VUT 001 MARABU: UNIVERSAL EXPERIMENTAL AIRCRAFT

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Abstract

The project VUT 001 MARABU represents new approach to development in several fields, and combines them together to create effective development and testing tool. For example, on the field of civil unmanned aerial vehicles, it provides piloted aircraft platform to overcome legislative and development problems at early design stages. ***The aircraft was built to support development of equipment for Unmanned Aerial Systems (UAS) and especially for aerial vehicles themselves (UAVs – Unmanned Aerial Vehicles).***

The project emphasizes civil applications that still fall behind military UAS/UAV applications. This "delay" is mainly caused by legislative limitations for operations of unmanned aircraft in the civil airspace. The solution adopted for VUT 001 Marabu project solves this issue through design of a piloted experimental aircraft. Since it is not primarily focused on the development of ground element, the acronym UAV is used in the paper.

The paper provides extension of the information given previously for example in [8] and [9].

1 Introduction

Development of new equipment, engines and other products for aviation industry requires extensive testing in the environment similar to considered operations. Expenses and resources needed often exceed possibilities of aviation producers (especially small producers). Within the Czech Republic the industry focused on specific fields of interest is recently quickly growing. Apart from traditional general aviation applications, the interest is focused also on newly evolving market of civil **unmanned aircraft systems**. Simultaneously, there exists demand for testing of new **small propulsion units** (for perspective small sport aircraft and UAVs).

Recent trend in the development of UAVs (Unmanned Aerial Vehicles) for civil sector is confronted with non-existence of regulatory requirements for their design and operations. Development of UAVs is practically always connected also to the development of a ground control station. Simultaneous development of both major elements (*an aerial vehicle* and *the ground control station*) makes first flight tests risky with high probability of aerial vehicle destruction. Such development approach is possible only for very small UAVs or for military aircraft (where producers have special ranges available for tests). Opportunities for such tests are very limited in European airspace. Furthermore, development can be very expensive. On the other hand, adaptation of existing design into OPV (Optionally Piloted Vehicles) cannot utilize full potential of the airframe for UAV missions.

The Institute of Aerospace Engineering (IAE) / Brno University of Technology therefore proposed development of special experimental aircraft VUT 001 Marabu to overcome abovementioned issues. **The concept proposes piloted airplane for the first stage – to overcome regulation barrier. After validation of basic aero-dynamic performance and operational characteristics, step by step adaptation to full UAV will take place.** Eventually, the pilot can be retained to overcome legal issues connected to unmanned vehicles (during otherwise fully automatic flights).

The Institute of Aerospace Engineering (IAE) / Brno University of Technology is a well known organization in Czech Republic focused on design of aircraft. In the past, several new concepts of aircraft were created at IAE under supervision of prof. Antonin Pistek (director of IAE and former chief designer of LET Kunovice company). Starting with an ultralight aircraft with advanced aerodynamic design, all metal structure and retractable landing gears (KP-2U Owl later renamed to Rapid200) and continuing with general aviation VUT100 Cobra, a 5-seater aircraft with advanced performance and modern avionic systems for pilot training, leisure flying and aerotowing designed under JAR/FAR-23 requirements. All the abovementioned aircraft significantly moved limits in their categories in terms of performance and use of progressive structural elements (from higher aircraft categories). Since 1996, almost 200 Rapid airplanes were built! IAE also significantly contributed to the development of Evektor EV55 (twin-turboprop 10-seater), Aero Ae-270 (single-turboprop 10-seater) and many other aircraft. Additionally, IAE was an active participant in UAVNET project supported by 5th FP EU. The project involved partners from 13 member states and was focused on utilization of UAVs in the civil airspace. Information gained through the project created base for the realization of own experimental aircraft designed fully on IAE.

VUT 001 Marabu is one of the few practical projects, where full coordination, design and into large extend also manufacturing was done within an university environment. Institute of Aerospace Engineering (IAE) had the unique opportunity to test and to verify some modern approaches, methods and solutions during designing of the prototype.

