with digital data output. The board is also embedded by sextuplet of triaxial magnetometers of the MAG3110 type (their arrangement is shown in Fig. 5) that serve to real-time computation of calibration data for the magnetometer installed in the sensor ADIS16405. The calibration data are computed by fitting ellipsis of the magnetic field vector trajectory. Due to presence of ferromagnetic materials in close surrounding of the sensors an ideal circular vector trajectory is deformed to an elliptical one (it is so called „hard and soft iron effect“).

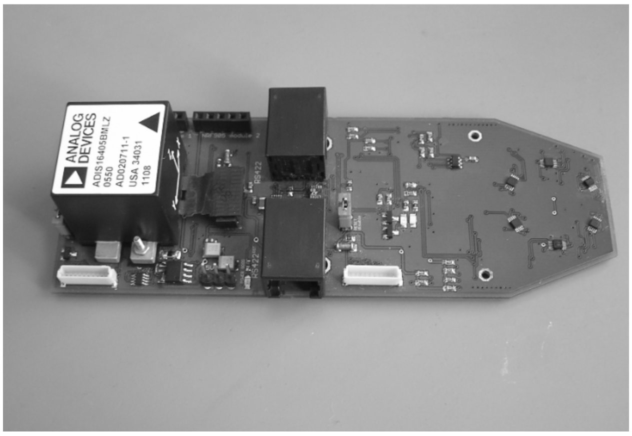

Fig. 5 Placement of sextuplet of calibration magnetometers

The last sensor installed on the artificial horizon board there is a GPS receiver. The altimeter board includes ultrasound sensors by using which one can estimate helicopter model speed in the z-axis. These sensors are fixed on a two-axis gimbal ensuring a continuous direction of sound waves vertically to the earth. For flight levels determination and filtering out a terrain ruggedness there serves a small pressure sensor.

Data from gyroscope serves as information about angular rates of the helicopter and its orientation towards the earth is based on Euler angles as follows for:

$$\bar{\omega}_{mesured} = \bar{\omega}_{real} + \bar{B}_{(t)} + \bar{v}\,. \tag{5}$$

The data are disturbed by a nose and time-variable bias that bring an error in correct computation of required variables. This is a reason why for the proper data processing the higher harmonics components are filtered by a low-frequency filter. Estimated Euler angles are computed as for each axis follows:

$$\begin{bmatrix} \widehat{angle}_{k+1} \\ \widehat{bias}_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & -dt \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \widehat{angle}_{k} \\ \widehat{bias}_{k} \end{bmatrix} + \begin{bmatrix} dt \\ 0 \end{bmatrix} \omega_e, \tag{6}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \widehat{angle}_{k} \\ \widehat{bias}_{k} \end{bmatrix} + v. \tag{7}$$

Here the measured output vector *y* for the x and y axes presents the angles calculated from the raw accelerometer data using gravitation vector filtration:

$$\Phi = atan2(g_{Y_b}, g_{Z_b})\,, \tag{8}$$

$$\theta = atan2(-g_{X_b}, g_{Z_b})\,. \tag{9}$$

The measured output *y* for the z axis yaw (ψ) there is the angle calculated from magnetometer data. *Mag_Y$_e$* is native data of magnetometer of axis y in Earth frame, *mag_Z$_e$* is for z axis.

$$\psi = atan(\frac{mag\_Y_e}{mag\_Z_e}) \tag{10}$$

The linear speeds *u, v, w* are estimated by the triaxial accelerometer output signals. From the accelerometer scalar equation for one axis

$$a_{meas.} = g + a_{real} + B + SFgcos\varphi + K(gcos\varphi)^2 + v \tag{11}$$

it follows that the accelerometer output except of the bias (*B*), scale factor (*SF*), g-squared sensitive drift (*K*), and own noise (*v*) is also influenced by a gravitation force component *g*. Due to this reason it is necessary to filter out this component of acceleration. The filtering runs in two steps:

