AUTOMATIC CONTROL SYSTEMS

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PRACTICAL EXPERIENCE OF INTELLECTUAL UAV ATTITUDE STABILIZATION SYSTEM COMPUTER-AIDED DESIGN

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Abstract**—***The problem of design of the intellectual attitude control system for small UAV is considered. This system is designated for UAV stability and controllability augmentation in the manual control mode. This problem is solved via combination of the traditional and robust control, and usage of the model-oriented design approach. The results of design are verified in the processes of multi-stage simulation and experimental flight tests; their interpretation is given.*

Index Terms—UAV; Stability and Controllability Augmentation System; attitude determination; attitude control; robust control; simulation; flight test.

I. INTRODUCTION

Besides the problems of the fully automated UAV flight control, there is growing interest during the last time to enhancing of the UAV manual control in order to alleviate the ground pilot load. In this case there are efforts of application of UAV attitude control, which can be used as the stability and controllability augmentation system (SCAS) for the ground pilot. The SCAS design at the modern stage of the flight control theory requires application of the intellectual UAV control system in order to increase the flight safety and to improve the UAV handling qualities [1]–[5].

It is necessary to note, that SCAS of this type are operating, when visual or telemetric contacts between pilot and UAV exist and human operator is acting on the reference values of the attitude control and the reference value speed control, if necessary. In the modern control theory there are significant amount of methods for synthesis of the angular stabilization systems [6]–[11]. These methods create the theoretical background of intellectual SCAS (ISCAS) based on the estimation of the controlled plant and minimization necessary performance indices, thus providing suboptimal control of UAV flight.

In this paper the ISCAS design problem is considered on the basis of the model-oriented design (MOD) [12]–[14] in order to provide the UAV operation in conditions of acting of external (atmospheric) and internal (parametric) disturbances. Model-oriented design gives possibility to keep the characteristics of stability and controllability as well as the performance index of the closed loop “UAV-ISCAS” at the acceptable levels.

II. PROBLEM STATEMENT

The initial data for design procedure are: given UAV and the mathematical model of its dynamics, given set of sensors and actuators and their characteristics, functions of the navigation and attitude control systems, and desired characteristics of the closed-loop “UAV-ISCAS”. Using this information it is necessary to synthesize the navigation and control algorithms (ISCAS software), to design ISCAS hardware and to verify designed software and hardware in accordance with requirements and standards issued by Federal Aviation Administration and (or) European Aviation Safety Agency likewise to ARP 4754 for aviation systems and DO-178B for airborne equipment [15]–[17]. Aforementioned MOD approach completely complies with these standards and requirements. This approach is based on several stages of system modeling, when each such stage is using “in-loop-simulation” technology. This technology supposes embedding of specific models in the closed loop system (in this case “UAV-ISCAS”) at each stage of the design process.

III. DESCRIPTION OF THE ISCAS DESIGN PROCEDURE

The flow chart of the design procedure is represented in the Fig. 1. As it was stated before the ISCAS design procedure is starting from the collecting of the initial data, including mathematical

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models of UAV and external and internal disturbances, acting on UAV in operational conditions, as well as models of sensors and actuators. Further stages of the design procedure include:

1. Synthesis of the control laws and navigation algorithms for selected modes and conditions of operation;
2. Simulation modeling using the mathematical models of the UAV dynamics and disturbances along with control laws and navigation algorithms in the closed loop "UAV-ISCAS" (Model-in-loop-simulation). Note that these models will be used in all further stages of design;
3. Verification and estimation of the simulation results and correction of parameters of control laws and navigation algorithms (hereafter we will include these procedures in corresponding stages by default);
4. Simulation with program realization of the ISCAS algorithms (Software-in-loop-simulation);
5. Simulation with control laws in microprocessor in the closed loop (Processor-in-loop-simulation);
6. Simulation with the Field-Programmable Gate Arrays (FPGA-in-loop-simulation) in order to develop the interface between microprocessors, sensors and actuators;
7. Simulation with complete set of hardware (Hardware-in-loop-simulation);
8. Flight tests along with estimation and verification of their results and possible correction of results of the previous design stages.

Physical realization of designed ISCAS consists of producing of navigation, information and control parts.

