AVIATION
2010
14(3): 77–82

PROPOSAL FOR NAVIGATION AND CONTROL SYSTEM FOR SMALL UAV

Grzegorz Kopecki[1], Jacek Pieniążek[2], Tomasz Rogalski[3], Pawel Rzucidło[4], Andrzej Tomczyk[5]

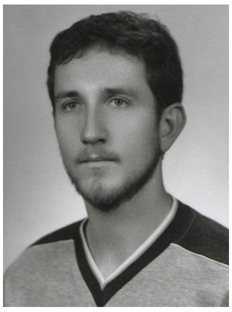
Rzeszów University of Technology, Department of Avionics and Control
Al. Powstancow Warszawy 8, 35-959 Rzeszów, Poland
E-mails: [1]gkopecki@prz.edu.pl; [2]jp@prz.edu.pl; [3]orakl@prz.edu.pl; [4]pawelrz@prz.edu.pl; [5]atomczyk@prz.edu.pl

Received 18 February 2010, accepted 23 August 2010

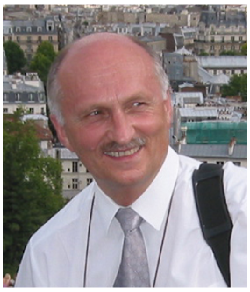
Grzegorz KOPECKI, PhD Eng
Education: 2001 – Rzeszów University of Technology.
Affiliation and functions: PhD – 2007, MSc Eng – 2001, Rzeszów University of Technology.
Research interest: aircraft control, UAV aircraft control.
Present position: Assistant professor in Department of Avionics and Control Systems at Rzeszów University of Technology. Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Avionics and Control Systems. Phone: +48 17 865 1835, fax +48 17 854 4319.

Jacek PIENIĄŻEK, PhD Eng
Affiliation and functions: PhD obtained in 2001 from Military University of Technology, Warsaw.
Research interest: research of autonomous UAV control and measurements systems and aircraft cooperative human and automatic control.
Present position: Assistant professor in Department of Avionics and Control Systems at Rzeszów University of Technology. Phone: +48 17 865 1783, fax. +48 17 854 4319.

Tomasz ROGALSKI, PhD Eng
Education: 1996 – Rzeszów University of Technology.
Affiliation and functions: MSc degree in 1996, PhD degree in 2004, Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, specialisation: Aircraft Control Systems.
Research interest: aircraft control, UAV aircraft control.
Present position: researcher and lecturer at Rzeszów University of Technology since 1996. Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Avionics and Control Systems. Phone: +48 17 865 1477, fax. +48 17 854 4319.



Pawel RZUCIDLO, PhD Eng
Education: 2001 – Rzeszów University of Technology.
Affiliation and functions: MSc degree in 2001, PhD degree in 2005, Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, specialisation: Aircraft Control Systems.
Research interest: aircraft control with an emphasis on interactions between human and machine.
Publications: author of over forty scientific papers and conference proceedings, author of one book.
Present position: researcher and lecturer at Rzeszów University of Technology since 2001. Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Avionics and Control Systems. Phone: +48 17 865 1833, fax. +48 17 854 4319.



Andrzej TOMCZYK, DSc Eng Assoc Prof
Education: 1970 – Warsaw University of Technology.
Affiliation and functions: MSc degree in 1970 at Warsaw University of Technology, PhD. degree in 1976 at Polish Academy of Science, DSc degree in 2000 at Military University of Technology.
Research interest: avionics and aircraft control systems, indirect control systems for general aviation, UAV aircraft control.
Present position: researcher and lecturer at Rzeszów University of Technology since 1976. Rzeszów University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Avionics and Control Systems. Phone: +48 17 865 1485, fax. +48 17 854 4319.

Abstract. The article presents the project of UAV control system realized at Department of Avionics and Control Systems of Rzeszów University of Technology. The project is based on earlier experiences. In the article general structure of the onboard control system is shown as well as the structure of control station. There are described in proposed control and navigation procedures as well as human factor, failure detection and system reconfiguration.

Keywords: aircraft control systems, UAV.

