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SIMULATORS FOR PILOT ASSISTING MODULE OF ADVANCED LIGHT AIRCRAFT CONCEPT

This paper presents the results of Pilot Assisting Module research performed on two light aircraft flight simulators developed in parallel at Brno University of Technology, Czech Republic, and Rzeszow University of Technology, Poland. The first simulator was designed as an open platform for the verification and validation of the advanced pilot/aircraft interface systems and inherited its appearance from the cockpit section of the Evektor SportStar. The second flight simulator, the XM-15, has been built around the cockpit of a unique agriculture jet Belfegor. It introduced a system architecture that supports scientific simulations of various aircraft types and configurations, making it suitable for conceptual testing of Pilot Assisting Module. The XM-15 was initially designed to support research on advanced flight control systems, but due to its continuing modernization it evolved into a hardware-in-the-loop test-bed for electromechanical actuators and autopilot CAN based controller blocks. Pilot-in-the-loop experiments of proposed Pilot Assisting Module revealed favorable operational scenarios, under which the proposed system reduces the cockpit workload during single pilot operations.

1. Introduction

1.1. Concept of advanced small aircraft

In recent years, the general aviation piston aircraft became increasingly popular as personal transportation aids. The impact of technology driven success in light and ultra-light aviation led to a significant reduction of their ownership and operating cost. Flying thus became accessible not only to a privileged group of people, but through a well-developed network of local

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airports it offered an alternative to railway or even car travel. Unfortunately for the industry, the general public didn't stop questioning the level of comfort and safety of light aircraft when compared to sophisticated airliners or business jets. It is the authors' belief that the main safety concern remain attributed to the single pilot operations of mostly amateur crews surrendering to the hazards of bad weather or in-flight failures and emergencies.

Fig. 1. Evektor SportStar light aircraft

A multi-modal fly-by-wire/light flight control system has the potential to significantly simplify piloting of a light aircraft and to reduce the number of errors attributed to human factors. Unfortunately, known commercial fly-by-wire/light systems are overly complex and prohibitively expensive designs for a potential tailored industrial application in the "light aviation". The main concerning issue is the overall fault-tolerance of electronic and electromechanical systems, with the acceptable system redundancy achieved through multiplication of expensive components [4, 6, 12]. In addition to the physical/hardware redundancy, a reliable flight control system requires implementation of a reliable and redundant control code based on (re)configurable control laws [5, 9]. Being aware of these difficulties, the authors have decided to focus their effort on automatic flight control system that supports piloting process of a light aircraft without introducing a control redundancy risk. The proposed solution of *Pilot Assisting Module* (PAM) uses an extended framework of classical autopilot, actively supporting the pilot during navigation procedures in high stress areas or assisting in resolution of different cases of panic, potential loss of orientation or on-board emergencies. The intended platform for an advanced light aircraft project equipped with PAM is the Evektor SportStar presented in Fig. 1.

1.2. Development of experimental flight simulators

The transition from flight control system's conceptual laboratory testing towards the airborne experiments should, in the best case, include pilot- and hardware-in-the loop simulations on a suitably adapted flight simulator. A modification of a high-end professional flight simulator for the purposes of an experimental flight control system testing is a possible but quite problematic option (simulator is withdrawn from routine training process, potential loss of certification/manufacturer's warranty, unavailable proprietary data protocols, different hardware standards, etc). A more flexible and affordable solution turned out to be a custom-designed experimental platform. Two unique experimental research simulators were developed in parallel at the Brno University of Technology (BUT) and Rzeszow University of Technology (RUT), to meet the specific objectives of PAM modeling, verification and validation.

2. SimStar experimental simulator

2.1. Cockpit configuration

The SimStar is a light aircraft simulator stationed at the Faculty of Information Technology at the Brno University of Technology. It is based on the cockpit section of an Evektor SportStar aircraft. Figure 2 depicts the SimStar with a closed canopy during a simulation break. Compared to the original aircraft, the simulator's cockpit is equipped with a dual 12" touch screen flight data visualization system, which can be seen in figure 3. The "smart screen" technology allowed for a rapid design changes and quick modifications of the display layout and played a vital role in the simulator's overall conceptual design. An instrument panel of a state-of-the-art light aircraft (LSA, ULL) typically features a "glass-cockpit" with a pack of backup analog instruments. These provide the crew with basic aircraft flight state information in an unlikely event of flight display breakdown. In order to comply with the current perception of the flight deck safety, an airspeed indicator and an altimeter have been installed into the instrument panel, to support the crew with a classical reference for flight data readout. One of the principal objectives during the instrument panel design phase was to enable a display environment with large digital screens that would have the potential to evolve into a standardized interface combining different, currently functionally isolated, replaceable units (radio, GPS, round dial instruments) as seen in modern integrated avionics solutions. One of the Primary Flight Displays (PFD) designs that accommodate the above mentioned principles can be seen in Figs 3 and 4.