The 1st one is designated mainly for the UAV attitude determination as necessary information for the UAV attitude control. The simplest way for such system creation is the usage of the 3-DOF rate gyros and accelerometers and their fusion via simple complementary filter [18], which must be implemented in the separate navigation microprocessor.

The 2nd part consists of the module of Global Positioning System (GPS), barometric altimeter and magnetometer for providing pilot with necessary information about UAV current position and heading angle. These sensors were not included in the attitude control loop. Besides them we used airborne telemetric equipment and airborne system for flight data records.

The 3rd control part includes microprocessor for implementation of ISCAS control algorithms, flight simulator for Windows and Linux platforms, Ground Control Station (GCS), and Remote Control Panel (RCP). It is necessary to note separately, that this part includes algorithms for GCS operation, which provide the displaying of the UAV current attitude, position and the flight director information for pilot.

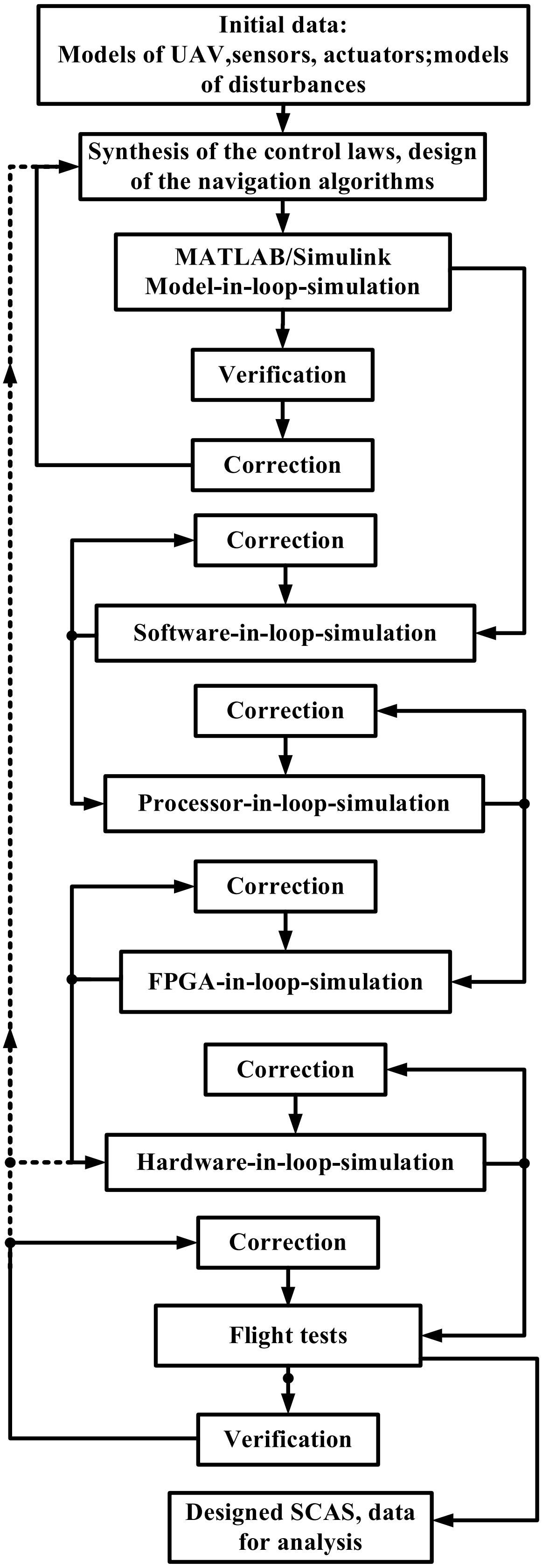


Fig. 1. Flow chart of the design procedure

Intellectual attitude control requires the development of the dynamic library of control laws for different flight missions and conditions of operation. Achieving of this goal requires multiple executing of procedure of the control law synthesis.

It is expedient to describe briefly the content of each stage of the design procedure.

