PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **10, 2 (36), 2019, 131-142**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Design and Testing of a Sensor Data Processing Unit for Dual-Control Missile Demonstrator

Witold BUŻANTOWICZ*, Jan PIETRASIEŃSKI

Military University of Technology, Faculty of Mechatronics and Aerospace,
2 gen. Sylwestra Kaliskiego Street, 00-908 Warsaw, Poland
**Corresponding author's e-mail address and ORCID:*
witold.buzantowicz@wat.edu.pl; https://orcid.org/0000-0002-4737-4857

Received by the editorial staff on 10 April 2018
The reviewed and verified version was received on 27 May 2019

DOI 10.5604/01.3001.0013.2120

Abstract. The article discusses aspects of the design and testing of a sensor data processing unit whose function relates to the static and dynamic stabilization of a missile airframe. The authors present a mathematical model of dual-control missile dynamics, along with the autopilot implemented based on two feedback loops – from acceleration and from angular rate of the airframe. The draft of the sensor data processing unit is presented in the form of three PCB packages, with connections for the installation of electronic components. In addition, a laboratory stand used in the experimental research, as well as selected results for the device are described.
Keywords: electronic circuit design, signal processing, autopilot, dual-control missile

This work has been compiled from the paper presented during the 22nd International Conference on Computer-Aided Design, Manufacturing and Maintenance, Pisz, Poland, May 14-18, 2018.

1. INTRODUCTION

In recent years, new solutions in methods for controlling missiles have been observed, in particular regarding the construction of dual-control missiles whose aerodynamic fins are located both in front of and behind the centre of the mass. These solutions are aimed at increasing both manoeuvring possibilities and control efficiency in the last phase of guidance on the target [1-4, 8].

Certain elements of the on-board equipment are particularly complex and difficult to implement. The correct measurement of parameters, as well as the accuracy and timing of data processing, determine the effectiveness of the whole guidance loop [5-7]. Many technological problems come to light only when the developed devices are put into practice. In terms of compliance with established construction requirements, the selection of sensory elements (among others, accuracy, stability, operational bandwidth and communication interfaces) is crucial for the success of the project [12].

The purpose of the article is to present a sensor data processing unit designed for a dual-control missile demonstrator. First of all, the dynamics of the dual-control missile with regard to the location and role of the missile autopilot is described. Next, a technical description of the developed unit and detail some selected research results are given. And finally, conclusions and final remarks.

2. DUAL-CONTROL MISSILE DYNAMICS

This paper relates to a cruciform dual-controlled, roll-stabilised missile. The motion of such a missile can be separated into two perpendicular channels. The dual-control missile airframe (Fig. 1) constitutes the MIMO-type system in the control plane, where the input is the n-dimensional vector of control signals and the output is the m-dimensional vector of airframe responses.

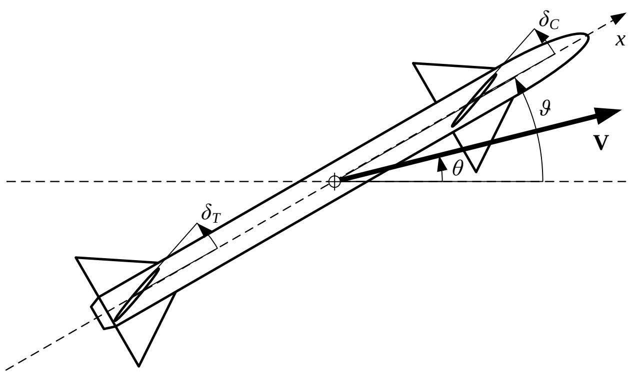


Fig. 1. Dual-control missile configuration

The dynamics of the dual-control missile in the pitch/yaw control plane is described by the vector-matrix system of equations:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u},\\ \mathbf{y} &= \mathbf{C}\mathbf{x},\end{aligned} \tag{1}$$

where **x** is the missile state vector, **y** is the output vector, **u** is the control vector:

$$\mathbf{x} \in \mathbf{R}^{5\times1}: \quad \mathbf{x} = \begin{bmatrix}\theta & \omega & \vartheta & \delta_C & \delta_T\end{bmatrix}^{\mathrm{T}}, \tag{2a}$$

$$\mathbf{y} \in \mathbf{R}^{2\times1}: \quad \mathbf{y} = \begin{bmatrix}\omega & \vartheta\end{bmatrix}^{\mathrm{T}}, \tag{2b}$$

$$\mathbf{u} \in \mathbf{R}^{5\times1}: \quad \mathbf{u} = \begin{bmatrix}[0]^{1\times3} & \delta_C^{com} & \delta_T^{com}\end{bmatrix}^{\mathrm{T}}, \tag{2c}$$

while **A**, **B** and **C** are matrices defined as follows:

$$\mathbf{A} \in \mathbf{R}^{5\times5}: \quad \mathbf{A} = \begin{bmatrix} -a_1 & 0 & a_1 & a_5^C & a_5^T \\ a_3 & -a_4 & -a_3 & -a_2^C & -a_2^T \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/\tau_C & 0 \\ 0 & 0 & 0 & 0 & -1/\tau_T \end{bmatrix}, \tag{3}$$

$$\mathbf{B} \in \mathbf{R}^{5\times5}: \quad \mathbf{B} = \left[\begin{array}{c|c} [0]^{5\times3} & \begin{array}{c} [0]^{3\times2} \\ \hline \begin{array}{cc} 1/\tau_C & 0 \\ 0 & 1/\tau_T \end{array} \end{array} \end{array}\right], \tag{4}$$

$$\mathbf{C} \in \mathbf{N}^{2\times5}: \quad \mathbf{C} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}. \tag{5}$$

In expressions (2a)-(4), the various symbols have the following meaning: θ – pitch/yaw angle of the missile velocity vector; ω – pitch/yaw rate of the airframe; ϑ – pitch/yaw angle of the airframe; δ_C^{com} and δ_C – commanded and actual canard deflection angle; δ_T^{com} and δ_T – commanded and actual tail fin deflection angle; τ_C and τ_T – time constants of canard and tail fin servos. The elements of matrix **A** in the equation (3) have the following form:

$$a_1 = \frac{\rho V}{2m} f_1(\theta, \vartheta), \tag{6a}$$

$$a_2^C = \frac{\rho V^2}{2I} f_2(\theta, \vartheta, \delta_C), \quad a_2^T = \frac{\rho V^2}{2I} f_2(\theta, \vartheta, \delta_T), \tag{6b}$$

$$a_3 = \frac{\rho V^2}{2I} f_3(\theta, \vartheta), \tag{6c}$$

$$a_4 = \frac{\rho V}{2I} f_4(\omega), \tag{6d}$$

$$a_5^C = \frac{\rho V}{2m} f_5(\theta, \vartheta, \delta_C), \quad a_5^T = \frac{\rho V}{2m} f_5(\theta, \vartheta, \delta_T), \tag{6e}$$

where: V is the module of the missile velocity vector, ρ – air density, m – missile mass, I – missile moment of inertia; $f_i(\cdot)$, $i \in \{1,\ldots,5\}$, are the functions dependent on time, geometric-mass and aerodynamic characteristics of the airframe. These have a complex character and have not been adduced for the sake of brevity.

The canard and tail fin servos are modelled as first order dynamics:

$$\dot{\delta}_C = \frac{\delta_C^{com} - \delta_C}{\tau_C}, \quad \dot{\delta}_T = \frac{\delta_T^{com} - \delta_T}{\tau_T}. \tag{7}$$

The lack of stationarity of the static and dynamic properties of the missile airframe determines changes in the characteristics of the entire guidance loop. In extreme cases, this can result in its stability being compromised. In order to compensate for the dynamic properties of the airframe and adverse flight conditions, an automatic control subsystem for the missile guidance system was designed, enabling established acceleration values to be achieved by the missile and providing stability of flight. Figure 2 presents the variant of the missile autopilot. It was obtained by covering the airframe using a double feedback loop: from angular velocity and from linear acceleration.