1. Introduction

At the Department of Avionics and Control Systems of Rzeszów University of Technology, the first control system for a UAV, assembled in the PZL-110 experimental aircraft and tested during flight, was designed and prototyped in 1995–1998 (Tomczyk 2003). Except for the takeoff and landing, the system–including among others such elements as the main computer and measurement units–achieved a fully autonomous mission. Communication was achieved with the use of RS 232/422/485 protocols. In 2000–2006 the team at the Department of Avionic and Control Systems was focused on an indirect (fly-by-wire) control system for a small general aviation (GA) aircraft (Dolega *et al*. 2007; Tomczyk 2004). The project was not connected with UAV, but the experience acquired during the realisation of the project is relevant to the current research project, which concerns a UAV control system for a small UAV. The GA control system was realised as a multiprocessor system. Communication between system elements was realised with the use of a CAN bus. The application of a CAN bus proved to be much better than the RS application since the system was open and flexible. Actually, the team of the Department of Avionics and Control Systems is designing a control system for a small UAV. A structure based on a CAN bus is implemented. Also, many tasks in the area of the human factor and problems of reconfiguration were taken into consideration, and research in this area will be continued. The UAV project is being realised together with the Department of Aircraft and Aircraft Engines of the Rzeszów University of Technology, where the UAV frame is being designed. The production of the UAV is not a typical commercial enterprise, but the aircraft is to serve as a demonstrator of technology and research tool. This article describes the UAV control system designed and outlines research.

2. General description of control system

The control system consists of two segments: onboard control system and operator's control station situated on the ground. It was assumed that the segments communicate with each other by means of radio transmission. The onboard system is responsible for control and sending information to the operator's control station.

2.1. Onboard control system

In experimental applications, elements of the designed system are changed during the realisation of the project. It was assumed that the system should be designed as plug and play, guaranteeing the possibility of easy extension and replacement of particular elements. For this kind of system, a digital bus turns out to be very good solution. Figure 1 presents the UAV control system with a CAN bus. As mentioned earlier, such a structure results from previous experience with the control system for GA aircraft. The system contains the following measurement units: one AHRS (attitude and heading reference system), one GPS receiver, and one ADC (air data computer). The three units provide measurement information to the FCC (flight control computer) and other equipment with the use of the CAN bus. Additional equipment necessary for the UAV are:

- flight data recorder (REC);
- camera and its control system (CAM);
- rescue system (RES);
- system monitoring and diagnostic unit for testing on the ground (EXTMON).

Servo control for the control surfaces may be realised in two ways, either autonomically by means of FCC or remote radio control.

The reconfigurable structure of the system enables a unified communication protocol. In the solution presented, the CANAerospace protocol is implemented (Stock 2006). Additionally, this protocol also enables easy implementation of hardware redundancy.

Digital communication between the onboard system and operator's station is achieved via a radio modem (R-MODEM) in both directions, with the camera picture sent as a SHF (super high frequency) signal (Kordos *et al*. 2008).

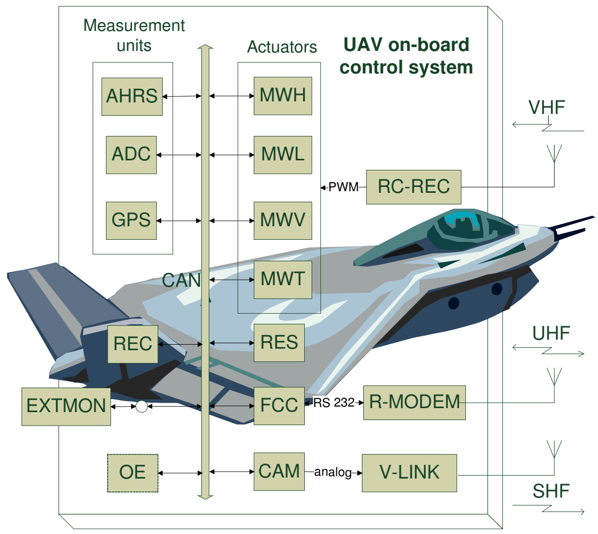


Fig 1. Block scheme of UAV onboard control system

Figure 2 presents the placement of elements on board the UAV. As mentioned above, in an experimental system additional measurement is frequently necessary. Here it is realised via additional modules P1–P4. Such modules provide information for different research in the area of control systems, discussed in chapter 3, as well as in the area of structural analysis (additional extensometers). The additional equipment is also necessary for UAV diagnostics.

