VUT 700 SPECTO project overview

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Abstract

The article is a summary of results achieved with the VUT 700 SPECTO aircraft. The development of the aircraft was connected with the data acquisition unit custom made simultaneously for the UAV. One of the entire system design objectives was to obtain a flying laboratory for dynamic measurements. The main part of the article is therefore dedicated to the identification of aerodynamic characteristics. The work compares the results of identified parameters using three different identification methods. The results aim at further project goals, such as the aircraft model in a simulator and a fully autonomous pilotless system.

1. Introduction: VUT 700 SPECTO

The VUT 700 SPECTO aircraft began to be created within the scope of student projects at the Brno University of Technology in 2007. In the course of two years, an optimised wing was gradually created [1], for which the fuselage, empennage, and control system installation was completed the next year [2]. The aircraft made its maiden flight in 2009. There were many objectives of the entire system design. The two most important were creation of a flying laboratory for dynamic measurements and fully autonomous unmanned aerial vehicle.

Table 1: General airplane characteristics

Wing Area	1.3 m^2	Weight in test setup	15.5 kg
Wing span	4.2 m	MTOW	20 kg
Mean aerodynamic chord	0.34 m	Maximum speed	150 km/h

Figure 1: Original VUT 700 SPECTO

1.2 Airplane modifications

One of the first modifications was rotary camera installation in the nose. Camera rotating platform is connected with operator helmet by a wireless connection operating at 5.8GHz. Helmet is fitted with VGA goggle and due a system of gyroscopes and accelerometers implemented to operator's helmet platform measures his head movements. The application was designed by colleagues from The Faculty of Electrical Engineering and Communication of the BUT [3]. Gradually, the aircraft was modified and some shortcomings were removed. The first problem to occur was the electromagnetic interference of the remote control with the measurement system. The interference was eliminated by changing the remote control frequency from 35 MHz (Graupner system) to 2.4 GHz (JETI system). Another flaw was proven to be the very high fuselage vibration caused by the piston engine. The original version was equipped with the MVVS 45 one-cylinder four stroke piston engine. The relatively light fuselage made as a sandwich laminate was not capable of damping the vibration of the one-cylinder internal combustion engine. Upon setting the engine at idle, the fuselage vibrated at one of its own frequencies. It was desirable to obtain a recording degraded by noise and vibration as little as possible in dynamic flight measurement. Thus it was decided to develop an electric powered modification of the airframe. The new aircraft received the designation VUT 701 eSPECTO. The type utilises the wings and the empennage of the older VUT 700 version, but it has a new fuselage with built-in sensors of the improved data acquisition unit. Instead of the camera platform in the nose, the aircraft was fitted with a fixed camera and an angle of attack measurement probe. The modified version VUT 701 eSPECTO was designed to maintain aerodynamic characteristics of the original airplane.

1.2.1 VUT 701 eSPECTO modification

The huge advancement of battery technology in recent years allowed for fitting an electric motor with battery capacity for a short flight of several minutes. From the standpoint of weight, the change of the power unit did not have a significant effect, the weight of the aircraft ready for flight measurements increased by 10 % due to the batteries and engine replacement. The maximum power output of the motor was kept very similar in order to secure a safe take off. The aircraft performance suffered only in terms of range and endurance. The aircraft was fitted with the AXI 5345/18 HD GOLD LINE motor with two propulsion Lithium-Polymer batteries. These six-cell batteries with a capacity of 5 000 mAh produce a voltage of 44.4 V when connected in series. Therefore, the output at the motor shaft is 2.8 kW, which is a value comparable with the maximum output of the MVVS 45 engine without using the muffler supplied by the manufacturer.

Figure 2: VUT 700 SPECTO and VUT 701 eSPECTO fuselages

1.2 SEDAQ Measurement system

The SEDAQ (Sensor Data Acquisition) measurement system was created on the basis of cooperation between the FSI Institute of Aerospace Engineering and the Intelligent System Institute at the FIT of the BUT [4]. The project was initiated almost simultaneously with the VUT 700 SPECTO airframe development. SEDAQ is therefore designed precisely for the needs of this aircraft. The SEDAQ records the data from individual sensors at a frequency of 100 Hz to an SD card. After the first tuning of errors in the unit operation, a second, more stable version was created, which was utilised for measurement. SEDAQ consists of the main recording unit connected with individual sensors via a bus. Every sensor is connected through an AD converter. The converters also secure the communication between the main unit and individual sensors. During the unit upgrade, the sensor bus architecture was changed from parallel to serial. Individual converters are linked with a shielded cable. The shielded cables were used after the occurrence of electromagnetic interference with the aircraft remote control as experienced during deployment of the first version of the SEDAQ unit. The system records the following parameters: Accelerations in three axes, angular speeds in three axes, temperature, static and dynamic pressure, angle of attack and elevator and engine control signals.