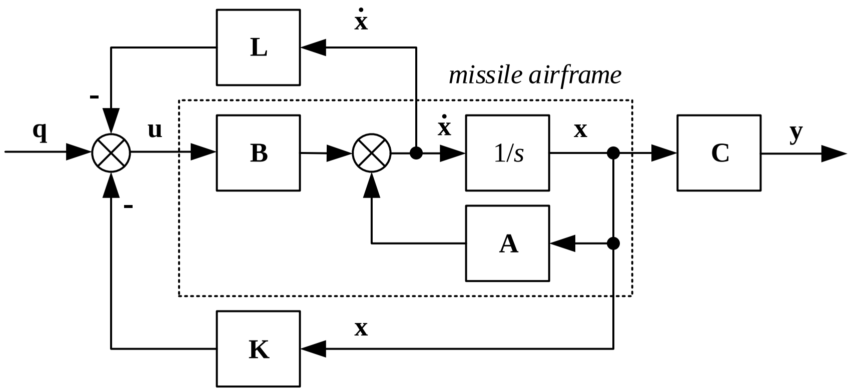


Fig. 2. Block diagram of the dual-control missile stabilization system in the pitch/yaw plane

The equation describing the motion of the dual-control missile with the stabilization loops is arrived at by including feedback signals from the gyroscope and the accelerometer in the mathematical model:

$$\dot{\mathbf{x}} = \left(\mathbf{I}+\mathbf{BL}\right)^{-1}\left(\mathbf{A}-\mathbf{BK}\right)\mathbf{x}+\left(\mathbf{I}+\mathbf{BL}\right)^{-1}\mathbf{Bq}, \tag{8}$$

where **I** is the identity matrix, **q** is the command vector:

$$\mathbf{q}\in\mathbf{R}^{5\times1}:\quad \mathbf{q}=\begin{bmatrix}[0]^{3\times1}\\ \kappa_C\\ \kappa_T\end{bmatrix}, \tag{9}$$

where: κ_C is the canard command, κ_T is the tail fin command. **K** and **L** are the gain matrices in the feedback paths:

$$\mathbf{K}\in\mathbf{R}^{5\times5}:\quad \mathbf{K}=\left[\begin{array}{cc|c} \multicolumn{2}{c|}{[0]^{3\times2}} & \\ \hline 0 & k_C & [0]^{5\times3} \\ 0 & k_T & \end{array}\right], \tag{10}$$

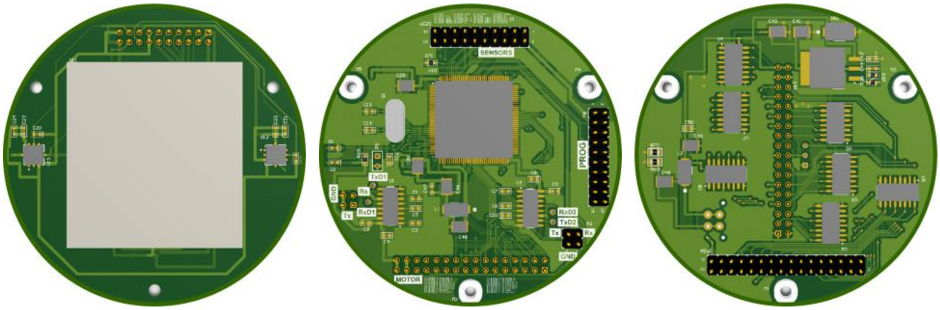
$$\mathbf{L}\in\mathbf{R}^{5\times5}:\quad \mathbf{L}=\left[\begin{array}{c|c} [0]^{3\times1} & \\ \hline l_C & [0]^{5\times4} \\ l_T & \end{array}\right], \tag{11}$$

where: k_C, k_T, l_C and l_T are the nonlinear gain functions of canard and tail fin deflection signal components, respectively.