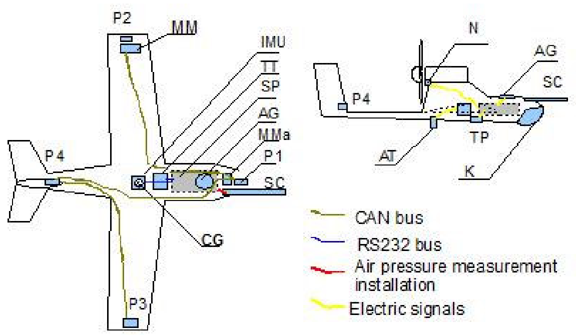


Fig 2. Scheme of control system installations on board the UAV

AG – GPS receiver antenna,
AT – teletransmission data antenna,
IMU – inertial measurement unit,
CAM – video camera module,
MM – magnetometer,
MMa – optional magnetometer placement,
N – angular rate sensor,
SC – yaw meter (measurement of slideslip angle and angle of attack, total pressure and static pressure),
FCC – flight control computer,
TP – temperature sensor,
TT – teletransmission module,
SM – gravity center.

Figure 2 shows the placement of the video camera. For the effective use of the UAV, the control of video camera movement is indispensable. The connection between the camera and the main CAN bus enables the use of the same radio connection channel both for aircraft control and for control of the video camera. In addition, the movement control system for the video camera uses flight parameters measured by basic equipment for UAV movement compensation (Pieniążek 2003).

2.2. On the ground control station

The main element of the on the ground control station is a PC computer. All other elements are connected with the use of typical interfaces (USB, RS-232, etc.). The control station includes the control stick and the manipulator (track ball) connected to the PC via USB. All indicators are displayed on an additional LCD panel with a DVI connection. An RC transmitter/receiver is also an element of the control station. The communication control station-onboard control system is realised via radio modem (R-MODEM). For video picture registration, a PCMCIA video card and video receiver (V-LINK) is installed.

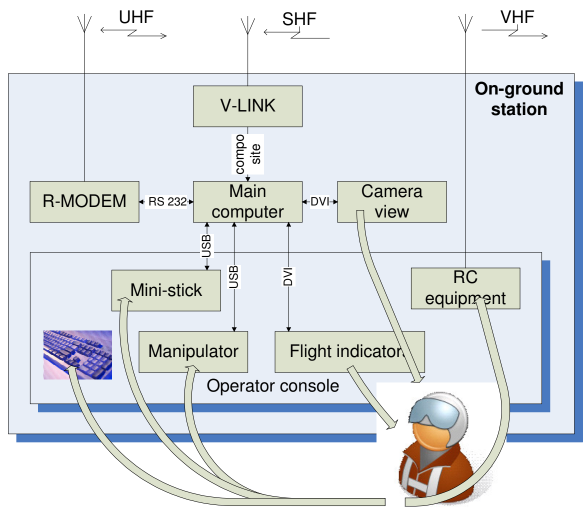


Fig 3. Block scheme of the on the ground control station

Figure 4 presents the set of indicators used for UAV control. There are classical indicators as well as a map indicator that enables presentation of planned and actual flight route.

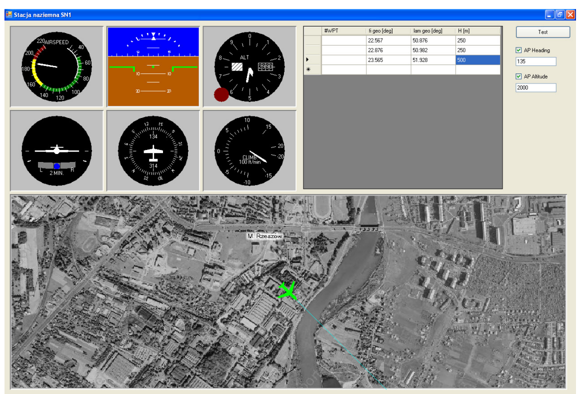


Fig 4. Exemplary set of indicators of control station on the ground

3. Major research problems in the project

As written in the introduction, the UAV being presented is being designed as a demonstrator of technology and research tool. The most important research tasks are presented in this chapter.