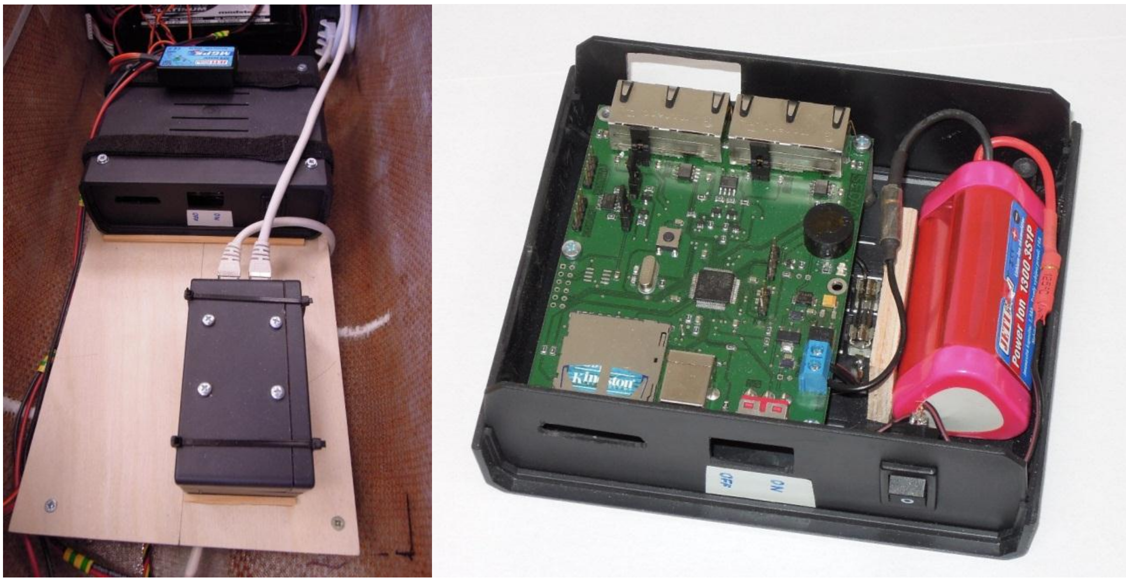

Figure 3: SEDAQ installation and a detailed photo

2 Identification methods

This chapter deals with identification of aerodynamic characteristics. The work compares the results of identified parameters using three different identification methods: Error Equation method, Output Error Method, and Filter Error Method. The first part is dedicated to methods brief description [5].

2.1 Error Equation Method

This method essentially belongs among the simplest identification methods. Parameter estimation is performed using the least squares method and consists in minimising the sum of the square of errors between the measurement and the calculated parameters. The method may be used for both the linear and nonlinear model. The main limitation of the method is the neglecting of error and noise with independent variables. Due to this assumption, the parameter estimate is biased. The accuracy of estimated parameters strongly depends on the measurement quality. An advantage of the method is the already mentioned simplicity and the possibility to eliminate inaccuracies by utilising precise sensors. The method is referred to with the EEM abbreviation below.

2.2 Output Error Method

Parameters are estimated iteratively by minimising the error between the system response measurement and its simulation. The Output Error Method (the OEM below) is based on the assumption that the process error is negligible. Unlike the EEM, it considers the error with independent variables. The parameter estimate takes place using the maximum likelihood method. Using this method, it is possible to obtain unbiased and consistent parameter estimate, provided the following preconditions are followed. The input signal is independent from the system output. The system is only burdened with the measurement error. And the control input is sufficient and changed so that it directly or indirectly initiates all kinds of system responses. The first precondition that the control signal is not dependent on the system response is easy to fulfil with stable aircraft. Unstable aircraft, which use feedback in their control, therefore require a special solution of this method.