All activities were done with huge involvement of IAE students. MSc. and Ph.D. students were involved in practically all aspects of design and production of the aircraft.

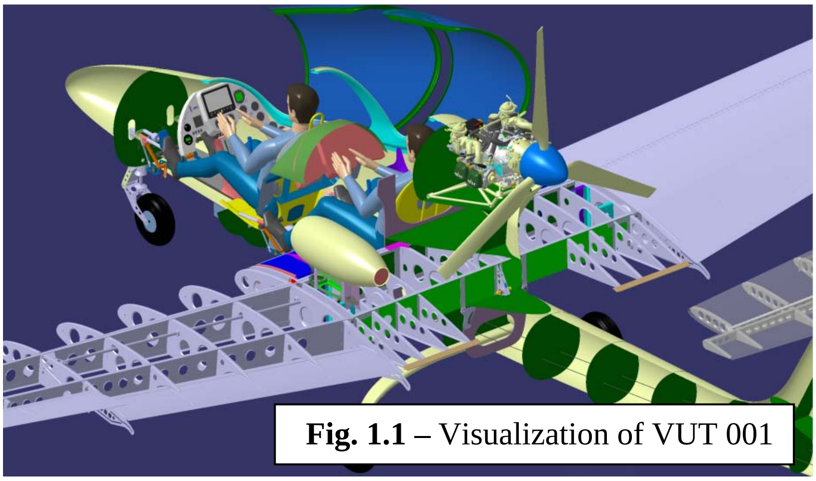


Fig. 1.1 – Visualization of VUT 001

Development of an experimental airplane is a multidisciplinary task involving expertise from wide variety of physical and mathematical disciplines. Furthermore, unconventional configuration imposes also serious legal barriers.

Basic requirements created for VUT 001 Marabu project were: *the airplane needs to have an empty space in the fuselage nose part for sensors (with an un-obscured forward view); acceptable operational endurance; and max. take-off weight of 600 kg. The structure should enable simple integration of systems for UAVs.*

2 Project VUT 001 MARABU

2.1 Concept

Abovementioned requirements led to development of the airplane with rear-mounted propeller powered by single piston engine supplemented by small experimental jet engine. Technological platform selected for realization included combination of the composite fuselage and all-metal wing. Design of the aircraft from the scratch enabled optimization of the airframe for wide variety of missions (from short-time low-altitude missions to mid-altitude missions lasting several hours).

Within the size of the aircraft (max. take-off weight of 600kg), the **move towards the concept of more-electric-aircraft is done as**

Tab. 1.1 - Partners involved in VUT 001 Marabu project

Partner	Role in the consortium	Activities in the project
Institute of Aerospace Engineering / Brno University of Technology (IAE)	Coordinator	Design of experimental aircraft, participation on fuselage production, final airplane assembly, holder of "Permit to Fly", test flights.
Prvni brnenska strojirna Velka Bites (PBS)	Partner	Development and production of TJ100M jet engine, further development and optimization of small jet engines for UAVs, experiments with the jet engine.
Jihlavan – Airplanes (JA)	Partner	Production of airplane metal structures (wing, horizontal tail unit), control system for flaps and trim.
Plast Service (PS)	Partner	Production of airplane composite structures (fuselage).

Fig. 1.2 – Unique pictures from production of the prototype

far as practically possible. This should offer significant advantage for integration of UAV systems into VUT 001 aircraft over existing conventional aircraft.