IV. MODEL-IN LOOP-SIMULATION

The dynamic characteristics of the UAV as a controlled plant are necessary for starting of the 1st stage of design procedure (Model-in-loop-simulation). Authors have chosen UAV with low-wing monoplane aerodynamic scheme. Analytical evaluation of its dynamic characteristics and their linearization are extremely difficult processes due to some specific peculiarities, which are immanent to UAV as controlled plant [6], [7], [14]. These include:

– the significant influence of the interconnections between the UAV longitudinal and lateral motions due to the aerodynamic, kinematic, and inertial cross couplings;

– the essentially nonlinear properties of the UAV aerodynamic characteristics at the high angles of attack, which appear in the process of the automated take-off;

– the impact of the wind shear, non-stationary flight dynamics due to the influence of the earth proximity during the UAV automated landing;

– the presence of delays and abrupt disturbances (for instance, some critical values of delay can destabilize system);

– the navigation errors (attitude estimation errors, true air speed and ground speed estimation errors, etc.).

Therefore the most valid data of the given UAV dynamic characteristics could be obtained with the experimental study. Authors developed the method of experimental estimation of the UAV dynamic characteristics, which are based on the usage of logic elements, the rule base, and consideration of the controlled plant from the "black box" point of view. It makes possible performing of the simulation based on Monte-Carlo method [19], [20] and usage of the expert estimation of the UAV pilot-operator as well as the estimations of the experimental team, which is could be considered as the expert group also. It was developed the set of programs in the Matlab/Simulink environment for computing based on the aforementioned method. On the basis of the developed mathematical model authors created methods of evaluation of errors between the real and model data in the on-line verification procedure (using telemetric data with sampling rate 30 Hz).

The next step is the development of the dynamic library of algorithms for ISCAS. They are designated for execution of the following functions:

– the UAV stability and controllability augmentation ;

– the avoiding of the UAV flight parameters from exceeding the operational restrictions;

– the transformation from the UAV arbitrary initial position to the position of the horizontal flight mode;

– the automatic control of the UAV angular and spatial position at all modes from the take-off to the landing in the presence of the parameters uncertainty;

– the maximal alleviation of the influence of the external as well as the internal disturbances, which could be structured and unstructured as well;

– the improving and simplification of the pilot's operations during the UAV manual piloting;

– the possibility of effective performance of the flight mission by the human pilot especially, when it is associated with precise piloting.

The stability and controllability requirements are based on the standard MIL-F-8785B [21], taking in account results of the ground and flight tests. The bump-less transfer from the manual to the automated mode is provided in order to avoid abrupt changes of the UAV motion parameters, as well as to provide soft transfer from semi-automated mode (with ISCAS) to the manual mode in a case of the ISCAS failure. ISCAS in combination with GCS provides the indication of the current and required (or director) UAV position signals.

The ISCAS control laws block consists of two components: the first one is determined by the method of the robust control synthesis for unstable and nonlinear plants using PD-controllers [22]; meanwhile the second one is the knowledge base of the control laws (dynamic library). All these measures provide the ISCAS operation in conditions of influence of structured and unstructured, external and internal disturbances, and sustaining the "UAV-ISCAS" closed loop performance and robustness indices at the desired level [7], [22], [23].

It is necessary to note that in the dynamic library of developed ISCAS algorithms the classic methods of decoupling are used [7], [8], [23]. For instance, the cross-coupling in the lateral motion control law between roll and yaw channels compensates side-slipping during turns and banks. The signal, which is proportional to the roll angle, is introduced in the pitch angle control law, thus avoiding the altitude variation during maneuvers in the horizontal plane. The signal, which is proportional to the position of the engine thrust control, being introduced in the yaw control loop, compensates the misalignment of engine.

Therefore designed ISCAS significantly decreases the influence of the human factor and simultaneously allows essential improving of the handling qualities and decreasing the pilot's load during flight control, using the advantages of the automatic stability and controllability augmentation system in combination with the knowledge base of the intellectual system.

V. SOFTWARE-IN-LOOP-SIMULATION

At this stage the language C/C++ code is generated automatically, using the Simulink/Embedded Coder and the Simulink block diagram instruments. This code is the realization of the program code of microprocessor [24], [25]. Compiled code is executed in the closed loop along with developed mathematical model of UAV. It allows even at the stage of simulation detecting the abundance of the syntax, semantic, and logic errors, which appears during the programming process. Usage of this approach allows decreasing the code volume on programming text language as well as the creation of the formal and clear description of the program behavior. It permits prompt modification of this program, if necessary. The realization of the entire design project is simplified essentially.

