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A family of universal miniature autopilots – design solutions, characteristics, hardware/software-in-the-loop simulations

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The article describes a family of miniature flight control and navigation systems, created in the years 2011-2016. The systems are used primarily in an experimental UAVs and in a light aircraft for research purposes. The article focuses on the hardware structure in an autopilot. Additionally, it describes the software structure and its development, as well as hardware/software- in-the loop simulation, which is an important phase during system development. The article shows also a scheme of a laboratory stand used for the Hardware-in-the-Loop simulations, as well as it presents exemplary results of the research.

I. Introduction

SMALL UAVs are very popular. In a university setting they enable low cost research in the area of aeronautical control systems; however, they require an autopilot hardware structure allowing modifications of algorithms. In an autopilot used for research purposes a total control over changes in the algorithms should be possible. It should also allow easy development of redundant and additional elements. Another important feature is the compatibility with the ground station in which the communication protocol is open for modifications. Implementation of the control laws should be possible using automatic code generation tools. The system should be fully compatible with the hardware-in-the-loop simulation stand (Ref. 1,2,4,6,7,16). In the case of research in the area of faults, the possibility to block a single control surface is also significant. What is more, the architecture should take into consideration a typical distribution of research on problems of measurement systems and problems of control.

There are several different kinds of autopilots which can be used in a small UAV, but in most cases producers do not offer a possibility to have control over changes in algorithms. It is almost impossible to buy an autopilot which is ready for research and which fulfills all the requirements mentioned. Therefore, researchers often have to prepare their own hardware. The article describes a family of miniature flight control and navigation systems, created in the years 2011-2016. The systems are used primarily in experimental UAVs and in a light aircraft. They are based on earlier experiences of the staff at the Department of Avionics and Control Systems (Ref. 2,3,9,14,15,17,18,19).

II. Architecture of miniature autopilots

Autopilots of the first generation were prepared for research in the area of handling quality modifications and typical UAV control (Ref. 13, 14). Also, tests of code generation methods were conducted. The first system belonging to the described family consists of 3 units: a power supply unit, a control unit, and a measurement unit (Fig. 1). In this system, the main processor is placed in the control unit, and it is responsible for both the flight control and complex algorithms. An additional processor, placed on a separate printed circuit board, is located in the measurement unit. It enables acquisition and preliminary processing of data obtained from sensors (Fig. 2).

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Due to this structure, the system can be used in unmanned vehicles and in general aviation airplanes. Additional elements (e.g. higher class measurement units, additional registration units) can be connected to the CAN bus.

Figure 1. The first autopilot presented in this paper.

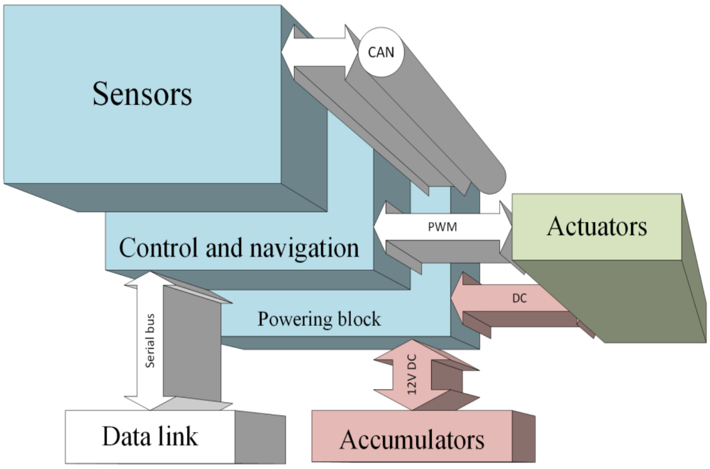

Figure 2. The architecture of the first autopilot described.

In the system presented, the CAN (Controller Area Network) plays the role of the major communications protocol. As a result, the system is open, and its extension is possible – additional components, e.g. a measurement data registration unit can be added. The system is equipped with basic measurement instruments essential for an autonomous flight: a 3-axis gyroscope, a 3-axis accelerometer, a GPS receiver, as well as the static and dynamic pressure sensors. It also includes a servo controller relying on the PWM signals. The system is used primarily in light UAVs.