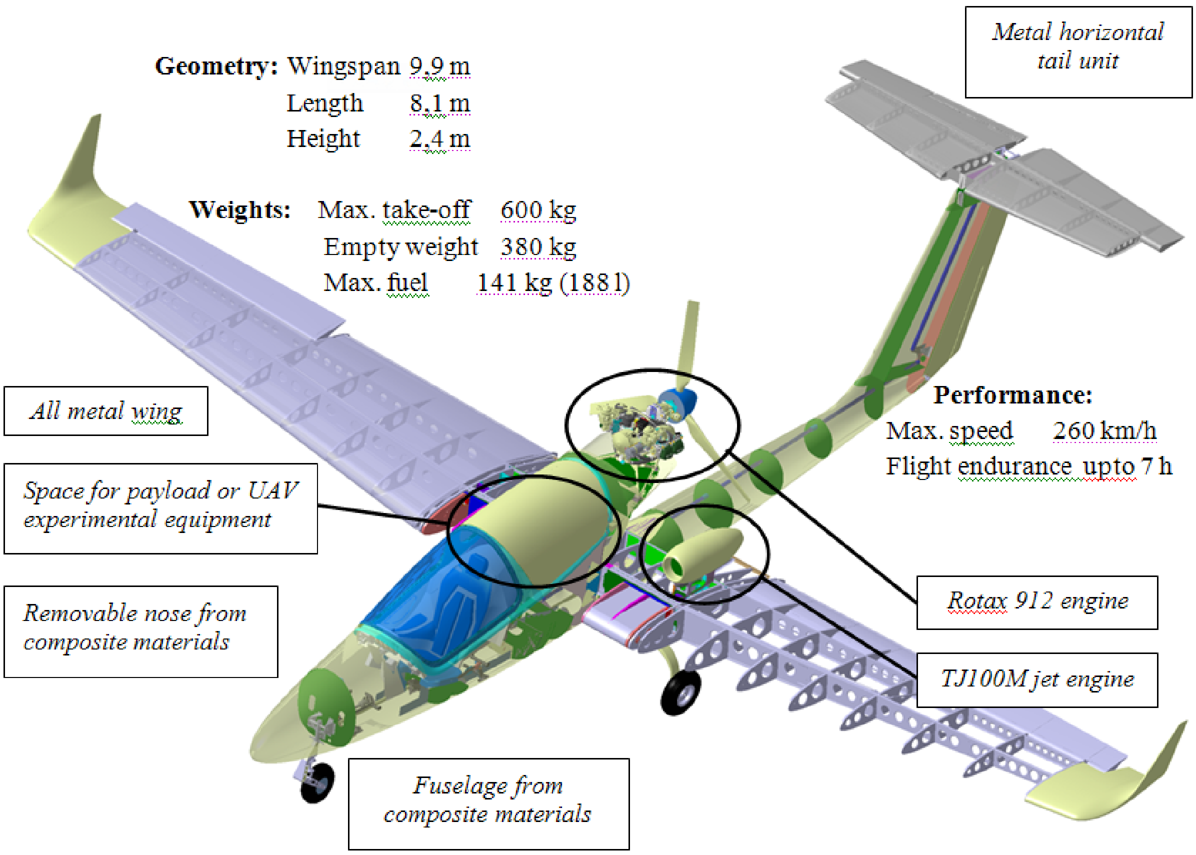
2.2 Structure, geometric and performance characteristics

The aircraft has combined structure composed of glass-fibre composite fuselage (with carbon-fibre reinforcement) and metal wing and horizontal tail unit. Major reason for the combined structure is reduction of development risks and reduction of development time for the airframe. Metal wing structure and horizontal tail unit were taken from successful Rapid200 aircraft (developed also at IAE). The fuselage, made of composite materials, is completely new.

One of the main IAE tasks was to design and manufacture the fuselage. An important part of the project was to focus as much as possible on utilization of computer-aided design (CAD), computer-aided manufacturing (CAM) and computer aided-engineering (CAE) during fuselage development.

CAD approach was used from conceptual design through preliminary design up to detail digital mock-up of the prototype. 3D models allowed quick evaluation

Fig. 2.1 – Aircraft structure (exported from CATIA model)



and comparison of preliminary concepts. Final design review processes and manufacturing (CAM) was based on 3D master model. Modern Computer Fluid Dynamics (CFD) tools were used in aerodynamic design of aircraft at two levels – evaluation of overall aerodynamic concept and *"fine tuning"* of particular details. Lay-up design of fuselage monocoque was optimized by finite element analyses before manufacturing.