Fig. 2. SimStar's cockpit section

Fig. 3. Instrument panel with a dual PFD

The basic principle upon which the PFD has been composed is the clarity and the readability of presented information. The flight displays support different modes of operation, ranging from traditional visualization of flight instruments, to enhanced synthetic vision concept with a tunnel in the sky flight path symbols. All of the tools have been implemented with a single vision – to provide the pilot with a concept of visual aids that would result into a safer flying.

2.2. Flight controls and force feedback

Since the visual stimulation does not provide the sole source of the flight status information, other perceptual channels needed to be included as well. A critical aspect of successful piloting of a light aircraft lies behind the unique perception of haptic clues experienced by the pilot in flight. Therefore, a cautious approach has been undertaken during the early stages of SimStar's conceptual design, to correctly include this requirement to the overall system's architecture. The currently installed force-feedback system for the control stick and the rudder pedals provides the crew with a virtual link between the maneuvering state of an aircraft and the forces acting in its control system. A side-by-side rudder pedal assembly found in a light aircraft is shown in Fig. 5. As part of the intended future research aims towards the identification of operational fly-by-wire modes, which would possibly eliminate the need for an active force feedback system and substitute it with smart visual clues, the loading mechanisms in SimStar can be optionally disengaged or modified to provide linear dependence between the perceived loading and an adequate control surface deflection.

Fig. 4. Initial design of instrument panel

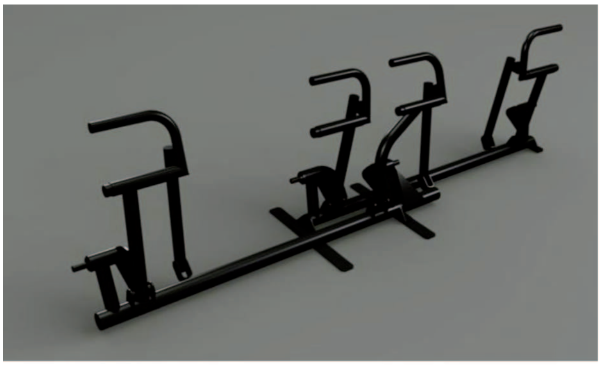

Fig. 5. Rudder pedals installation

2.3. Audio and visual system

In addition to the previously mentioned components, SimStar has been equipped with devices supporting voice activated communication between the pilots or between the pilot and the SimStar operator. It not only provides for more realism, but helps to identify and prevent possible emergencies.

Fig. 6. SimStar during flight simulation

Simulator's principal multimedia platform features a planar 4m/3m projection screen and an audio system providing enhanced authenticity during simulated flight operations. For the convenience, the simulator currently resides on a stable platform and an alternation to a 6DOF (Degrees Of Freedom) motion pad is planned as a part of the perspective upgrades. A typical simulation run is presented in Fig. 6. Modular design of simulator's hardware and software architecture allows for a direct integration or sharing of different flight models. By applying extension blocks, the simulator can be subsequently used for hardware-in-the-loop ground based simulations of experimental avionics. The simulator's architecture supports data recording capability, used to store the time histories of the simulated flights. These are a valuable source of information for post-processing and subsequent debugging tasks.

Fig. 7. SimStar in a stand-by mode

3. XM-15 simulator

3.1. Simulator design

The flight simulator designed at RUT, Faculty of Mechanical Engineering and Aeronautics, Department of Avionics and Control, is based on the cabin section of the M-15 Belfegor, an agriculture jet built in Poland at the beginning of 1980's. One cockpit of this aircraft has been adopted by RUT in the 1990's for educational and research purposes. Functionality of the XM-15 has been improved during past years by adding visualization system, force feedback (FF), real-time rapid prototyping environment (RTRPE), electronic instrument panel and a set of flight simulator applications (FSA). The main block modules of the XM-15 simulator (Fig. 8) are connected using CAN (Controller Area Network) data bus [1]. Application of CAN network and *CANaerospace* standard communication protocol [2] led to an open architecture compatible with the state-of-the-art on-board systems and enabling hardware-in-the-loop simulations of electromechanical actuators, instrument panels and inceptors equipped with standardized CAN controllers [9].