3. DESCRIPTION OF THE DATA PROCESSING UNIT

The values of angular rates and linear accelerations of the airframe in feedback paths are provided by sensors located on the missile's board. MEMS-type integrated measurement units are used (among others) for the measurement of angular rates and linear accelerations in missiles. Gyroscopes and accelerometers produced using MEMS technology are characterised by small sizes, high resistance to impact and other mechanical damages, as well as a wide operating temperature range and low power consumption. They are hence suitable for use as sensory elements in devices with special operational requirements [9, 12].

Figure 3 shows the elements of the sensor data processing unit designed for the dual-control missile demonstrator. The unit consists of an AP-01 sensor package, an AP-02 microcontroller package, and an AP-03 interface package. The scope of its tasks includes: a) receipt of data from on-board sensors and optical seeker; b) data processing; c) determination of canard and tail fin deflections on the basis of signals received from the seeker, the state of the missile, the guidance method, and environmental parameters; and d) communication with the proximity fuse, the radio-control, and the diagnostic unit.



a) b) c)

Fig. 3. Elements of the sensor data processing unit: a) AP-01 sensor package, b) AP-02 microcontroller package, c) AP-3 interface package

The AP-01 sensor package allows for the linear accelerations and the angular rates of the airframe to be measured. It also provides the set of measurement data for the AP-02 microcontroller package. The essential element of the AP-01 package is an integrated MEMS-type ADIS16375 sensor, combining a 3-axis gyroscope with the measurement range ±300°/s and a 3-axis accelerometer with the measurement range ±18 g. The unit is complemented by two uniaxial analogue ADXL001 accelerometers, with the measurement range ±70 g, which are used to measure normal accelerations of the airframe.

The AP-02 microcontroller package is designed to receive measurement data from the AP-01 sensor package, determine the canards and tail fins deflections, and produce control commands for actuators *via* the AP-03 package. The package includes: a STM32F103ZET microcontroller with the ARM Cortex-M3 processor; a microcontroller power supply system; two MAX3232CSE units for the conversion of UART interface voltages; communication interfaces (20-twin block for communication with the AP-01 sensor package and 32-twin block for communication with the AP-03 interface package); a 20-twin block service connector; and passive elements for voltage filtration.

The AP-03 interface package consists of seven ACPL-247 units and a 32-twin block connector. The ACPL-247 units, each of which consists of four optocouplers, are used as separators for implementing the galvanic isolation between digital signals from the microcontroller and signals transmitted to actuators, while acting as voltage converters for the microcontroller outputs and actuator control inputs. The 32-twin block connector provides communication between the AP-03 interface package and the AP-02 microcontroller package.

4. EXPERIMENTAL RESEARCH

4.1. Laboratory Stand

Preliminary, autonomous research on the data processing unit was conducted on the improved laboratory stand, which is described in detail in [9]. The stand comprises: a gimbal platform with a microprocessor control unit; a communication module with a socket for embedding the device being tested; and two PCs with dedicated software and the wire set (Fig. 4).

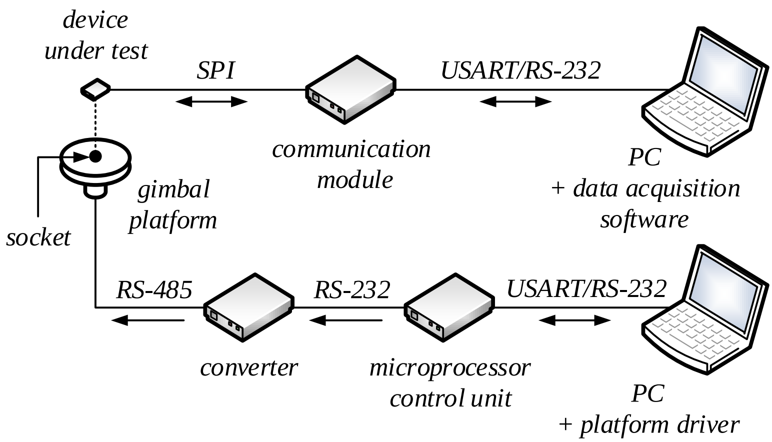


Fig. 4. Block diagram of the laboratory stand

The design of the gimbal platform is based around the MG-TC 2636B camera drives, ensuring both the horizontal (without limitation) and vertical (in the range of ±90°) rotation of the measurement platform, with a maximum angular rate of 180°/s. In order to ensure the measurement is stable and repeatable, a platform driver application that communicates with the platform control system *via* the RS232/RS385 interface and the PELCO-D protocol was developed using the Embarcadero RAD Studio XE3 environment. The microprocessor systems, meanwhile, were programmed in Keil µVision 4 IDE.