VI. PROCESSOR-IN-LOOP-SIMULATION

At the stage "Processor-in-loop-simulation" the verification of the program code in the chosen microprocessor is executing. For this stage of the ISCAS design the following basic qualitative and evaluative parameters are used: effective speed of microprocessor, the volume of the address memory, possibility of the address extension and forming of the additional address domains, command system of the microprocessor [25]. As to the choice of the microprocessor operating system, it is expediently to give preference to real time operating system, designated for UAV module Avionics, possessing file system certified by standard DO-178B [26].

VII. FPGA-IN-LOOP-SIMULATION

The stage "FPGA-in-loop-simulation" is designated for design and verification of scheme, printed circuit board, and physical ISCAS structure, based on usage of the multiple programmed logic gate arrays [27]. Using this verification it is possible to evaluate how much resources must be used for printed circuit board design. The following possibilities appears: variations of the printed circuit size, amount of layers, amount of inputs/outputs of the pulse-width modulation (PWM) blocks; the variation of allocation of the navigation system main components and MicroSD slot for airborne flight data acquisition system. It is possible also to determine ports for connection the wireless telemetry, GPS module, additional sensors and, eventually, to achieve decreasing of the mount/dismount complexity.

It is obvious, that usage of "FPGA-in-loop-simulation" shortens time of development, adjustment, and errors detection on the earlier design stages.

VIII. HARDWARE-IN-LOOP-SIMULATION

At the final stage "Hardware-in-loop-simulation" the simulation is executing using all "UAV-ISCAS" hardware and software in the closed loop. During the process of this testing the designer can choose the method of differential equations solving and method of model time changing (fixed or variable steps). It is possible also to simulate the navigation measurements errors, to take into account diverse disturbances acting on UAV, to observe all processes in the closed loop (i.e. to realize the visual programming principle) and to represent the simulation results in forms of tables and plots. In order to illustrate the efficiency of the practical usage of the designed ISCAS, the 3D-modelling on the basis of the "Flight Simulator" is performed.

IX. FLIGHT TESTS

This final stage provides the experimental investigations of stability and controllability of the "UAV-ISCAS" closed loop system, and the algorithms verification of the designed ISCAS. Results of the flight tests are background for the decision making concerning the performance of ISCAS operation in real time. The qualitative and quantitative estimations of stability and controllability of the "UAV-ISCAS" closed loop are made on the basis of the set of special maneuvers made under given conditions (different deflections of each control surface in some predetermined sequence). It is the obligatory content of the human pilot flight mission [28].

For estimation and final parameters adjustment of the designed ISCAS the flight series were performed in the different modes of its operation with speeds from 11 to 20 m/sec at the altitudes up to 200 m. The UAV model with low-wing monoplane aerodynamic scheme was chosen for the flight tests. The COTS (Commercial-Off-The-Shelf) RC model Cessna® 350 Corvalis® [29] is the example of such UAV. The photo of this UAV is represented in the Fig. 2; meanwhile the geometric and mass-inertial characteristics are given in the Table. In the process of the designed ISCAS flight tests authors have used portable GCS [1]. Figure 3 shows the visual information on the GCS display, which determines UAV current attitude, altitude, velocity, heading, rotation rate of engine and other flight parameters.

The results of one test from the flight tests series during the period equal 1150 sec from the take-off moment to the landing moment are represented in the

Figs 4–9. Figures 4–6 represent: the plots of the transient processes of two UAV attitude angles (roll and pitch); the plot of the UAV ground velocity and altitude under conditions of the external atmospheric disturbances, which were characterized by ground wind having velocity r.m.s about 3.5 m/sec.

Fig. 2. UAV test model

UAV CHARACTERISTICS

Wingspan (m)	1.45
Length (m)	0.965
Wing area (m²)	0.233
Take-off weight (kg)	1.5
Wing load (kg/m²)	6.4
Max speed (m/sec)	20
Moments of inertia: I_x, I_y, I_z, I_{xz} (kg*m²)	0.08, 0.129, 0.163, 0.041

