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To cite this article: O V Drozd and P V Avlasko 2020 *J. Phys.: Conf. Ser.* **1515** 052003

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# An automatic test complex for unmanned aerial vehicle engines

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**Abstract.** One of the most important components of an aircraft ground testing infrastructure is hardware and software test benches with complete or partial imitation of the aircraft in complex, on-board electronic equipment and controls. The development and debugging of such complexes is a complicated problem. The solution for this problem is presented in in the form of the automatic test complex for unmanned aerial vehicle engines and propulsion devices mounted on the Gough–Stewart platform manipulator. The complex is based on the modular measuring platform and also includes a set of various sensitive elements for forces, vibration, speed, torque, video and sound registration. The article also describes the procedure for one of the functional assessment stages of the UAV engine test complex, notably, the assessment of the tensometric measurement accuracy. Further development of the complex associated with the software implementation of atmosphere, wind turbulence models and modules for preliminary formation of test scenarios-UAV flight paths.

## 1. Introduction

An important place in the process of design an aircraft is occupied by the processes of technical solution control and testing, the purpose of which is to provide aircraft overall reliability and ability to fully perform assigned functions. The entire range of carry out tests is divided into two categories: flight and ground experimental tests. When conducting a complex of ground tests, a preliminary assessment is made for the amount of external destabilizing factors (climatic, mechanical, electromagnetic effects, etc.) and their various combinations, as well as assessment technical characteristics of units, systems and their complexes as a part of the aircraft [1, 2]. One of the most important components of the aircraft ground testing infrastructure is hardware and software test benches with complete or partial imitation of the aircraft in complex, on-board electronic equipment and controls. The set of test benches forms the Virtual Iron Bird [3–5], which allows complex debugging of the following aircraft systems: power supply, fuel, hydraulic, pneumatic system, etc.

The similar test complexes are developed with a large use of mathematical modeling and simulation, hardware-in-the-loop tools and other types of resource-saving approaches to debugging complex technical systems [6–8]. The development and debugging of the test complex is a complex engineering problem itself, the solution to which is presented in the paper.

## 2. The UAV engine test complex

To investigate the traction characteristics and the spatial displacement of autonomous vehicles it can be used the well-known Gough–Stewart platform (platform manipulator) with an octahedral



arrangement of prismatic actuators (figure 1), or legs all of them connected simultaneously to a fixed base and a moving platform through spherical joints, or attachments [9].



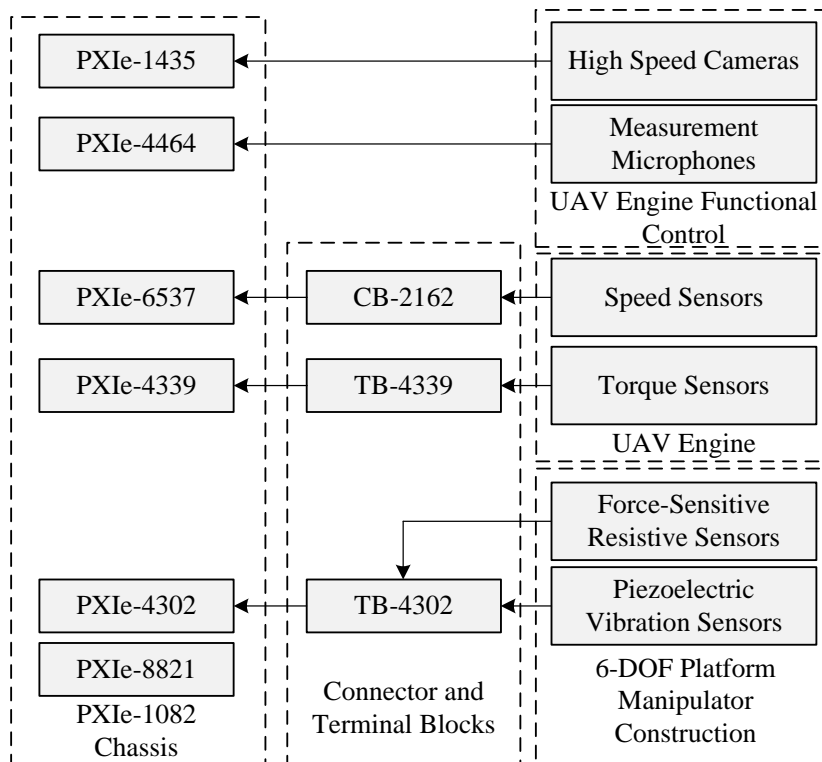
**Figure 1.** The platform manipulator as a part of the flight simulator for Diamond DA42 Twin Star aircraft (Institute for System Dynamics, University of Stuttgart, Germany) [10].