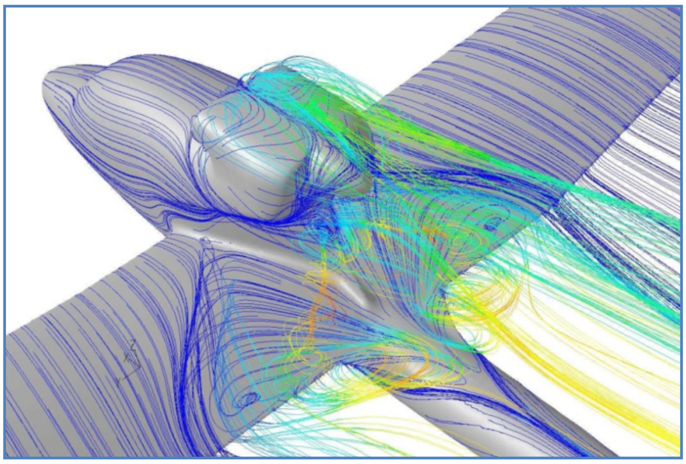


Fig. 2.2 – CFD analysis of airflow around the rear part of the fuselage

The practical application of CAD, CAM, CAE led to sufficiently lightweight, technologically effective and dimensionally precise structure on the first attempt. These state of the art methods have also capability to speed up certification process with civil aviation authority. **For the first time in the Czech Republic, primary fuselage structure of the aircraft went through certification process in accordance with EASA Certification Specifications**.

More details on fuselage design and manufacturing can be found in [7].

2.3 Small jet engine for UAVs – TJ100M

The concept and structure of this experimental aircraft was significantly affected by the decision to make flight evaluation of small jet engine originally developed for UAV applications. Apart from UAV applications, TJ100 is used for aerial targets and as an additional engine for motorized gliders. The

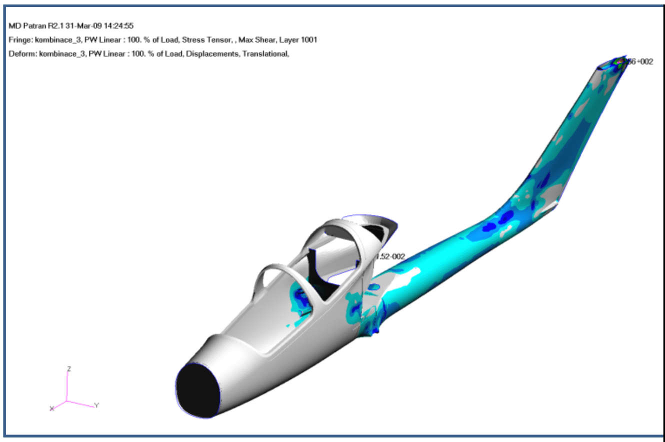


Fig. 2.3 – Comparison of Finite Element analysis (MSC PATRAN/ NASTRAN) and structural test of composite fuselage

Fig. 2.4 – TJ100M installed on the wing centre section of VUT 001 Marabu

Fig. 2.5 – Yabhoon UAV

producer of the engine (PBS) is a major partner in the project and also one of the significant Czech producers for UAV market. Jet engines produced in PBS can be found in Yabhoon UAVs (see fig. 2.5). Figure 2.4 shows installation of TJ100M on the Marabu wing centre section and fig. 2.6 parameters.