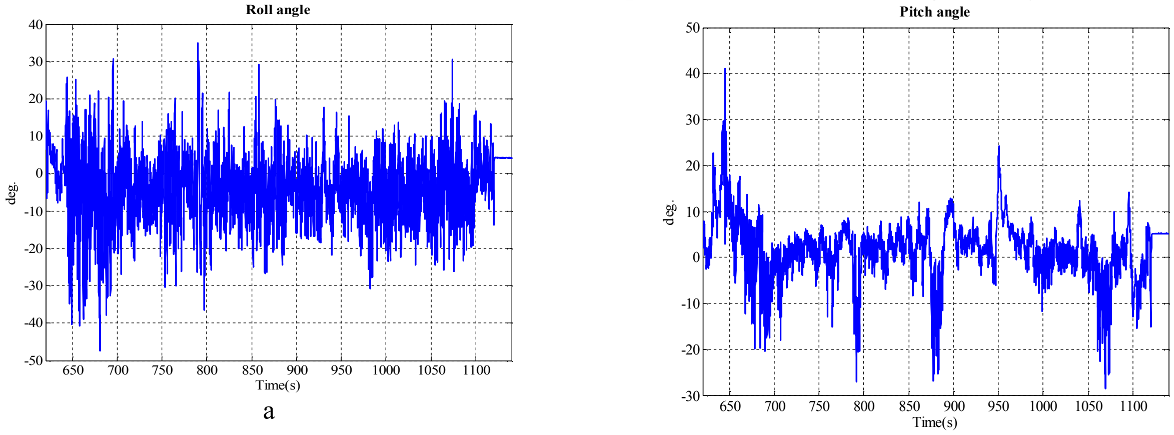
Fig. 3. UAV Ground Station

During this experiment authors tested different modes of the UAV operation, such as automated control of the UAV attitude, transforming the UAV arbitrary initial spatial position into the horizontal flight position, and automated flight altitude control. It was done in order to make general testing of the flight modes, the ISCAS performance in these modes, as well as to perform further improvements and adjustments of the mathematical model of the controlled plant as well as the designed ISCAS control laws.

Figures 7 represent the plots of the angular rates measured by the navigation system (roll rate and pitch rate); and the control surfaces deflections. In these plots the period from 750 sec to 805 sec is marked with vertical lines. During this period the ISCAS was switched off and human pilot performed UAV flight control in the pure manual mode.

Results of the UAV flight tests in the turbulent atmosphere show that the maximal spans of the magnitudes of the pitch rate signals in the manual mode control without ISCAS usage equals: +35deg/sec, -50deg/sec. For the roll rate signals these spans are: +110 deg/sec, -75deg/sec. Meanwhile the same spans in a case of ISCAS usage are +10, -28 deg/sec for pitch rate and +48, -25 deg/sec for roll rate.

Figure 8 shows the deflections of elevator and ailerons, which are essentially less than in a case of manual control without ISCAS (at least more than two times). So the control power is decreasing, thus causing of the energy saving of the UAV engine battery and decreasing of the actuators wearing. The 3D plot shown in the Fig. 9 demonstrates 3D flight path during experimental flight, where sign "triangle" denotes take-off moment and sign "circle" denotes landing moment. It could be seen from this Figure, that ISCAS can be successfully used for manual following of the arbitrary complicated flight paths. So all given Figures show that the stability and controllability characteristics are improved and the requirements of the UAV flight safety are satisfied.