3.1. UAV mathematical model identification and improvements

The first task realised after UAV structure and control system hardware preparation is in-flight testing for the identification of the parameters of the mathematical model. The general form of the dynamic process is given by equation 1, where state variables are in the column vector x, and control variables and disturbances are in u and z respectively.

$$\begin{aligned} \dot{x} &= f\left(x,u,z\right) \\ y &= g\left(x,u,z\right) \end{aligned} \tag{1}$$

Some state variables depend on the other, as presented in equation (2).

$$x_1 = a\frac{dx_2}{dt} + \Delta \tag{2}$$

where:

Δ - additional coefficient.

The structure of the aircraft model is presented in figure 5.

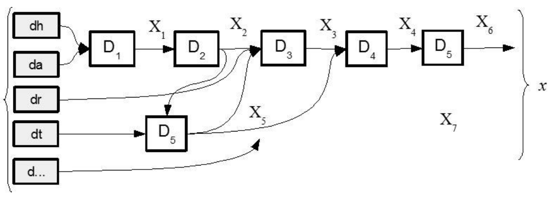


Fig 5. General structure of the aircraft model D_i – dynamics, x = {X_i} – states (X_1 – pitch and roll rate, X_2 – pitch and roll angles, X_3 – yaw rate and altitude, X_4 – heading, X_5 – speed, X_6 – position, X_7 – state variables connected with mission), u = {dh, da, …} – control signals

3.2. Control and navigation procedures

Three modes of flight control are planned:

A. Direct manual control;
B. Indirect manual control;
C. Autonomous control.

The basic method of UAV control is autonomous control, in which the desired mission is realised. Manual control is planned only for takeoff and landing.

Ad. A. Direct manual control is realised via:

1. Typical radio control equipment or,
2. With the use of a special teletransmission modem with signals coded before sending and verified after receiving (preferred variant).

Control surfaces and throttle control is realised with the use of control laws:

A1. Control surfaces are deflected proportional to steering stick deflection

A2. Deflection of control surfaces is a monotonic function of steering stick deflection (the function is defined and coded in the station on the ground).

Direct control with the use of the specialised teletransmission modem should be realised with signals received and verified by the on the ground station. If visual contact with the UAV is impossible, the operator has to receive actual flight parameters (measured data or video view from the onboard video camera).

Ad. B. Direct control (manual, operator-aided control) is the connection of manual control and automatic attitude stabilisation. Control signals sent from the station are treated as the desired attitude or other flight parameters. There are planned variants of direct control:

B11. Pitch control with limitations $\Theta \in (\Theta_{\max}, \Theta_{\min})$,

B12. Flight path angle control with limitations $\gamma \in (\gamma_{\max}, \gamma_{\min})$,

B13. Rate of climb control with limitations $w \in (w_{\max}, w_{\min})$,

B21. Autothrottle $N \in (N_{\max}, N_{\min})$,

B22. Indicated air speed control with limitations $V \in (V_{\max}, V_{\min})$,

B31. Roll angle control with limitations $\Phi \in (\Phi_{\max}, \Phi_{\min})$,

B32. Magnetic heading control,

B33. GPS track control.

The default control option is the first in the group (B11, B21, B31). Other modes will be activated after choosing.

Indirect control can be realised if confirmation of correct transmission is received by the on the ground station and flight parameters are available for the operator.

The operator's manual control relies on choosing control modes and desired values of controlled parameters.

Alternate inactive control laws (e.g. B11 if B12 is chosen) are used as safety functions to prevent limitations being exceeded (e.g. pitch limitation in case of unfavourable desired path angle and desired throttle parameters).

In addition, during the development of the system, procedures facilitating the stabilisation of flight parameters will be implemented:

- Automatic heading stabilisation: if desired and actual roll angle is smaller than boundary value, heading stabilisation is switched on.
- Automatic altitude stabilisation: this mode will be switched on in two cases: a) if desired and actual flight path angle are smaller than boundary value, or b) if actual flight path angle is smaller than boundary value and desired flight path angle is constant longer than boundary time interval, automatic altitude stabilisation is switched on.

Ad. C. Autonomous control enables the planned mission to be realised, i.e. aircraft tracking along a desired trajectory, which is defined by navigational coordinates, measured by a GPS receiver. A perpendicular flight profile is also defined. The time at which an aircraft is at a desired point can also be planned.