The system presented is intended mainly for research purposes. Experience gathered during the design phase and the operational phase of the first version of the system, allowed us to notice certain drawbacks of the structure. Namely, at first it was assumed that algorithms will be coded manually by a computer programmer. This slowed down the prototyping process of the algorithms tested. As a solution to this problem, different microcontroller unit was introduced. It allowed easier code generation. The overall size of the autopilot remained the same, an identical system of mechanical fasteners was used. Fig. 3 shows the structure of the second autopilot described.

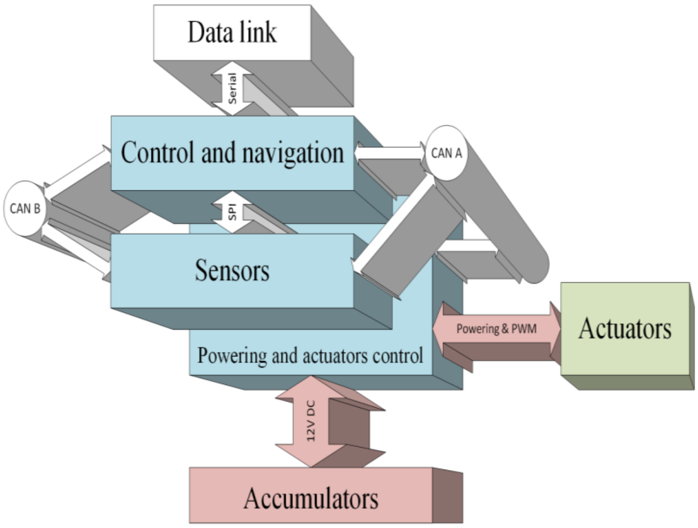

Figure 3. Hardware components of the second autopilot.

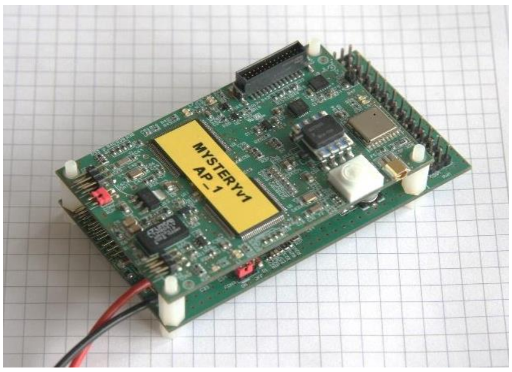

Figure 4. The second autopilot described in this paper.

The autopilot of the second generation, like its predecessor, has a modular structure, and it relies on the board-to-board connection. The upper board, shown in Fig. 4, includes integrated circuits of the autopilot. The lower board contains a power unit and servo controllers sending the PWM signals. Unlike the first-generation system, the system of the second generation can be extended to include redundant components – further addition of modules is possible due to the board-to-board connection. The system relies on two data buses. Communication between microcontrollers occurs through the two data buses, as well as via an additional SPI connection. The first data bus (CAN A), so-called main bus, receives the control signals. The second data bus (CAN B) is an auxiliary/measurement bus. Its role is to acquire data essential for flight control. This data is sent from a measurement microcomputer (Ref. 5, 10, 11).

In the first version, the control computer and the measurement computer were placed on different boards. In the second version, two independent microcontrollers – the measurement computer and the control computer – are both placed on the upper board. Due to the use of two microcontrollers with a high measuring capacity and large memory capacity, the use of automatic code generation and Matlab-Simulink environment was possible. Fig. 5 shows the structure of the created measurement unit; this structure allowed the automatic code generation.