a

b

Fig. 4. Plots of UAV attitude angles: a is the roll angle; b is the pitch angle

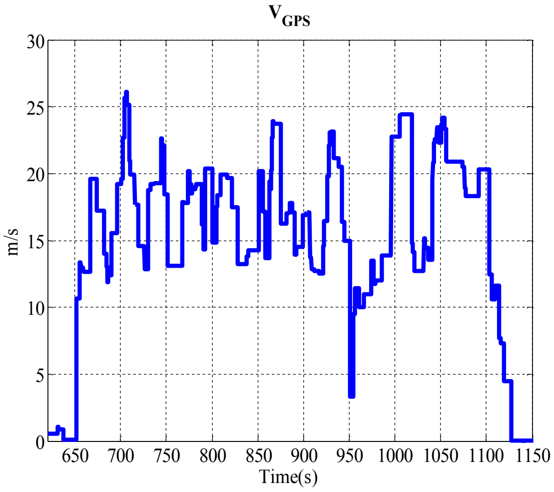


Fig. 5. Plot of the UAV ground speed

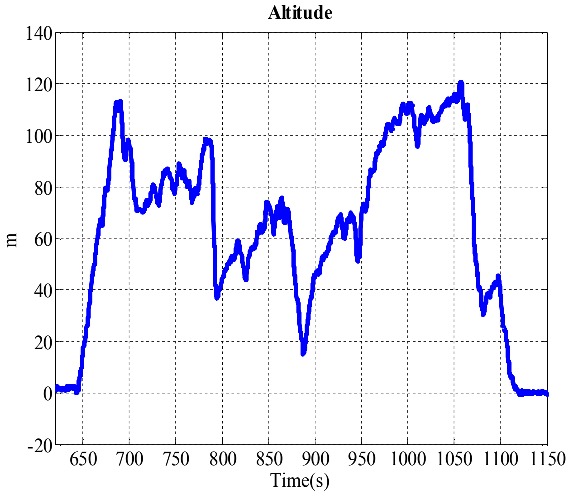
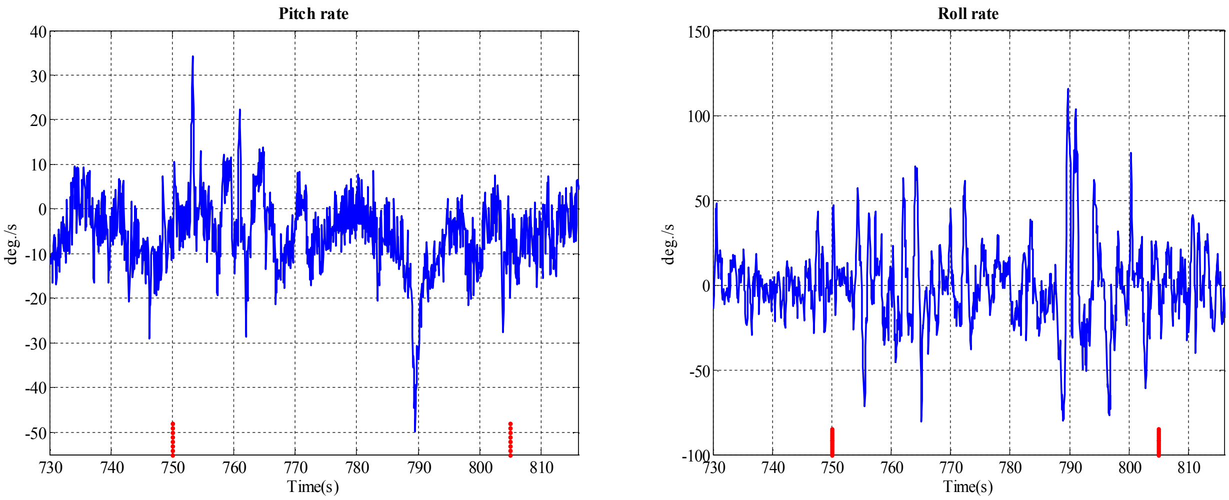