UAV control is achieved as indirect flight control (B), but a superior module that controls the aircraft on the desired trajectory determines desired flight parameters. The cases of trajectory and perpendicular flight profile definitions that were considered are presented here:

- polygon line trajectory;
- curved line trajectory;
- holding realisation;
- pressure height stabilisation (H_{STD}, H_{QFE}, H_{QNH});
- GPS altitude stabilisation;
- flight path angle or instrumental climb rate stabilisation;
- instrumental air speed stabilisation;
- GPS velocity stabilisation.

As a next step, the task of object observation will also be considered. Depending on the properties of the additional equipment, UAV control can be based on:

- navigational calculations and flight realisation based on GPS.
- feedback from the object, e.g. optical feedback after observation of stationary or moving object.
- control of observing equipment with the use of additional rules.

Take off and landing, will be achieved manually by an operator on the ground. Autonomous take off and landing may be considered in versions of the next system.

As a basic variant, navigation with a GPS receiver is planned. Incorporation of an air data computer and attitude and heading reference system is also being planned. This equipment enables wind velocity and direction calculation if the GPS receiver is working correctly. In case of the absence of a GPS signal, inertial navigation based on true air speed and magnetic heading is possible.

3.2. Human factor in UAV control system

Direct manual control and indirect control means the presence of a human in the UAV control process (Pieniążek 2008). From a technical point of view, the process of human behaviour can be divided in three main phases:

- perception of data from the human environment;
- analysis of the process state using additional information from memory and deciding what to do;
- taking action.

Figure 6 presents the model of human activities. This model unites phases from the MAGSI model (monitoring, generating, selecting and implementing) and OODA (observation, orientation, decision and action) model (Kaber *et al.* 2004; Proud *et al.* 2003). Every activity is connected to appropriate human resources, or some activities are distinguished by function. For example for perception, senses and a low level of neural system are necessary. But for the observation process, senses and intellectual resources are required. The two phases of decision activity are strongly dependent on knowledge and the ability to process data effectively and quickly.

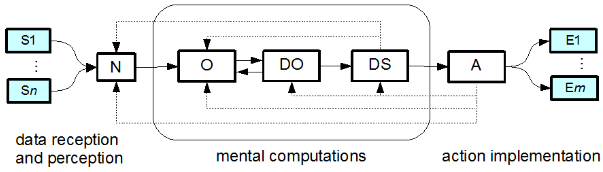


Fig 6. Human activities in control tasks Si – senses, N – neural structures in the perception stage, O – process of orientation in current state, DO – decision-option generation, DS – decision-selection from options, A – implementation of action, and Ei – effectors (hand, finger, foot, etc.)

The general shape of the models presented is similar to the structure of the technical controller, with measurement devices, a computer for data processing and implementation of the control algorithm, and output devices for transforming commands into physical signals. But if human action is analysed as the control action, the situation becomes more complicated. Reaction depends on many different personal components such as general physiological state, environmental condition, and various personal abilities. In the approach presented, the equipment necessary for an operator during control is treated as elements aiding the action of the operator.

In general, in the nested loops of the control process, control actions in the inner and outer loops are different. Inner controllers are rather simple and fast, but outer controllers become slower and more complicated, and usually there is more state variables used in the control process. The inner loop control shows different properties at different levels of automation. Automation at a lower level (e.g. attitude control) unburdens an operator and enables other tasks to be completed. Also remote transmission, necessary for manual control, cannot always be treated as reliable; sometimes it must be broken intentionally. But in some flight phases, manual inner loop control is necessary. Outer loops are necessary for decision-making. Monitoring of actions applied is also necessary. These tasks engage heavily computational resources and are very monotonous if done by a human. During long UAV missions, automatic control is applied, with a human as an emergency controller. Only during the most specific and complicated phases of the mission does a human take full or partial control. An appropriate level of automation in every situation is very important for optimal and safe system operation.

The approach presented is also used during the design of interfaces for the control station computer. The information displayed not only provides visualisation of the actual flight parameters, but also aids the operator's decisions during the control process. The correct way of displaying information also decreases the psychophysical load.

Algorithms aiding the operator's decisions are another research problem in this area.