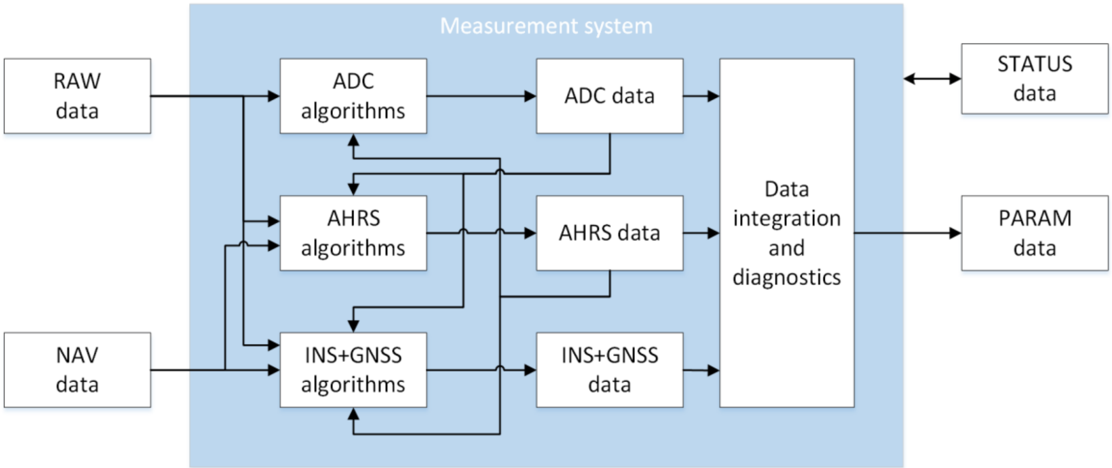

Figure 5. The measurement unit.

The units presented in Fig. 5 are typically used in the flight control systems, such as Air Data Computer, AHRS module, and the navigation module. Calculated data are sent to the block Data integration and diagnostics. This block executes algorithms, whose task is to verify if the data measured and calculated are correct. It also forms the PARAM structure which includes all data essential for flight control.

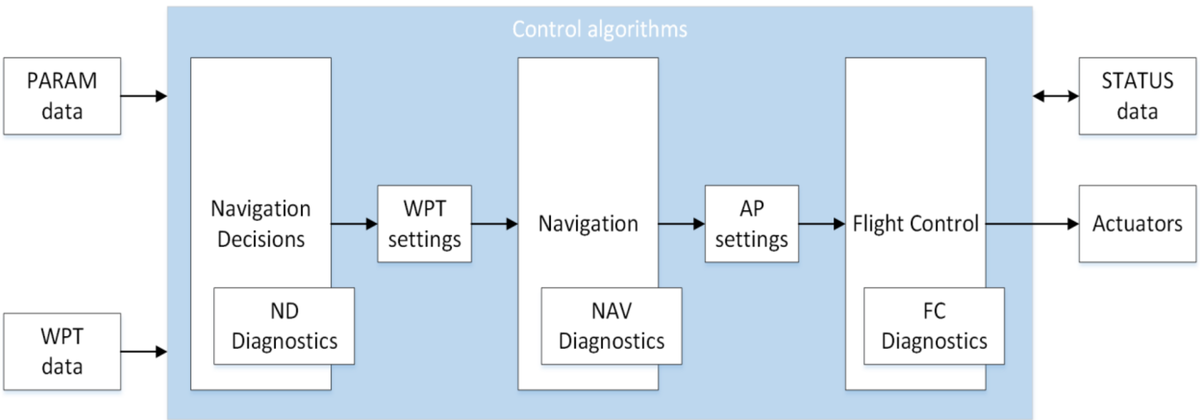

Figure 6. The flight control unit.

The presented software structure enables research work on various types of control algorithms (Ref. 8,14). First, the algorithms are verified with Matlab-Simulink. Next, using the template presented, automatic code generation is performed; the generated code allows direct implementation of the algorithms on the microprocessor. The automatic code generation facilitates the algorithm implementation. The environment variables have to be consistent with Matlab. This research ensures that the structural data generated from the Matlab environment and from the programming environment have been correlated both in the measurement unit and in the control unit.

III. A laboratory stand for hardware/software-in-the-loop tests

The hardware/software-in-the-loop tests are a very important aspect of research on autopilots. Therefore, a special laboratory stand, enabling simulations of the system to operate as a whole, was built. Fig. 7 shows a schematic representation of the laboratory stand created.