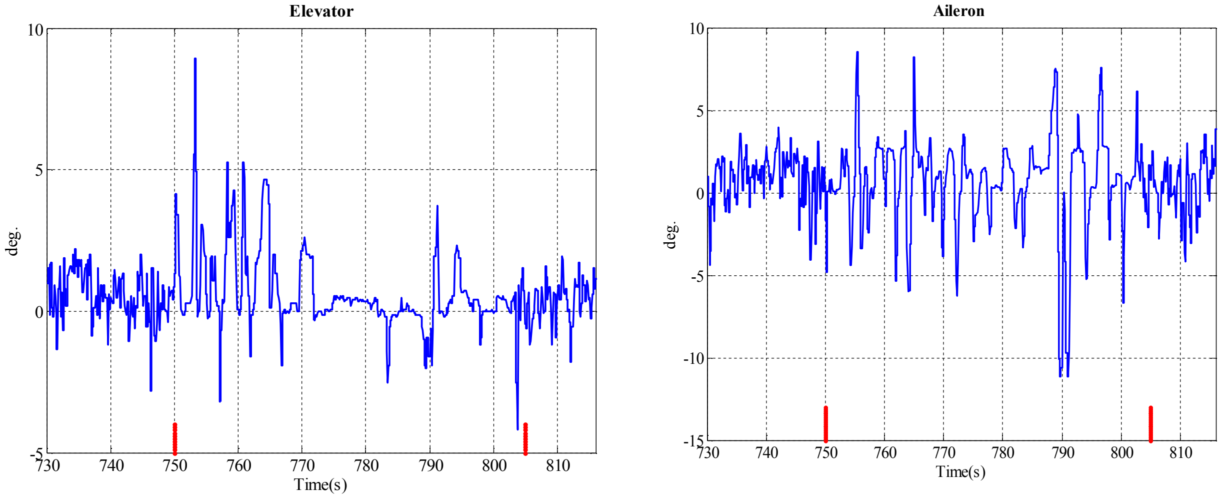
Fig. 6. Plot of the UAV altitude



a

b

Fig. 7. Plots of UAV angular rates: a is the pitch rate; b is the roll rate



b

a

Fig. 8. Plots of the control surfaces deflections: a is the elevator; b is the aileron

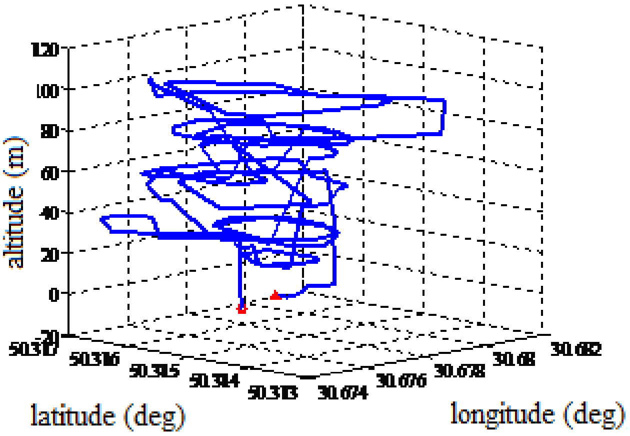


Fig. 9. 3D flight path of UAV in the topocentric frame

CONCLUSION

In this paper authors described their practical experience and vision of the solution of the intellectual attitude control design problem for UAV. Designed control system can be considered as intellectual stability and controllability augmentation system (ISCAS) for UAV in a case of visual or telemetric contact between ground pilot and UAV.

The "skeleton" of the design procedure for such system is proposed. It is based of multistage procedure of "in-loop-simulations", providing design of ISCAS, which is able to withstand the influence of the external and internal, structured and unstructured disturbances. This approach essentially decreases design time and project expenditures.

Results of simulation and flight tests confirm the correctness of the design stages, operability of ISCAS algorithms, and demonstrate satisfying of the design requirements.

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А. А. Тунік, К. Ридло, О. В. Савченко, К. В. Мельнік. Практичний досвід комп'ютеризованого проектування інтелектуальної системи кутової стабілізації повітряного безпілотного повітряного судна

Розглянуто задачу проектування інтелектуальної системи кутової стабілізації для малого безпілотного повітряного судна. Ця система призначається для покращення стійкості і керованості безпілотного повітряного судна в режимі ручного управління. Поставлену задачу вирішено за допомогою сполучення елементів традиційного і робастного управління з використанням методів модельно-орієнтованого моделювання. Результати проектування верифікуються за допомогою багатоетапного моделювання та експериментальних льотних випробувань. Наведено їх інтерпретацію.

Ключові слова: безпілотне повітряне судно; система покращення стійкості і керованості; система орієнтації; система кутової стабілізації; робастне управління; імітаційне моделювання; льотні випробування.

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А. А. Туник, К. Рыдло, А. В. Савченко, К. В. Мельник. Практический опыт компьютеризированного проектирования интеллектуальной системы угловой стабилизации беспилотного воздушного судна

Рассмотрена задача проектирования интеллектуальной системы угловой стабилизации для малого беспилотного воздушного судна. Эта система предназначена для улучшения устойчивости и управляемости беспилотного воздушного судна в режиме ручного управления. Решение поставленной задачи осуществлено за счёт сочетания элементов традиционного и робастного управления с использованием методов модельно-ориентированного проектирования. Результаты проектирования верифицируются с помощью многоэтапного моделирования и экспериментальных лётных испытаний. Приведена их интерпретация.

Ключевые слова: беспилотное воздушное судно; система улучшения устойчивости и управляемости; система ориентации, система угловой стабилизации, робастное управление; имитационное моделирование; лётные испытания.

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