Such manipulators are used for the design and research both in space engineering, and in production of new appliance, medical equipment, etc. [11–13]. In the paper, it is considered a hardware-software complex for testing an unmanned aerial vehicle (UAV) engine installed on the Gough–Stewart platform manipulator (the mechanical system Moving Platform-UAV). The developed UAV engine test complex provides the following measurements and the ground functional tests:

- torque, speed and power on the propeller shafts of UAV propulsion devices;
- forces acting along the longitudinal, transverse and vertical axis of the moving platform;
- electric power consumed by the UAV engine;
- UAV vibration and acoustic characteristics;
- video recording of UAV operation process;
- documentation and visualization of measurement results.

Consider the structural organization of the test complex used in the ground tests of the UAV engine. The measuring instruments of the bench are based on the PXI standard modular measuring platform (National Instruments, USA), which includes the PXIe-1082 chassis, the PXIe-8821 embedded controller and a set of input-output modules. The use of modular measuring instruments provides a comprehensive recording of vehicle operation parameters in real time with global synchronization between modules. The measuring platform includes the following modules (figure 2):

- filtered input module for voltage, thermocouple, and current measurements PXIe-4302 with terminal block TB-4302;
- universal bridge input module PXIe-4339 with terminal block TB-4339;
- digital input-output module PXIe-6537 with interface module CB-2162;
- sound and vibration module PXIe-4464;
- Camera Link frame grabber module PXIe-1435.



**Figure 2.** The block diagram of the connection between the components of the measuring platform.

For recording parameters of the UAV engine, it can be used a set of sensitive elements:

- force-measuring strain gauge sensors, 6 pcs., built into the six extensible supports;
- piezoelectric vibration sensors (PVS), 4 pcs., one for each UAV propulsion device, installed near the mounting points of the propeller shafts;
- speed and torque sensors (TS), 4 pcs. each, mounted on the propeller shafts;
- measuring microphones and high-speed cameras, 2 pcs. each, placed on tripods.

Power supply of the UAV engine is provided by four laboratory power supplies EA-PSI 9060-170 WR 3U (Elektro-Automatik, Germany). Brief technical characteristics of the test complex are presented in table 1.

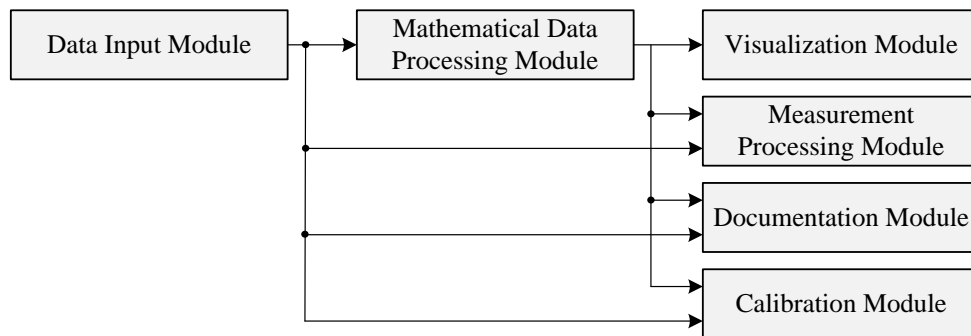
**Table 1.** Technical characteristics of the UAV engine test complex