2.3 Filter Error Method

This method, together with the OEM, belongs to two most widespread identification methods. The OEM gives good results only in a calm atmosphere. This is caused by the fact that only the measurement error is considered, but the process error is ignored. In presence of turbulences, it is therefore appropriate to choose a more complex method. The Filter Error Method, (further referred to as FEM), is a method which considers the process error. Another advantage of the method is the feedback in the algorithm, which numerically stabilises the calculation and, unlike the OEM, it allows for parameter identification even for inherently unstable aircraft.

From the OEM, the FEM differs in that the system output is based on the system state estimate. Due to the introduction of the process error into the calculation, it is impossible to determine the system states using a deterministically simple integration. For the system states estimate, the Kalman filter for linear systems or the expanded Kalman filter for nonlinear systems is therefore used.

3 Flight measurements

With the final form of the VUT 701 eSPECTO aircraft, five flight measurements were performed. The first three flights were without autopilot stabilisation, the last two already with the installed autopilot. The difference between these flights was so large that the first three flights were only used for calibration flights, but not for identification. It turned out that the remote pilot is unable to recognise the roll of the aircraft flying at an altitude of 300 m above the ground with an accuracy of 10 – 15 degrees. For comparison, two screenshots from the camera located in the aircraft nose are presented in the figure 4. Left shows a horizontal flight controlled by the RC pilot and right flight stabilized by the autopilot. Used autopilot system was ArduPilot Mega 2.5 [6].

Figure 4: Zero roll horizontal flight by RC pilot and autopilot

3.1. Endurance and typical flight speed

The endurance of the aircraft with the battery propulsion is very low in comparison with piston engine. The real time of flight of the VUT 701 eSPECTO aircraft with electric propulsion from batteries ranged between 12 and 15 minutes, depending on the commanded motor output. Although the maximum output of both propulsion units is comparable, the electric engine was used for a much slower flight in the area of modes for maximum endurance due to achieving the highest possible endurance and utilisation of the time for measurement. With an effort to fly in the design travel mode for the piston engine aircraft, the endurance would be approximately just 5 minutes using electricity. The average value of the lift coefficient with the piston engine ranged around $c_L = 0.16$, while with the electric propulsion, it achieved a value of $c_L = 0.44$. This was shown in the flight by a marked decrease of the directional and lateral stability.

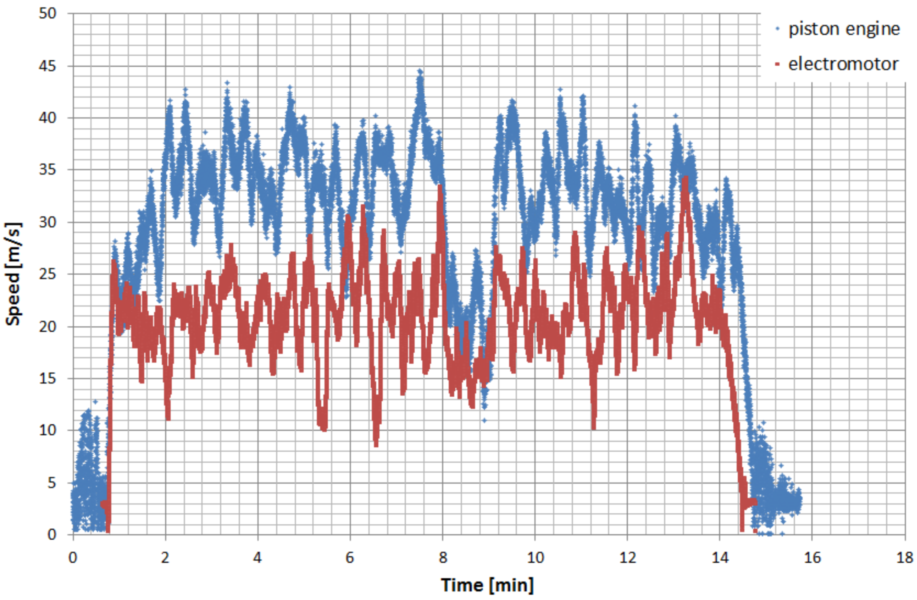

Figure 5: Typical operation speed history with piston engine and electromotor

3.2 Drag polar measurement

The measurement of the drag polar using the classic measurement is performed by stabilising the aircraft in various equilibrium modes of flight in a glide without the motor thrust influence. In case of the eSPECTO aircraft, this approach is excessively demanding concerning both the time and the piloting standpoint, therefore the polar was determined using the graphical method from the drawn dependency of c_L on c_D. The values of lift and drag coefficients were determined based on the measurement of acceleration and angle of attack of the selected parts of the flight measurement recording. For the calculation, the sections when the aircraft flew in a symmetrical flight with the propeller in a feathered condition were used. The polar was solved numerically from the balance equations for the flight with the feathered propeller (propeller drag neglected).