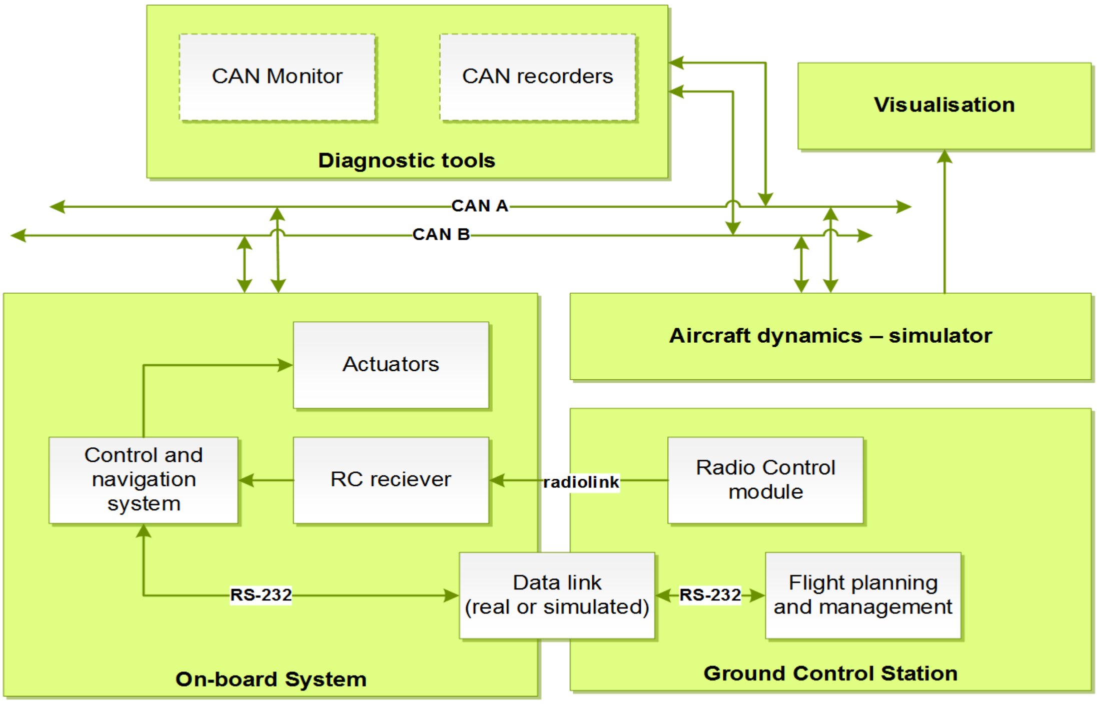

Figure 7. Laboratory stand for hardware/software-in-the-loop-tests – schematic representation.

The described laboratory stand consists of: a PC computer for flight dynamics modeling (X-Plane flight simulation environment), a PC computer for the data monitoring and registration (CAN Monitor system), a module consisting of an autopilot, a ground control station, and an on-board data recorders. Such a configuration allows to perform the tests of both hardware and software. For communication between all components of the stand, the CAN bus is used. Communication between particular modules is realized by means of the CAN bus. The CAN aerospace protocol is used. Conducting functional tests of the system is simpler due to registration and monitoring of the flight parameters on a PC. CAN Monitor software enables also a direct observation of registered parameters. During the laboratory tests, the ground control station was connected with the RS-232 cable in order to diminish the negative consequences of electromagnetic radiation on humans. Wireless

Figure 8. Multiplex Cularis aircraft.

transmission is tested independently. Tests were conducted with Multiplex Cularis - a popular aircraft model (Fig. 8). For Hardware-in-the-Loop simulations, X-Plane was chosen for modeling aircraft dynamics. In this simulator the calculation of aircraft behavior is based on the Blade Element Theory. Aircraft aerodynamics is based on the aircraft geometry, and extended by using parameters such as airfoil characteristics. Additionally, weight parameters used for calculation of inertia force and moment, such as CG location, weight, weight shift have to be taken into consideration.

For autopilots of the first generation, the X-Plane simulation model of the aircraft was used, but without an accurate model tuned-up to real aircraft. Tests conducted in the simulation environment where mainly aimed at system tests, flight control tests (e.g. control laws limiting pilots input which aimed at not exceeding the flight envelope), and determination of failures in the code implemented on the autopilot module.