Particular modules and subsystems of the XM-15 flight simulator are grouped into following functional blocks:

- aircraft dynamics and atmosphere models,
- inceptors and FF system,

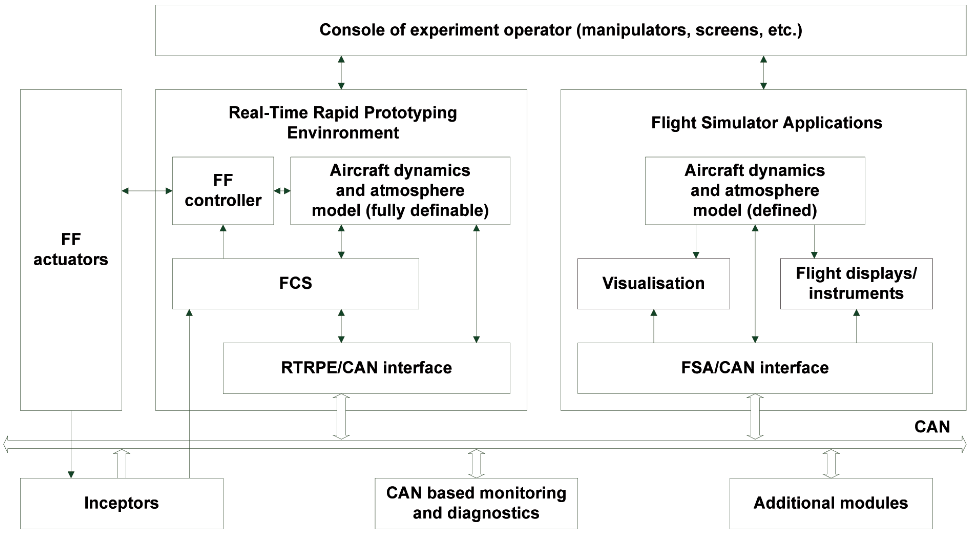

Fig. 8. Block scheme of the experimental simulator XM-15

- flight control system (FCS),
- flight displays and visual system,
- monitoring and experiment management,
- extension modules (e.g. hardware in the loop).

3.2. Aircraft Dynamics

The block structure of the XM-15 simulator allows for a convenient integration of aircraft dynamics and atmosphere models within the RTRPE framework. Above this, the XM-15 also supports the implementation of external models in the form of separate applications. The simulator has by default integrated a non-linear aircraft dynamics model of PZL-110 Koliber [8]. Bi-directional accessibility to parameters of external models is performed through *TrueSight* application, which is a software element of FSA/CAN interface.

3.3. Inceptors and force feedback

The design philosophy behind the XM-15 retained the concept of using the original inceptors: control wheel, rudder pedals and thrust lever. Control inceptors' deflections are transmitted via mechanical linkages to a block of potentiometers located at the back of the simulator. The deflections/translations are processed within the A/D converters of RTRPE or inside a customized data acquisition unit. To compute the desired forces on the control wheel, the XM-15 force feedback controller accounts for the actual flight parameters, simulated wind effects and the inceptors' position. Forces in the pitch and roll channels are transmitted by the FF actuators, assisted by a set of springs and levers. The yaw channel is during simulations proportionally loaded to match the rudder deflection.

3.4. Flight control systems

The FCS block emulates the following control systems depending on selected aircraft configurations:

- mechanical control system based on levers, cables, pushrods and springs,
- mechanical control system with hydraulic amplifiers,
- fly-by-wire system in direct, CAS (Control Augmentation Stabilization) and SAS (Stability Augmentation System) mode.

The FSC block natively features control algorithms for classical or a Total-X based autopilots with longitudinal and lateral-directional modes [7]. Due to the simulator's open architecture and its inbuilt hardware-in-the-loop capability, real autopilot hardware can be integrated and tested within the XM-15 as well. The FCS architecture was primarily designed to support the simulations of PAM. This solution enables an interactive support of piloting process. After the activation, PAM trims the aircraft to execute a predefined flight plan with energy conserving control and navigation algorithms [3]. The pilot can step in and manually control the aircraft during all phases of flight, while the FCS prompts him/her to actively manage aircraft's total energy states and thus actively influence noise and emissions. PAM may positively contribute to the improvements of piloting skills and prevention of potential losses of control in panic cases or while flying in bad weather conditions.