3.3. Failure detection and system reconfiguration

The system is being planned as an active fault tolerant flight control system (AFTFCS). In case of failure, the system will be reconfigured. Fault detection is carried out by means of hardware and analytical redundancy. To detect a faulty signal, information has to be received from two independent sources. To identify the faulty signal (i.e. specify which signal is faulty), information from three independent sources must be acquired. This can be achieved best by multiplying sensors. However, this solution increases the system's cost and weight, which is an important drawback especially in case of small unmanned aircraft. Analytical redundancy is therefore frequently used (Dolega *et al.* 2006).

During research, several methods of state estimation (e.g. state observers, Kalman filtering) will be implemented for failure detection. Advanced filtration methods will also be used for estimating measured data. The role of a human in AFTFCS with the approach presented in chapter 3.2 will also be taken into consideration.

4. Conclusions

In this article a few aspects of the navigation system for a small UAV were presented. The UAV is being designed and constructed at Rzeszów University of Technology. The structure of the system being presented is based on experiences collected during earlier research. The aim of the entire project is to design and prototype a UAV technology demonstrator and research tool. The research is focused on single UAV operation. A small UAV provides the possibility of low cost in-flight testing in the research area presented. The proposed approach in the area of control systems gives the possibility of analysing the influence of the human factor in a UAV. There are some proposals of autopilots for a small UAV with a closed structure. Use of a CAN bus with CANAerospace protocol makes the system open and universal. Major research problems appear not only in UAVs but also in manned aircraft. The technology demonstrator and low cost in-flight testing also provides new possibilities for education and in-flight laboratory classes, which is important for the university.

References

Dolega, B.; Kopecki, G. 2006. Fault detection and isolation in attitude and heading reference systems for fly-by-wire control system for general aviation aircraft, in *SAE Paper, 2006-01-2415, General Aviation Technology Congress,* Wichita 2006.

Dolega, B.; Tomczyk, A. 2007. Pilot-friendly flight control system for general aviation aircraft, in *2-nd European Conference for Aerospace Sciences (EUCASS)*, 2–6. July 2007.

Kaber, D. B.; Endsley, M. R. 2004. The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task, *Theoretical Issues in Ergonomics Sciences* 5: 113–153.

Kordos, D.; Rzucidło, P. 2008. Remote data transmission system, in *III International Conference „Scientific aspects of UAV"*. Cedzyna, PL, 7–9 May 2008.

Pieniążek, J. 2008. Automation in unmanned aircraft system, *Scientific Proceedings of Riga Technical University, Series 6 "Transport and Engineering. Transport. Aviation Transport"*. Riga: RTU, (27): 188–196.

Pieniążek J.: *Software-based camera stabilization of unmanned aerial vehicle*, Aircraft Engineering and Aerospace Technology, vol. 75, no. 6, 2003, pp. 575–580.

Proud, R., Hart, J., Mrozinski, R. 2003. Methods for determining the level of autonomy to design into a human spaceflight vehicle: a functional specific approach, in *Performance Metrics for Intelligent Systems, PerMIS '03, NIST Special Publication 1014.*

Stock, M. 2006. CANaerospace – interface specification for airborne CAN applications, *Stock Flight Systems* 1.7.

Tomczyk, A. 2003. In-flight tests of navigation and control system of unmanned air vehicle, *Aircraft Engineering and Aerospace Technology* 75(6): 581–587.

Tomczyk, A. 2004. Facilitated airplane – project and preliminary in-flight experiments, *Aerospace Science and Technology*. Elsevier.

PASIŪLYMAS MAŽŲ BEPILOČIŲ ORLAIVIŲ NAVIGACIJOS IR KONTROLĖS SISTEMOMS

G. Kopecki, J. Pieniążek, T. Rogalski, P. Rzucidło, A. Tomczyk

S a n t r a u k a

Šiame straipsnyje aprašomas bepiločių orlaivių kontrolės sistemos projekto įgyvendinimas Ržešovo technologijos universiteto Aviacijos prietaisų ir kontrolės sistemų katedroje. Projektas atliktas remiantis ankstesne patirtimi. Pateikta ne tik borto sistemų bendroji struktūra, bet ir kontrolės stočių struktūra. Darbe nagrinėjamas žmogaus veiksnys, gedimų aptikimas ir sistemų rekonfigūravimas pasiūlytose kontrolės ir navigacijos procedūrose.

Reikšminiai žodžiai: orlaivio kontrolės sistemos, bepiločiai orlaiviai.