Research was conducted in both static and dynamic conditions. Static tests were performed in order to determine the level of self-generated noise in the channels of the accelerometers and gyroscopes. For dynamic conditions, the main objective was to verify the accuracy and stability of the indications. This included a series of tests involving multiple, long-term sensor rotations towards various axes, as well as rotations of a random nature, with fixed and variable angular rates.

Essential simulation tests were performed in the HIL (hardware-in-the-loop) mode. Peripherals drivers were compiled into MEX files, allowing for their use in the MathWorks Matlab environment. In response to programmatically applied deflections of control surfaces, the sensor data processing unit, installed on the MG-TC 2636B gimbal platform, reproduced the movement of the missile airframe in the pitch/yaw plane. The dual-control missile airframe and actuators were modelled as software modules [11]. The measured values of angular rates and linear accelerations were transmitted through the RS-232 interface to the PC, where they were inputted to feedback paths with **K** and **L** matrices (cf. Fig. 2). On the basis of the measured variables and the specified geometric-mass characteristics of the airframe, the aerodynamic control surfaces, the autopilot configuration, the rocket engine parameters and the combustion profile characteristics, the software produced a three-dimensional simulation of the missile flight, as well as an airframe oscillation visualization [10].

4.2. Simulation Results

Figures 5-6 illustrate the step responses of the dual-control missile airframe model. Waveforms obtained for the unstabilised airframe are marked by the dashed lines, and waveforms for the airframe with the stabilization loop implemented based on the data processing unit presented in the article are marked by the solid lines. Commands given to the canards and tail fins, forcing the reaction of the missile airframe, are shown in Fig. 7. The acceleration a and angular rate ω were normalised.