3.5. Flight deck and visual system

The flight deck of the XM-15 simulator is based on the original M-15 Belfegor cabin (Figure 9), with the analogue indicators at the instrument panel being replaced by a single 24" LCD screen. This solution introduced more flexibility into the visualization of different types and configurations of classical analogue indicators, as well as digital displays (Figure 10).

3.6. Monitoring and diagnostics

The XM-15 experimental platform offers monitoring and data acquisition capability on three different levels. Particular parameters are processed in RTRPE system and can be observed, tuned and recorded during the experiments from the operator's console. External data recordings, monitoring and diagnostics are also possible with the use of *CAN Monitor* system [9].

Fig. 9. General view of XM-15 simulator

Fig. 10. Flight deck of XM-15

TrueSight application offers a simultaneous access to the internal parameters of the FSA and to data transferred via CAN bus, with an option to list specific parameters which are to be recorded.

4. Pilot assisting module

4.1. Total-X control theory

It is industry's belief that a control system with a direct stabilized control of airspeed and flight path will be a major step in making personal air transport more accessible to broad public [10]. This opinion motivated the experimental implementation of a flight control concept known as the Total

Energy/Heading Control System (TECS/THCS, Total-X). The total energy E_T of an aircraft in longitudinal motion can be defined as the sum of energies: $E_{Kinetic}$ and $E_{Potential}$

$$E_T = E_{Potential} + E_{Kinetic} = mgh + \frac{mV^2}{2} \tag{1}$$

The rotational energy, as part of the total kinetic energy of the rigid body system, is assumed to be near zero during steady or quasi steady flight states, as the climbing, cruise and approach pitch rates approach zero, $q \approx 0$. Furthermore, considering the application on general aviation class of non-aerobatic aircraft, rotational energy terms can be fully neglected. The difference (error) between commanded energy and actual flight state is defined as:

$$E_e = mg(h_{cmd} - h) + \frac{m(V_{cmd}^2 - V^2)}{2} \tag{2}$$

The principal motivation behind TECS strategy is to drive the energy error to zero with minimal dissipation or build up of total energy. By differentiating $E_{e,}$ we can obtain formulas for energy rate error $\dot{E}_e$ and energy rate $\dot{D}_e$ distribution error (3-4), as taken from Ref 11.

$$\dot{E}_e = Vmg\left(\gamma_e + \frac{\dot{V}_e}{g}\right) \tag{3}$$

$$\dot{D}_e = -\gamma_e + \frac{\dot{V}_e}{g} \tag{4}$$

where,

$$\dot{V}_e = \dot{V}_{cmd} - \dot{V}, \quad \gamma_e = \gamma_{cmd} - \gamma$$

In steady level flight conditions, the aircraft drag is compensated by the engine thrust T and rate of energy change can be produced directly by the change of thrust $\Delta T_{cmd} = \dot{E}_e$. In TECS control laws, the amount of total energy rate $\dot{E}_e$ is influenced by inputs through different thrust settings (5), whereas the changes of pitch attitude lead to energy redistribution (6) with the elevator control θ_{cmd}. The TECS control strategy allows thrust and elevator control coordination in a decoupled response, causing the γ_{cmd} having a negligible influence on speed fluctuation and vice versa.

$$\delta T_{cmd} = \frac{K_{TI}}{s}\left\{\left(\gamma_{cmd} + \frac{\dot{V}_{cmd}}{g}\right) - \left(\gamma + \frac{\dot{V}}{g}\right)\right\} - K_{TP}\left(\gamma + \frac{\dot{V}}{g}\right) \tag{5}$$

$$\delta\theta_{cmd} = \frac{K_{EI}}{s}\left\{\left(-\gamma_{cmd} + \frac{\dot{V}_{cmd}}{g}\right) - \left(-\gamma + \frac{\dot{V}}{g}\right)\right\} + K_{EP}\left(-\gamma + \frac{\dot{V}}{g}\right) \tag{6}$$

The core feedback integral K_{TI}, K_{EI} and proportional K_{TP}, K_{EP} gains are designed to yield identical dynamics for energy rate error $\dot{E}_e$ and energy distribution rate error $\dot{D}_e$ for either a flight path angle command or a longitudinal acceleration command. Proportional feedback gains operate with absolute values of energy rate and energy distribution rate. The TECS doesn't commands elevator deflection directly, but generates a pitch attitude command, which is under the action of a pitch inner loop subsequently transformed to an elevator input. Similarly is a thrust scaling inner loop transforming the thrust commanding signal into thrust lever setting.