The X-Plane simulation model was also developed for autopilots of the second generation. In order to do this, the following steps were taken. First, geometrical parameters where determined using 3-D scanning methods of real aircraft model. These were used to define the aircraft geometry for modeling in simulation environment.
Next, cloud points obtained from this process were transformed into a solid model and prepared for further application in computational fluid dynamics (CFD) methods. Tests relying on these methods were used to calculate aerodynamic characteristics. Then, weight parameters were set up for the model (weight, CG position, moments of inertia). Moments of inertia were calculated from performed measurements. For the propulsion modeling, wind tunnel tests were performed. These steps led to the development of the X-Plane simulation model. They were also used for developing models used for the synthesis of control laws.

In order to verify the simulation model, responses of the model aircraft (simulation tests) were compared with the responses of a real aircraft (data from flight tests).

The simulation model and the X-Plane environment connected with the CAN bus can be used for checking systems, a part of control laws (in particular control laws for reconfiguration in case of different aircraft failures). This facilitates system development and allows detection of design errors, especially errors in the software.

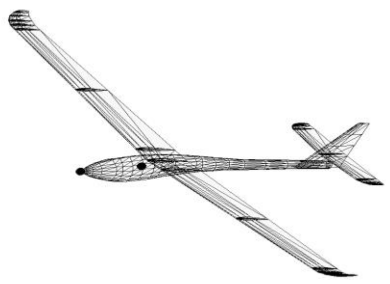

Figure 9. Geometry of aircraft realized in X-Plane.

IV. Exemplary results

The autopilots presented are universal, and they can be used in different types of aircraft. Fig. 10 shows an

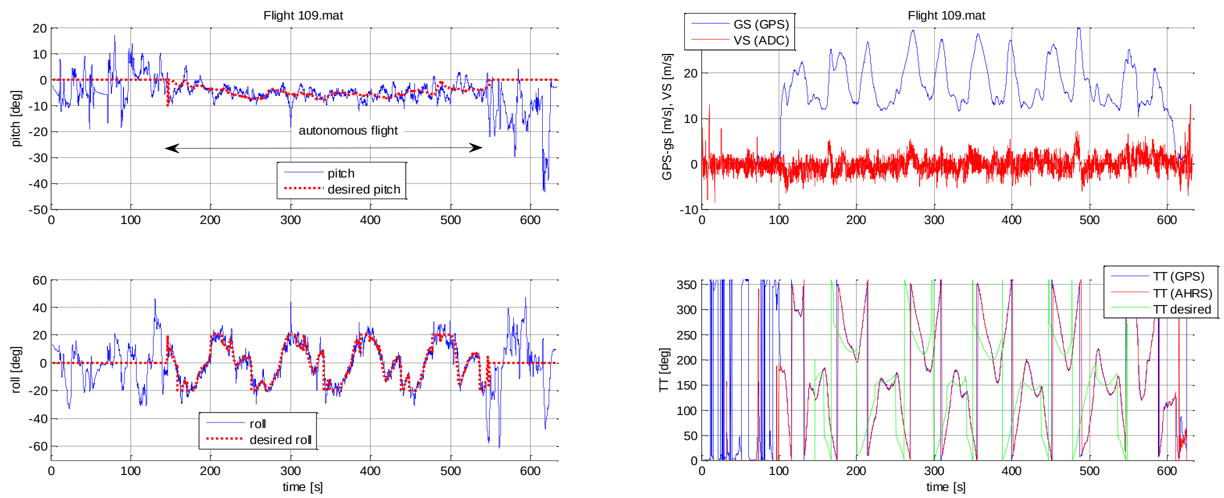

Figure 10. Exemplary data registered during an autonomous flight of Multiplex Cularis model aircraft (flight 109).

exemplary set of data registered during the tests of flight control laws performed with the Multiplex Cularis model aircraft, flying on the first autopilot described above.