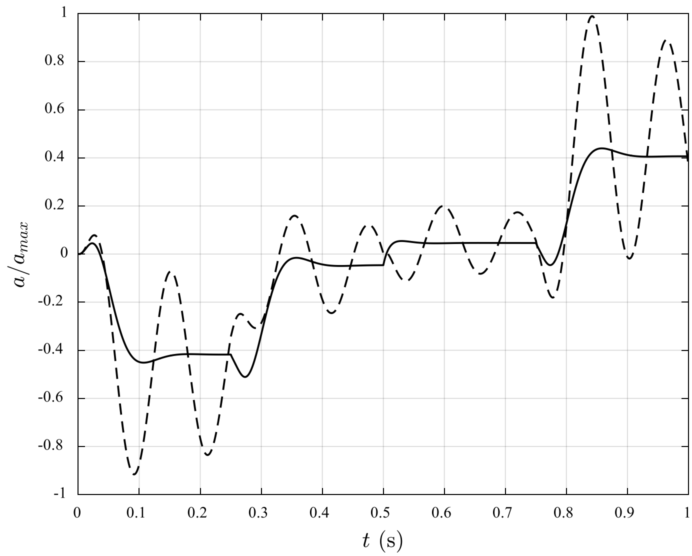


Fig. 5. Normalised accelerations of the missile airframe

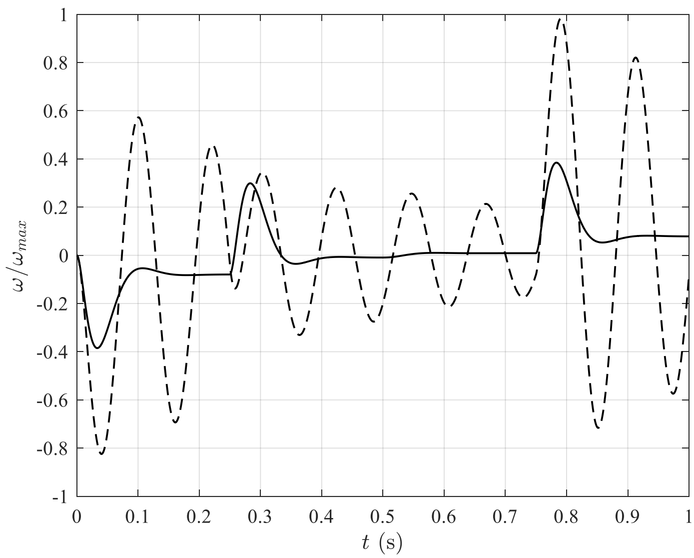


Fig. 6. Normalised angular rates of the missile

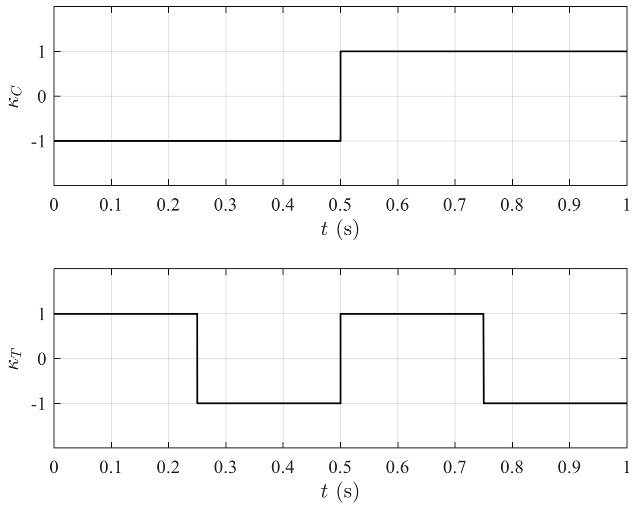


Fig. 7. Control commands

Figure 8 shows the simulation software panel designed for visualizing the missile flight trajectories and the oscillations of the airframes.

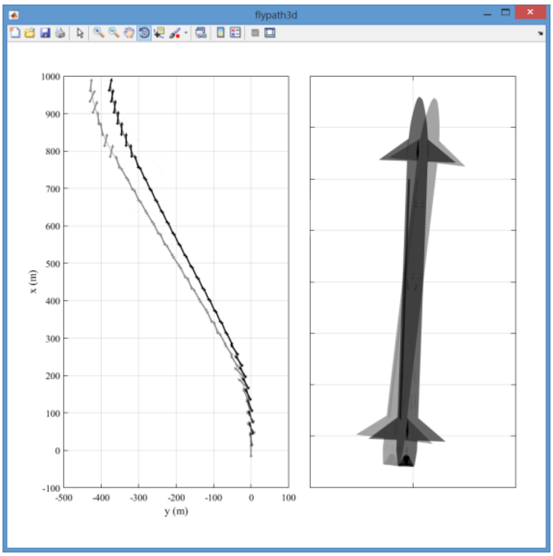


Fig. 8. Missile flight trajectories in the yaw plane

The flight trajectory of the unstabilised missile and the angular position of its airframe are marked in grey, while the flight trajectory of the missile equipped with autopilot and the angular position of its airframe are marked in black.

5. CONCLUDING REMARKS

This article describes the sensor data processing unit of a dual-control missile demonstrator and gives selected research results. The developed module, which uses the 3-axis gyroscope and a 3-axis accelerometer contained in a single integrated measurement unit (IMU) including two uniaxial analogue accelerometers, is used as the measurement device for the dual-control missile autopilot. Both the static and dynamic research was carried out using the original simulation software and the laboratory stand, which was developed using high speed rotating camera drives. Research conducted in the HIL mode showed the proper operation of the unit and its components under laboratory conditions. Static tests confirmed the level of self-generated noise of the tested sensors in the channels of both the accelerometers and the gyroscopes. In line with expectations, the double feedback loop stabilised the static and dynamic characteristics of the missile airframe.