4.2. Total-X based Pilot Assisting Module

The concept behind the Total-X algorithms inspired the authors to further investigate on PAM, which would assist pilots of light aircraft during maneuvering and navigation tasks, while minimizing acoustic emissions and reduce fuel consumption [3], being simultaneously a flight assisting tool and an autopilot. In the case of aircraft fitted with standard avionics, these would require to be re-equipped with an extended set of sensors and a control panel that would introduce an intuitive flight planning capability. After the activation, PAM initiates an electromechanical system, which trims pilot's inceptors (pitch channel and thrust lever) to execute the flight plan in accordance with the energy conserving control and navigation algorithms.

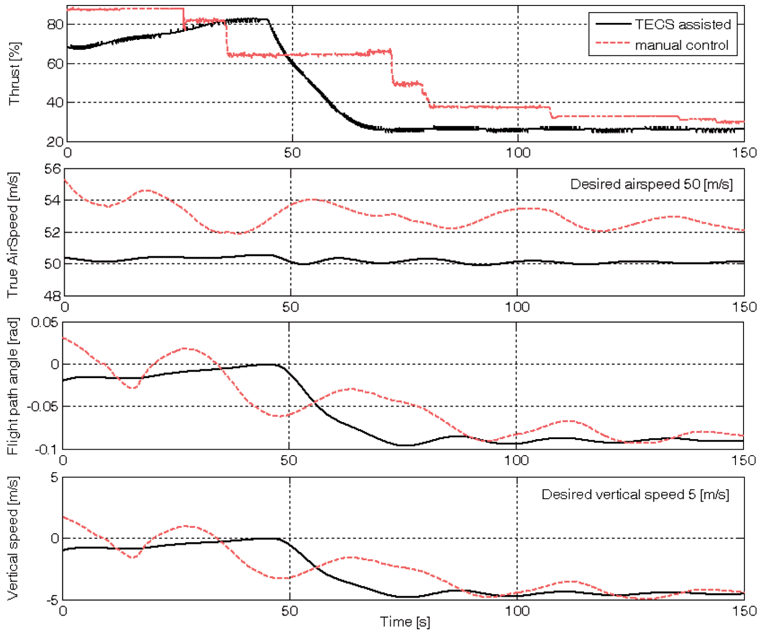

Fig. 11. Simulations of fully manual and PAM assisted approach

Simulations of PAM have been performed on the XM-15 flight simulator. A set of the flight parameters was recorded during a fully manual as well as during the PAM assisted descend on the initial approach to EPRZ runway 09 (Rzeszow-Jasionka airport), where test cases have been executed in moderate turbulence conditions. A comparison between the manual and an electronically assisted flight control indicated PAM's capability to support the pilot in maintaining precisely a constant airspeed and the desired trajectory. The manual flight regime exhibited a significant throttle activity during the approach descent; while PAM assisted flight maintained a constant engine setting at reduced thrust (Figure 11). Performed experiments indicated the average thrust setting being about 10% higher for the manual mode compared to the PAM assisted control logic [3].

5. Summary

The design philosophy behind the experimental flight simulator SimStar was directed towards the concepts primarily related to the advanced pilot-aircraft interfaces. Light aircraft equipped with integrated flight displays featuring synthetic vision technology; an electronic assistance module and a smart autopilot (PAM), have the potential to introduce new customers to the light aircraft market and change the current perception of safety and comfort.

The experimental flight simulator XM-15 was originally developed for the purposes of a fly-by-wire flight control system design and verification. Real time rapid prototyping environment integrated within the XM-15 allowed design, prototyping and testing of advanced flight control modes, including unconventional models and algorithms. Favorable results in real time experiments of Total-X based autopilot led to further investigations on PAM. The flight assisting tool has been verified during the simulated flight trials, which confirmed the rationality of its practical implementation.