In the first step the data from accelerometer are re-counted from the body frame to the earth frame using the rotation matrix that contains Euler angles estimated by the discrete Kalman filter. From the data there is subsequently subtracted the gravity acceleration vector having the components [0, 0, *g*]

$$\overline{accl\_data_e} = T_{BE}^{-1}\overline{accl\_data_b}\,, \tag{12}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_e = \begin{bmatrix} accl\_data_x \\ accl\_data_y \\ accl\_data_z \end{bmatrix}_e - \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}_e. \tag{13}$$

In the second step of the procedure the vector of linear acceleration vector is transformed into the body frame from reason of expressing the gravity acceleration vector in the body frame that we want to filter:

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_b = T_{BE} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_e, \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}_b = \begin{bmatrix} accl\_data_x \\ accl\_data_y \\ accl\_data_z \end{bmatrix}_b - \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_b \tag{14}$$

Acquirement of the speed vector components runs on basis of estimation of these values by a similar discrete Kalman filter like that one used for estimation of the Euler angles:

$$\begin{bmatrix}\widehat{speed}_{k+1}\\ \widehat{bias}_{k+1}\end{bmatrix} = \begin{bmatrix}1 & -dt\\ 0 & 0\end{bmatrix}\begin{bmatrix}\widehat{speed}_{k}\\ \widehat{bias}_{k}\end{bmatrix} + \begin{bmatrix}dt\\ 0\end{bmatrix} a_E \, , \qquad (15)$$

$$y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\widehat{speed}_{k}\\ \widehat{bias}_{k}\end{bmatrix} + v \, . \qquad (16)$$

Here, as the measured output y there serves: in the x and y axis the speed derived by the GPS receiver and in the z axis the speed derived using ultrasound sensor.

4. EXPERIMENTAL RESULTS

To verify correctness of the hardware and the debugged program, the helicopter model was tested in the following manoeuvre: as the input signal we have chosen a ramp function of increasing the collective pitch angle of the main rotor blades θ_o while other control variables were kept on the zero level. During the test there was not blowing wind.

Fig. 6 shows time responses of the system, namely the control variables:

θ_{1s} – longitudinal cyclic pitch
θ_{1c} – lateral cyclic pitch
θ_o – main rotor collective pitch angle
θ_{oT} – tail rotor collective pitch angle

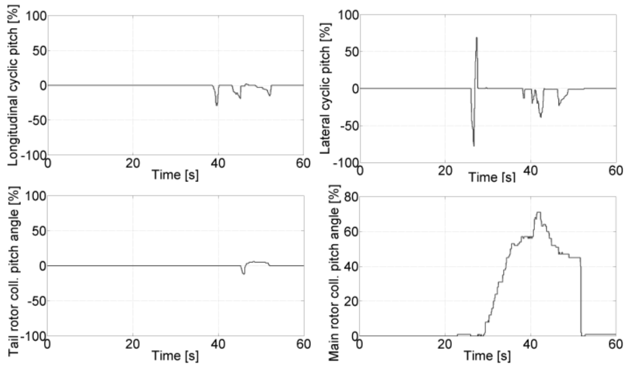

Fig. 6 Time responses of the control variables θ_{1s}, θ_{1c}, θ_o, θo_T

In time t = <0 s; 30 s) the helicopter was landed on the earth and overshoots in the time courses of the lateral cyclic pitch were caused by testing establishment of connection between the helicopter and the operator. The test of response to the ramp signal θ_o was running within the time interval t = <30 s; 38 s>. During this interval the main collective pitch angle θ_o presented the only control variable. In the time t> 38 s the operator made a manual intervention there, the helicopter was stabilized, and afterwards it landed.

In Fig. 7 there are shown time responses of the helicopter state vector x (included linear speeds, angular rates and Euler angles) that corresponds to the system reaction to inputs described above. The components of angular velocities p, q, r show oscillation of the system that is substantially caused by vibration of the helicopter motor. From time responses of linear speeds u, v, w and Euler angles Φ, θ, ψ it follows that the helicopter has a tendency to lift up its nose and to move backward what is a typical phenomena of the helicopter behaviour and it also try to move in direction to the right what is caused by thrust force of tail rotor. Significant error of estimated linear rates at the end of analysed time interval is due to hard landing and follow-up sliding of the helicopter on the surface. Aerodynamics forces are caused by autorotation of main rotor.