Parameters	Values
1. Digital input/output channels	32
2. Analog input channels	32
3. Analog input channels with galvanic isolation	8
4. Analog input channels for bridge-based sensors	8
5. Input frequency range	5 Hz–5 kHz
6. Measuring range of forces acting on the moving platform	5–1000 N
7. Measuring range of moments acting on the longitudinal, transverse and vertical axis of the moving platform	1–100 N·m
8. PVS dynamic acceleration range	up to 500 m/s <sup>2</sup>
9. PVS operating frequency range	2 Hz–10 kHz

Parameters	Values
10. Nominal TS torque	50 N·m
11. Maximum speed of the TS shaft	8000 rpm

The software of the complex is responsible for ensuring the interaction of the measuring platform elements, test processing and recording (figure 3). The structural organization of the software includes modules for calibrating sensitive elements, data input and mathematical processing, visualization, measurement results processing and their documentation.

When the program starts, the firmware of the measuring platform modules is initialized and input and output measuring channels are formed. Further, information is obtained from the sensitive elements through the measuring channels, followed by data visualization, storage of received and processed measurement results. The next step in obtaining information from the sensors is to determine the information processing mode. This requires actions by a user to select the data mode. Next, depending on user's actions, visualization or storage of received and converted information occurs.



**Figure 3.** The block diagram of the interaction between the program modules.

Mathematical processing of measurement data includes the following procedures:

- calculation of the main force, force moment vector components and the Tait–Bryan angles (yaw, pitch and roll) of the system Moving Platform-UAV;
- spectral analysis of natural oscillations of the system Moving Platform-UAV and sound vibrations produced by the UAV propulsion devices in various operating modes.

The interaction between the software and the measuring equipment is carried out by the Virtual Instrument Software Architecture (VISA) standard using the standardized input-output interface and supporting GPIB, USB 3.0 and VLAN interfaces.

### 3. Functional assessment of the UAV engine test complex

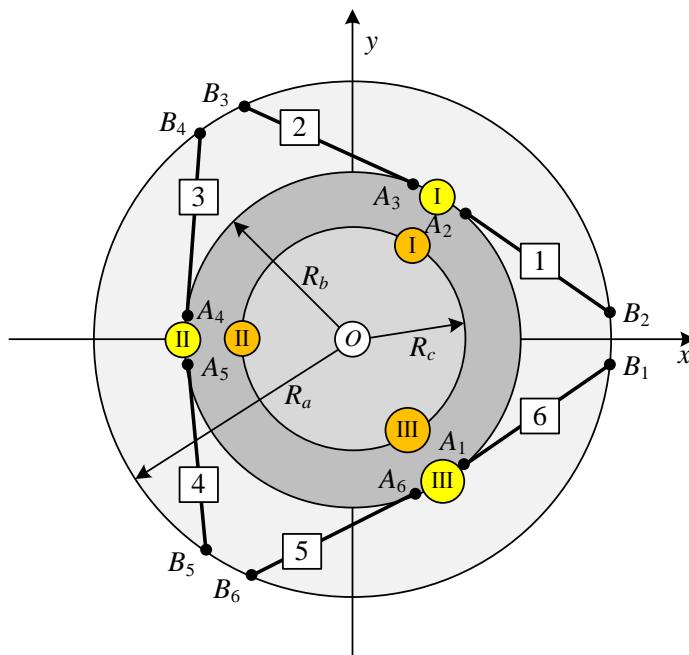
Briefly consider a procedure and results for one of the functional assessment stages of the UAV engine test complex, notably, the assessment of the tensometric measurement accuracy. As a reference mass, it can be used the set of calibration weights 7424-F1W (TROEMNER, USA) with its nominal value of 1 to 100 grams accuracy class F1, corresponding to the requirements of the National Voluntary Laboratory Accreditation Program (USA), and ISO/IEC 17025 standard.