The development of the flight simulators presented in this paper was uniquely different, but mutually complementary. Fusion of solutions designed at BUT and RUT accelerated progress and motivated future research at both institutions. Practical experimental tests of similar concepts preformed in parallel on two independently developed experimental platforms allows a rapid and precise verification of proposed systems. However, the complexity of man-machine interactions and unforeseen aspects due to human factors call for a more rigorous pilot-in-the-loop testing, which can be performed on type correct and certified flight simulators only.

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Symulatory do badań modułu asystenta pilota zaawansowanego samolotu lekkiego

Streszczenie

W ostatnich latach małe samoloty ogólnego przeznaczenia zyskują na coraz większej popularności jako środki transportu osobowego. Szybki postęp w dziedzinie lekkich i ultra-lekkich konstrukcji lotniczych prowadzi m.in. do redukcji kosztów ich wytwarzania oraz eksploatacji. Czynniki te, w połączeniu z dynamicznym rozwojem sieci lokalnych portów lotniczych i lądowisk sprawiają, że małe lotnictwo staje się dostępne nie tylko dla wąskiej grupy entuzjastów, lecz również

dla osób pragnących wykorzystać je jako środek transportu alternatywny dla kolei, czy też pojazdów samochodowych. Niestety, małe samoloty o napędzie tłokowym postrzegane są z reguły jako niezbyt wygodny środek lokomocji, szczególnie w stosunku do samolotów liniowych lub odrzutowych samolotów dyspozycyjnych. Główny problem związany jest jednak z wykonywaniem operacji lotniczych w załodze jednoosobowej, w dodatku przez pilotów amatorów.

Zastosowanie pośredniego układu sterowania samolotem (ang. *fly-by-wire*) może w znacznej mierze ułatwić proces pilotowania i zredukować niektóre błędy powodowane czynnikiem ludzkim. Wprowadzenie złożonych systemów sterowania do prostej konstrukcji lotniczej prowadzi jednak do wielu problemów, zarówno natury technicznej (problem niezawodności złożonego systemu elektromechanicznego) jak i ekonomicznej. Mając na uwadze zalety oraz wady układów sterowania, zarówno klasycznych jak i klasy *fly-by-X*, autorzy pracy zdecydowali się na realizację systemu sterowania, który z jednej strony ułatwi pracę pilota, a z drugiej strony nie będzie wymagał rezygnacji z mechanicznego połączenia sterownicy/orczyków i płaszczyzn sterowych. Proponowane rozwiązanie bazuje na zmodyfikowanym układzie autopilota, który aktywnie wspiera pilota m.in. w sytuacjach stresowych związanych z utratą orientacji, zagubieniem i niektórymi usterkami urządzeń pokładowych. Zastosowana koncepcja algorytmów sterowania bazująca na metodzie Total-X umożliwia również redukcję emisji hałasu i zużycia paliwa.

Bezpośrednie przejście z etapu testów laboratoryjnych do prób w locie jest ryzykowne i kosztowne. Z tego też względu autorzy pracy postanowili wykonać testy na symulatorze lotu, włączając pilota w pętlę sterowania. Modyfikacja dostępnego, profesjonalnego symulatora lotu nie była możliwa ze względów formalnych (wyłączenie urządzenia z procesu szkolenia i czasowa utrata certyfikacji). Możliwym i znacznie korzystniejszym rozwiązaniem okazała się budowa eksperymentalnych symulatorów lotu, zorientowanych na klasę samolotów lekkich i ultra-lekkich. W pracy przedstawiono dwa eksperymentalne symulatory lotu, które powstały w Politechnice Rzeszowskiej i Politechnice Brneńskiej. Symulatory powstały w kooperacji, aczkolwiek różnią się od siebie zasadniczo. Pierwsze z urządzeń (zaprojektowane i zbudowane w Politechnice Brneńskiej, Wydział Technologii Informacyjnych) bazuje na kokpicie popularnego samolotu lekkiego *Evektor SportStar*. Symulator zaprojektowany i wykonany w Politechnice Rzeszowskiej na Wydziale Budowy Maszyn i Lotnictwa wykorzystuje kabinę samolotu M-15. Symulatory posiadają modułową konstrukcję i umożliwiają testowanie m.in. elektromechanicznych układów wykonawczych, paneli kontrolnych i sterownic wyposażonych w standardowe interfejsy komunikacyjne.