Fig. 2.6 - TJ100M characteristics:

Outside diameter	272 mm	
Length	485 mm	
Total Weight	19 kg	
Max. thrust	>1 kN	
Nominal thrust	>0,89 kN	
Idle thrust	<0,16 kN	
SFC*	<0,12 kg·N^{-1}·h^{-1}	
Fuel	JET A-1	
Engine RPMs:	- idle	30 000 min^{-1}
	- max.	58 000 ÷ 60 000 min^{-1}
Reaction time 75% to 95% thrust - <10s		
DC power:	- 28 V starter/generator	
	- 1000 W generator power (total)	
	- 750 W generator power (available for electric system)	

* SFC – Specific Fuel Consumption

3 Aircraft Systems

Besides structural design and issues connected to aircraft performance and characteristics, there was a great challenge to bring systems of proposed “Platform Aircraft” as close to UAV applications as possible.

Table 3.1 – Comparison of systems in typical conventional aircraft and VUT 001 Marabu

System	**Type of System**	
	Conventional Aircraft (FAR-LSA, CS-VLA)	**VUT 001 MARABU**
Primary Flight Controls	Mechanical (push/pull rods, cables, etc.)	Mechanical (push/pull rods, cables, etc.) – provisions are done to mount autopilot servos (positioned close to aircraft centre of gravity)
Trim System	Mechanical (cables, etc.)	Electrical (elevator, rudder)
Flaps Extension/Retraction	Mechanical (push/pull rods)	Electrical (electromechanical strut)
Electric System	Simple with 1 alternator and 1 battery (optionally, second alternator to increase capacity is used interconnected with the single battery used also for ALT1)	**2 alternators** and **2 batteries** create redundant system with two independent channels. Additional independent channels can be supplied by own energy sources (batteries, fuel cell stacks, etc.). First flights were performed using only main system with one alternator.

In contrast to modern aircraft in higher categories, for aircraft with take-off weight close to 600 kg (and with limited budget available), systems driven by modern electronics are not available. In spite of great step forwards in utilization of modern composite materials in the structure of light sport aircraft, electric operation of systems (as well as computer control) is still not established for this size of aircraft. Modern conventional aircraft in such category still use proven mechanical control system, simple electrical system without back-up for instruments (there are no critical functions needed for VFR flights), mechanical operation of most secondary controls (i.e. flaps, trims), etc.

As mentioned above, VUT 001 MARABU airplane should serve as "a testbed" for the equipment being developed for UAS. **Great attention is given to** design of systems that will **bring the aircraft** (as far as possible) **towards the concept of "more-electric-aircraft".** In other words, the target is to use as many electrically driven systems as possible. The table 3.1 describes measures used to bring proposed Experimental Platform (VUT 001 Marabu) as close to the needs of modern UAS as possible. Starting with analysis of current regulation requirements to practices used to increase safety/reliability of used solutions.

Since CS-VLA [2] regulation used as a major design standard for VUT 001 Marabu has not sufficient design guidance in the area of safety/reliability assessment, Functional Hazard Analysis (FHA) was done in compliance with closest higher regulation, CS-23 (namely CS-23.1309) [3]. As a guide, widely accepted FAA AC 23.1309-1D [4] was used. As a proof of safety to fulfill legal requirements of CS-VLA, simplified list of critical functions was created as a part of certification documentation.

3.1 Perspective development of systems

The design of selected systems creates space for redundancy of functions. This is especially true for electrical system, where possibility to extend the system for future additional independent back-up system was prepared.

Extended electrical system proposed for VUT 001 Marabu uses two batteries and independent channels for each alternator. Such system has 4 sources of electrical power combined in two independent channels. Just for comparison, even in higher aircraft classes (manned airplanes certified in accordance with

CS-23) – such solution is commonly used for a single-engine IFR aircraft (Instrument Flight Rules). Sometimes, certified IFR aircraft may even have only one alternator and two batteries.

This should enable testing of equipment with critical functions, where back-up is necessary. If common reliability levels of typical equipment are considered, this should enable future certification of critical functions to the level equivalent to Class I and Class II aircraft defined in recommendations of AC 23.1309 (see. [4]).