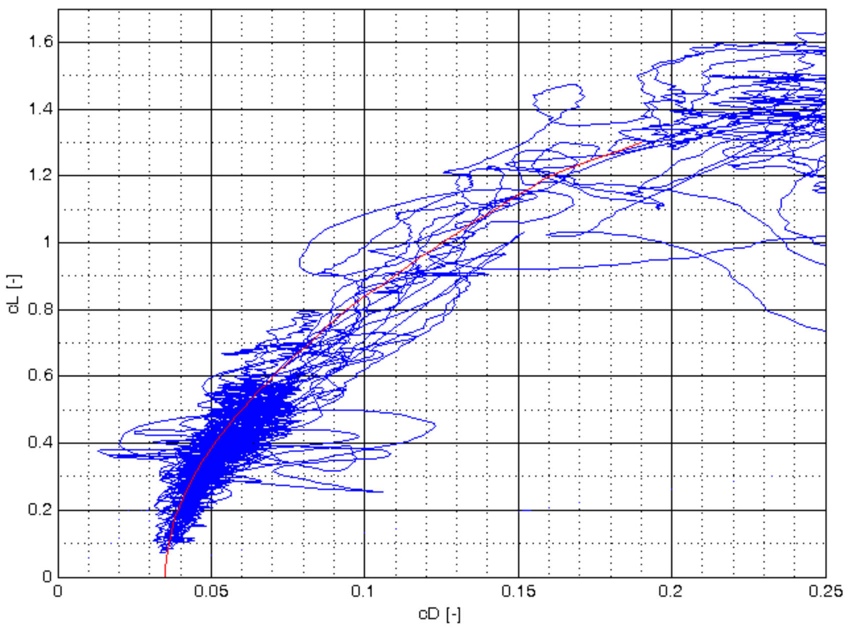

Figure 6: Drag polar graphical estimation

3.3 Dynamic Measurements

Dynamic measurements were initiated by a simple impulse into the elevator. The entire manoeuvre was repeatedly performed with a varying intensity of the impulse and at different speeds. The measurement took place in a stabilised mode of the autopilot, which kept the aircraft in a zero roll position and in a constant heading. The cycle excitation magnitude was set by gain variation of the autopilot regulator in the elevator channel in combination with a simple intervention of the pilot into the control. The largest dynamic response was achieved by setting the gain on the regulator in the autopilot so high that the autopilot, in an effort to return the aircraft into the horizontal position, itself caused aircraft oscillation.

4 Analytic solution and DATCOM results

Two further methods to obtain reference values for identified aerodynamic parameters estimation were deployed. The first analytical aerodynamic derivations prediction was performed as described by Danek [7]. The second approach was DATCOM [8].The results obtained using both methods differ relatively significantly. Both approaches represent a tool for preliminary determination of the aerodynamic characteristics needed for the analysis of stability and manoeuvrability of the aircraft. The best accuracy of DATCOM may be expected with larger aircraft with a human crew, for which the program was compiled. The program has a limited range of usable Reynolds numbers. The flow around wings and the tail unit of the VUT 700 SPECTO aircraft is outside the stated range. The values are extrapolated and their accuracy must be interpreted accordingly. The program also does not include the effect of the laminar boundary layer. The results can thus be only taken as informative and will serve for comparing the identified values.

5 Identification results and methods comparison

5.1 Parameters estimation

Altogether eight parameters were identified. There were three zero angle of attack coefficients c_{D0}, c_{L0} and c_{m0}. The next are drag coefficient derivation due to power of angle of attack c_{Da2}, lift coefficient derivation due to angle of attack and elevator deflection c_{La} and c_{Ld} and moment coefficient derivations c_{ma} and c_{md}.