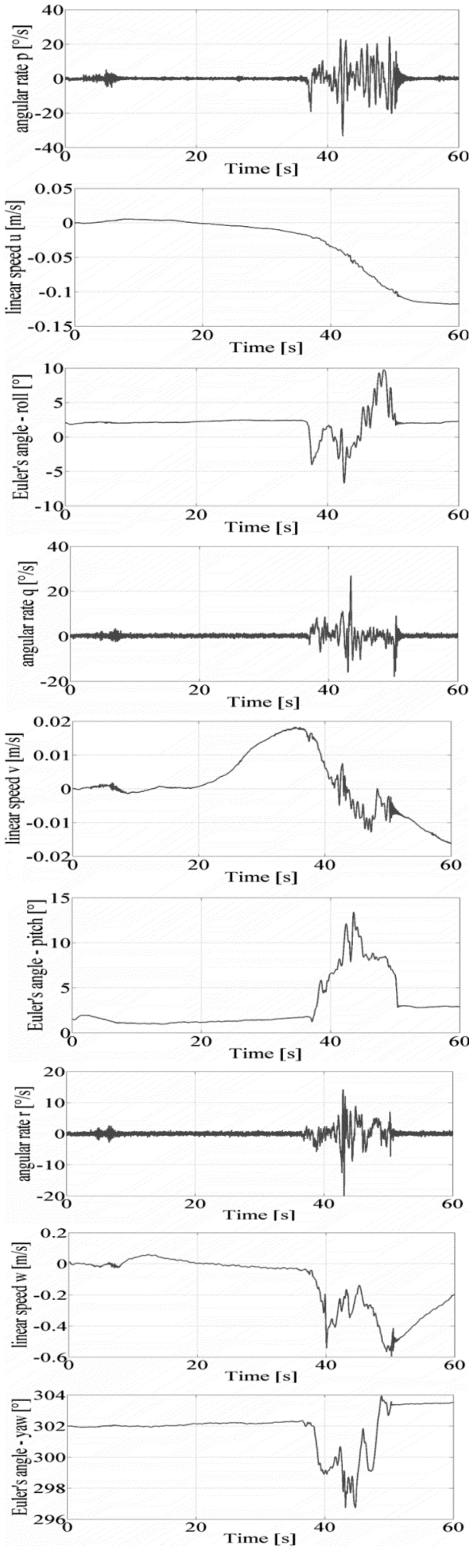

Fig. 7 Time responses of the helicopter state vector

5. CONCLUSIONS

The paper deals with development of hardware for a sensoric subsystem of a small helicopter real model in order to get data from sensors of various types. After acquisition and signal data processing there follows real-time calculation of the helicopter state vector components. Designed hardware is able to process large dataflow at high sampling frequency (820Hz) in real time. Real time means, that all data are processed during the sampling period. For signal processing a discrete Kalman filter was used.

The data processing in real-time is important from view of utilization the sensoric subsystem as a tool enabling to deliver precise data about state variables for the helicopter to the control centre. After development and verification of the sensoric subsystem the future research will concentrate to development of a complete unmanned aerial vehicle.

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Pavol Fedor received the Ing. (MSc) degree in Technical Cybernetics at the Faculty of Electrical Engineering, Technical University of Kosice in 1980 and PhD degree in the field of Electrical Drives and Electrical Traction in 1986 from the same university. In 1995, he was given the academic degree “Associate Professor”. During 1996 – 1998, he was involved in research for continuous line control in USS firm, Kosice. At present he works as a Professor at the Department of Electrotechnics, Mechatronics and Industrial Engineering at the Faculty of Electrical engineering and Informatics Technical University of Kosice. He has extensive experiences in installing of control systems in industry. In theoretical area his current research activities are focused on the development of control structures by means of Lyapunov´s second method for electrical drives and multi-input multi-output systems.

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