This allowed both for the mitigation of transition processes and the shortening of their duration, which positively translated into the time necessary to obtain accelerations and steering moments required by the missile.

The next stage of development will focus on the verification of the correct operation of the device at a military training area, using a dual-control experimental missile model.

FUNDING

The authors received no financial support for the research, authorship, and/or publication of this article.

REFERENCES

[1] Idan Moshe, Tal Shima, Oded M. Golan. 2007. "Integrated Sliding Mode Autopilot-Guidance for Dual Control Missiles". *Journal of Guidance, Control and Dynamics* 30 (4) : 1081-1089 (DOI: 10.2514/1.24953).

[2] Tournes C.H., Y.B. Shtessel. 2008. "Integrated Autopilot and Guidance for Dual Control Missiles Using High Order Sliding Mode Control and Observers". *IFAC Proceeding Volumes* 41 (2) : 6226-6231.

[3] Yan Han, Haibo Ji. 2012. "Integrated Guidance and Control for Dual-Control Missiles Against Ground Fixed Targets". *Automatica* 48 (10) : 2686-2692

[4] Schroeder K. Wayne. 2001. *Dual-control scheme for improved missile maneuverability*. Patent No. US RE37,331 E.

[5] Siouris M. George. 2004. *Missile Guidance and Control Systems*. New York: Springer.

[6] Yanushevsky Rafael. 2007. *Modern Missile Guidance*. New York: CRC Press.

[7] Zarchan Paul. 2012. *Tactical and Strategic Missile Guidance*. Reston: AIAA.

[8] Bużantowicz Witold, Jan Pietrasieński. 2018. "Dual-control missile guidance: A simulation study". *Journal of Theoretical and Applied Mechanics* 56 (3) : 727-739.

[9] Bużantowicz Witold, Dariusz Rodzik, Jan Szczurko. 2016. Laboratory Stand for Inertial Sensor Testing and Verification. In *Proc. of 17th International Scientific-Practical Conference MIET*, Odessa 189-190.

[10] Bużantowicz Witold. 2016. "Matlab Script for 3D Visualization of Missile and Air Target Trajectories". *International Journal of Computer and Information Technology* 5 (5) : 419-422.

[11] Bużantowicz Witold. 2016. "Computer-aided missile autopilot analysis and synthesis" (in Polish). *Mechanik* 89 (7) : 654-656.

[12] Bużantowicz Witold. 2012. *Scientific Report: The Concept of Short-Range Missile Guidance & Control – Design of On-Board Sensor Data Processing Unit* (in Polish). RMN No. 08-683/2012 Warsaw: Military University of Technology (unpublished).

Projekt i badania układu przetwarzania danych z czujników aparatury pokładowej demonstratora rakiety o usterzeniu podwójnym

Witold BUŻANTOWICZ, Jan PIETRASIEŃSKI

Wojskowa Akademia Techniczna, Wydział Mechatroniki i Lotnictwa, ul. gen. Sylwestra Kaliskiego 2, 00-908 Warszawa

Streszczenie. W artykule przedstawiono zagadnienia związane z projektowaniem i testowaniem układu przetwarzania danych z czujników aparatury pokładowej, planowanego do zastosowania w demonstratorze rakiety przeciwlotniczej o usterzeniu podwójnym. Zaprezentowano model matematyczny ruchu rakiety wyposażonej w podwójny układ sterów aerodynamicznych z uwzględnieniem układu stabilizacji charakterystyk statycznych i dynamicznych kadłuba. Opisano układ przetwarzania danych z czujników aparatury pokładowej, zrealizowany w postaci trzech płytek obwodów drukowanych z połączeniami do montażu podzespołów elektronicznych. Przedstawiono budowę stanowiska laboratoryjnego przeznaczonego do testowania zaprojektowanego urządzenia i zaprezentowano wybrane wyniki badań symulacyjnych.

Słowa kluczowe: projektowanie układów elektronicznych, przetwarzanie sygnałów, pilot automatyczny, rakieta o usterzeniu podwójnym