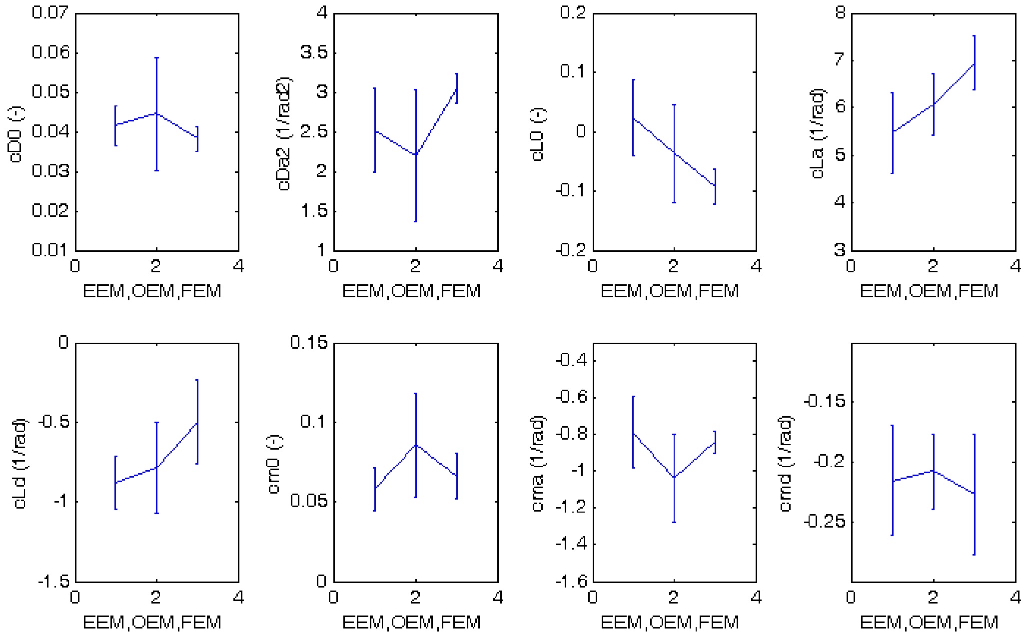

Figure 7: Parameters estimation

Table 2: Estimated parameters comparison

	EEM	OEM	FEM	Analytic	DATCOM	
c_{D0}	0.0416	0.0445	0.0383	-	-	[-]
c_{Da2}	2.5165	2.1976	3.0486	-	-	[rad^{-2}]
c_{L0}	0.0240	-0.0368	-0.0925	-	-	[-]
c_{La}	5.4744	6.0817	6.9494	5.7139	6.24	[rad^{-1}]
c_{Ld}	-0.8768	-0.7876	-0.4977	0.4681	0.2807	[rad^{-1}]
c_{m0}	0.0582	0.0857	0.0663	0.0878	-	[-]
c_{ma}	-0.7868	-1.0363	-0.8409	-1.257	-1.498	[rad^{-1}]
c_{md}	-0.2154	-0.2077	-0.2269	-1.623	-0.907	[rad^{-1}]

Lift and moment coefficient derivation due to the elevator deflection were not estimated correctly. The cause was found in the measurement design. Two reasons were identified as the main source of inaccuracy. The first was assumption of a rigid body. Actually the empennage is mounted on two beams which are slightly bending under load. The second reason is elevator deflection measurement accuracy. The measurement unit records only control signal of the servo motor. The real deflection depends on servo motor time delay and mechanical transfer deformation and a clearance. These shortcomings are connected to following consequence. Estimated derivation due to elevator deflection has the meaning of balanced flight. There were not distinguished lift and moment effect by the elevator deflection properly. The lift coefficient derivation due to elevator deflection includes effect by moment caused by elevator deflection. The tail unit beams stiffening and measurement of exact elevator deflection should be implemented to reach better results in parameter estimation.

5.2 The methods comparison

All three methods have their advantages and disadvantages. The first two methods - EEM and OEM – do not consider the process error. The EEM method is in principle the simplest, the main disadvantage against the OEM can be seen in the statistical estimate of parameters. The estimate using the least squares method is impartial only in case that the independent variables are measured without an error, which cannot be achieved in fact. The maximum likelihood estimate utilised by the OEM gives an impartial estimate of parameters even when independent variables are measured with an error.