Safety/reliability assessment of systems in aircraft of similar sizes is not normally performed. However, with the introduction of UAS (Unmanned Aerial Systems), the importance of safety assessment will quickly grows. Also higher level of automation in conventional small aircraft is a strong driver for further development of safety analyses in this class. Therefore, modification of existing methods and development of new methods of safety assessment as well as practical realization is important for the future.

4 Production of the prototype and flight testing

The design and production of the VUT 001 Marabu airplane was done at Brno University of Technology/Institute of Aerospace Engineering.

Fig. 4.1 – Photo from final assembly of the prototype

Academic environment is usually different from industrial practice. This fact significantly affected design process, but it also offered opportunity for young engineers and researchers to practically apply modern tools for development of state of the art product. The aerodynamic concept was optimized using CFD (Computer Fluid Dynamics) methods to enable excellent performance characteristics. The structure of the fuselage was designed using composite materials to enable light and stiff structure. Modern FEM (Finite Element Methods) for structural analysis were applied to further reduce weight of the structure and to enable quick definition of dimensions for critical structural parts. All these activities were to large extend performed by young engineers, researchers and students. This could be done as a result of IAE's long time activities focused on building of capacities for research and development.

VUT 001 Marabu took-off for the first time on 29th April 2010. First test flights were performed in Kunovice (south east part of the Czech Republic). Test-pilot Stanislav Sklenar reported excellent handling and performance characteristics.

Flight testing was performed in traditional aviation region, southeast Moravia. Marabu pilot, Stanislav Sklenar is considered to be top test-pilot with long time experience.

5 Future perspectives of the Marabu project

Possible civil UAS applications are widely discussed in aviation community for a long time. The equipment suitable for wide variety of missions can be installed and operated/tested on VUT 001 Marabu. There is already ongoing cooperation with several industrial partners on development and testing of equipment primarily designed for UAVs.

Furthermore, since Marabu is universal experimental aircraft developed within the university environment, there are several other possible applications for future.

Chapter 5.1 lists most suitable applications. Chapter 5.2 gives information on most promising directions for future development of VUT 001 Marabu.

Fig. 6.1 – Chiefdesigner (A. Pistek) and TestPilot (S. Sklenar)

5.1 Applications

Chapter 2 discussed (among others) performance and characteristics of VUT 001 Marabu aircraft. Such characteristics enable for example:

UAV related applications

- Development of sensors and components for critical systems of UAVs (control system, sense and avoid, etc.)
- Low cost testing of monitoring equipment for various missions (with flexible changes of trajectories and altitudes) without the need for special restricted airspace.
- Simulation of different mission profiles

Non-UAV mission

- Flight measurements of characteristics for developed engines (for example small jet engines similar to TJ-100M)
- "Low-cost" flight testing of non-conventional propulsion units (small turboprop engines, hydrogen fuel cells propulsion, etc.)

5.1 Perspective Development

As explained in detail in the introduction, step-by-step integration of UAS equipment is considered for VUT 001 project. Integration of selected sensors and systems is planned for the second phase of the project (after flight evaluation of the platform in conventional configuration).

Currently, IAE is focusing on evaluation of flight performance of the prototype. The roadmap for integration of UAV systems into the airplane is also being prepared. Activities are directed to sensors providing basic navigation capabilities and sensors necessary for "sense and avoid" capability.

6 Conclusions

Lack of legislation for design and operation of civil UAVs (or UAS) makes development of equipment and systems for such unmanned vehicles complicated. In the highly competitive environment, it is necessary to start development and testing of such equipment well before all legislative issues are solved. European environment makes experimental flights of fully autonomous vehicles extremely difficult and expensive (due to the heavy air traffic over Europe). Alternative ("low cost") approaches have to be developed. VUT 001 Marabu is the example of such approach – piloted experimental aircraft for development and testing of the equipment with step-by-step adaptation into UAV.

Specific development environment (university) makes this project even more attractive to potential partners with guarantee that knowledge developed will have direct way to education and application in European aviation industry.

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Fig. 6.2 – First flight of VUT 001 Marabu took place in Kunovice on 29th April 2010