Consider the layout of the control point placement and the corresponding markup on the surface of the moving platform (figure 4). Calibration weights are placed at the control points located near the attachment points of the movable support pairs. The control points are divided into a main group (highlighted by yellow) located on the outer circle with the radius  $R_b$  of the mobile platform and an additional group (highlighted by orange) on the inner circle (radius  $R_c$ ). The designation  $R_a$  indicates

the radius of the platform manipulator fixed base, designation  $O$  denotes the center of mass of the moving platform.

Control points are distributed as follows:

- the pair: support 1 (the attachment points  $A_1, B_1$ ) ↔ support 2 (the attachment points  $A_2, B_2$ );
- the pair: support 3 (the attachment points  $A_3, B_3$ ) ↔ support 4 (the attachment points  $A_4, B_4$ );
- the pair: support 5 (the attachment points  $A_5, B_5$ ) ↔ support 6 (the attachment points  $A_6, B_6$ ).



**Figure 4.** The layout of the control point placement on the mobile platform of the manipulator.

The test procedure included the following checks which involve the application of a given load to one or more control points at the same time:

- concentrated load in the attachment point area for the support pair;
- concentrated load at the center of gravity of the moving platform
- distributed load in the control point area located within the diameter of the moving platform;
- load along the chords of the moving platform circle with fixation at the control points.

Table 2 presents the results of assessment procedure for the tensometric measurement accuracy carried out by using the UAV engine test complex.

**Table 2.** Assessment the tensometric measurement accuracy carried out by using the UAV engine test complex.

Parameters, measurement conditions, units	Values
1. Weight applied to the force-sensitive sensors $s_1, s_2$ mounted on the movable support pair (I), the value of calibration weight is 10 g, N	$s_1: 0.0982, s_2: 0.0941$
2. Weight applied to the force-sensitive sensors $s_3, s_4$ mounted on the movable support pair (II), the value of calibration weight is 10 g, N	$s_3: 0.0820, s_4: 0.0822$

3. Weight applied to the force-sensitive sensors $s_5, s_6$ mounted on the movable support pair (III), the value of calibration weight is 10 g, N	$s_5: 0.0880, s_6: 0.0947$
4. Calculation results of the force vector components, the mass distribution at the support attachment points: I – 10 g, II – 20 g, III – 50 g	x-axis: 0.0036, y-axis: 0.0037, z-axis: -0.0320
5. Calculation results of the force moment vector components, the mass distribution at the support attachment points: I – 10 g, II – 20 g, III – 50 g, N·m	x-axis: 0.0034, y-axis: -0.0032, z-axis: 0.0000
6. Mass applied to the center of gravity of the moving platform, the value of calibration weight is 10 g, N	0.1460
7. Duration of the transition process for the force-sensitive sensors, the value of calibration weight placed at the support attachment points I–III is 20 g, s	$s_1: 1.78, s_2: 1.87, s_3: 1.80, s_4: 1.85, s_5: 1.82, s_6: 1.80$

According to the test results, it was found that the UAV engine test complex corresponds the established requirement and provides a relative error of tensometric measurement no more than 5%.

#### 4. Conclusion

Complex testing of unmanned aerial vehicle systems involves the extensive use of hardware and software testing systems. The hardware-software unmanned aerial vehicle engine test complex mounted on the Gough–Stewart platform manipulator is proposed. This test complex provides measurement of the UAV movement parameters in the space, the mechanical and electrical characteristics of the engine and propulsion devices and audiovisual fixation of the test process.

Further development of the complex may be associated with the software implementation:

- models of the Earth's atmosphere (COESA-1976 and ISA-76), the T. von Kármán and H. L. Dryden spectral wind turbulence models;
- modules for preliminary calculation of a flight path and formation of test scenarios.

It is also planned to introduce data exchange interfaces with software simulator for UAV pilot workplace and remote controllers of the aircraft.

#### Acknowledgments

The work was supported by the Ministry of Education and Science of the Russian Federation (Agreement No. 075-11-2019-078).

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