The variance of values of individual methods is caused especially by two factors. The first of them are atmospheric turbulences. Due to the time constraints of flight measurement team and the instability of the weather, it was impossible to perform measurements in a calm atmosphere in the course of the two reserved months. The second factor causing the variance of the estimated parameters is related to the OEM method. In the chapter describing this method, it was said that the input signal must be independent on the system output. The input signal was combined from the interventions of the pilot and the autopilot while using the stabilised mode, which means that one of the basic conditions of using the method was not fulfilled. The series of dynamic manoeuvres without the influence of the autopilot on the elevator was flown only without lateral stabilisation by the autopilot. These measurements are not suitable for aerodynamic characteristics identification due to the unobserved roll.

6 An RC simulator model

One of the possible applications of the results of the dynamic measurements is the transfer of the parameters of the real aircraft to the model in an RC simulator. The prepared virtual model of the VUT 700 SPECTO aircraft has two goals. Firstly, it is a training tool for pilots. The VUT 700 SPECTO is largely a student project, which means that there is a constant demand for new pilots with experience with larger RC models. The stabilised mode of the autopilot facilitates the control very much, but until the project is brought to a fully autonomous system, the aircraft will not be able to fly without an experienced pilot. The second goal of the simulator is the possibility of interactive presentation of the project during various popularisation events for students, where it is needed to present the results of the scientific work in a popular form and to impress in a strong competition of other fields.

From the large amount of RC simulators, ClearView RC Simulator was selected. It is a commercial simulator which offers a very good quality to price ratio. Entering the model parameters is not performed directly via aerodynamic derivations, but via parameters, which more or less match them. For the most authentic settings, measurement results and subjective comparison with the actual model by the pilot will be used together. The model dynamics settings are not the subject of this work and will be solved within the scope of further student projects and activities at the Institute of Aerospace Engineering.

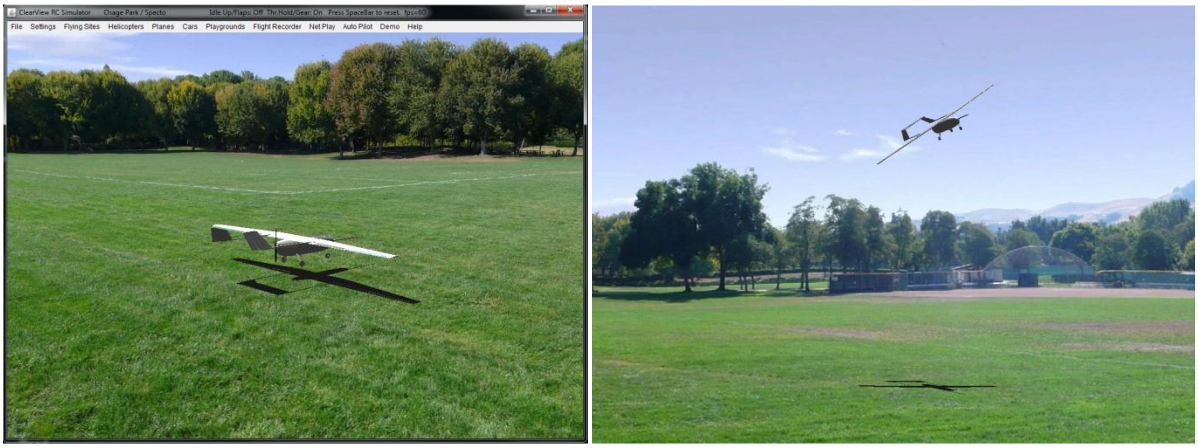

Figure 8: The VUT 700 SPECTO model in the RC simulator

7 Conclusion

The article deals with the development of the VUT 700 SPECTO experimental aircraft from its design up to the dynamic measurements for purpose of identifying the aerodynamic characteristics. In the first part of the work, the characteristics of the aircraft and its measuring equipment were stated. The theoretically focused chapter briefly introduces selected identification methods.

The main goal of aerodynamic characteristics identification from the performed flight measurements was fulfilled, but the identified parameters did not fully achieve the expected values. With derivations, only the values corresponding to the influence on the equilibrium flight were obtained. In order to obtain derivations based on the deviation of the elevator, it is necessary to perform several proposed measures, so that the expected results can be achieved.

The project VUT 700 SPECTO and its variant VUT 701 eSPECTO is still in progress. The electric powered aircraft is in service as the dynamic flight laboratory. The original prototype with piston engine is foreseen to become an autonomous UAV in the near future.

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