The exemplary test performed on the aircraft model, includes the data used to verify the accuracy of mathematical model for the X-Plane simulation environment. Fig. 11 shows the pitch angle distribution, with phugoids in the aircraft gliding motion, registered during a real flight. Fig. 12 shows the distribution obtained during simulations performed with the use of the laboratory stand described.

In Fig. 13 an exemplary set of data registered during flight of Piper Seneca V airplane (the second autopilot described above was used) is shown. The data were registered in order to verify the correct operation of the system, as well as to test methods of analytical redundancy. Measurement algorithms were created using automatic code generation.

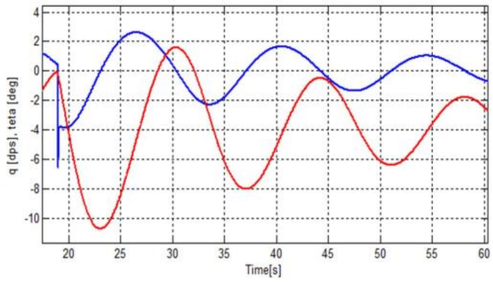

Figure 12. Pitch angle distribution with phugoids for Multiplex Cularis simulation model.

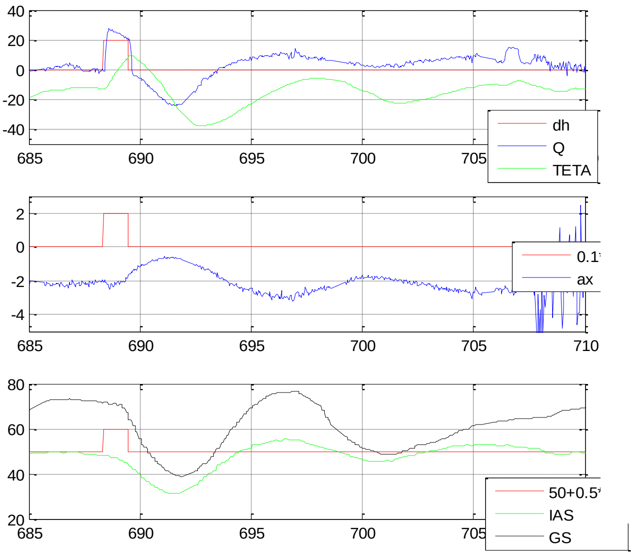

Figure 11. Pitch angle distribution with phugoids for Multiplex Cularis airplane - gliding.

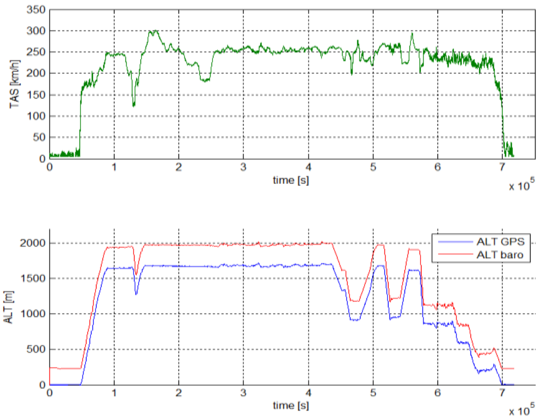

Figure 9. Exemplary data registered on the Piper Seneca V airplane (flight 1/150717).

V. Conclusions

Hardware tools are very important and necessary for research in the area of control systems. The specificity of research tasks, very often makes the costs too high for commercial systems. To avoid problems with systems compatibility, a tailor-made hardware was prepared. The presented solutions can be used in different kind of research in the area of control systems.

As emerging from the article, the autopilots described can be used in a variety of tests, such as, for example, the tests of control algorithms, or tests of measurement algorithms. In the case of the second autopilot presented above, it is possible to apply the mechanisms of automatic code generation. This significantly reduces the time needed to perform the tests, and facilitates the research. Moreover, the laboratory stand described allows detection of errors during the test phase, and hence, the creation of the whole system is facilitated as well.

The simulation model described in the article is used for Hardware-in-the-Loop simulations. Authors have positive experiences with X-Plane used for simulation of aircraft dynamics; however in their research work (e.g. control law synthesis), they use analytical models (nonlinear and linearized models).

The systems presented are very useful for research in the area of control systems synthesis.

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