„POLITEHNICA” UNIVERSITY of BUCHAREST

DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

PHD THESIS

OPTIMIZATION AND CONTROL OF ELECTRICAL SYSTEMS FOR AUTOMATION OF A SPACE PROPULSION TEST STAND

\- Summary -

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BUCHAREST 2023

Contents

List of Abbreviations

$ - US Dollar(s)
AC – Alternating Current
COMOTI – National Research Institute of Gas Turbines, Bucharest
DAQ – Data Acquisition
DC – Direct Current
DSP – Digital Signal Processor
DV – Discharge Valve
EMC – Electromagnetic Compatibility
ECU – Engine Control Unit
FADEC – Full Authority Digital Engine Control
FBG – Fiber Bragg Grating
FFT – Fast Fourier Transform
FPGA – Field Programmable Gate Array
GB – Gigabyte
HIL – Hardware-in-the-Loop
I/O – Input/Output
IEPE – Integrated Electronics Piezo-Electric
NGV – Nozzle Guide Vane
P2 – Output pressure
PC – Personal Computer
PID – Proportional Integral Derivative
PLC – Programmable Logic Controller
RAM – Random-access memory
RF – Radiofrequency
RX – Reception
SCADA – Supervisory control and data acquisition
SDR – Software Defined Ratio
SSD – Solid-state drive
TRL – Technology Readiness Level
TX – Transmission
USB – Universal Serial Bus
WSN – Wireless Network Sensor

Chapter 1

Introduction

1.1 Description of Topic of Study

Optimization and control of electrical systems is a key issue in the development and performance improvement of aerospace propulsion systems. Aerospace thrusters (turbines, space thrusters, etc.) are at the heart of any aeronautical or space mission, so it is very important that they are tested in specially designed test stands to ensure optimum safety and performance.

Aerospace propulsion test stands are used to test and validate the performance of engines and propulsion systems. They are commonly used in the aerospace industry, but also in other areas where combustion propulsion systems are required. The stands are designed to simulate conditions relevant to the operation of thrusters in the environment in which they must operate: at high altitudes or in space.

The main components of the propulsion test stands include the test engine or thruster itself, the fuel system, the cooling and/or lubrication system, the exhaust system, the electrical and electronic systems, including the control system and data acquisition.

Control and optimization of the electrical systems of these test stands are essential to ensure the accuracy and safety of the tests. Aerospace propulsion test stands include a variety of electrical and electronic components that must be controlled and monitored to ensure proper system operation. These include: sensors, actuators (such as flaps, valves/valves, pumps, fans), control software. Software may include control algorithms, control systems, and systems to protect against surges or other problems.

Optimization of electrical systems in aerospace propulsion test stands can improve the performance and efficiency of tested assemblies and the stand. There are several optimization techniques that can be used, such as:

- ***Automated control:*** Automated control is used to adjust thruster parameters in real time, based on sensor data and control instructions programmed into the control software. Automated control can be achieved using a variety of techniques, such as logic decisions, PID (proportional-integral-derivative) control or adaptive control. Automated control can provide precise and fast adjustment of engine parameters, improving performance and reducing fuel consumption.

- ***Performance monitoring:*** System performance monitoring can be used to identify performance problems and optimize engine parameters. This can be done by monitoring critical parameters such as fuel consumption, temperature and engine speed and analyzing the data collected to identify trends or problems.
- ***Optimization of electrical circuits:*** Electrical circuit optimization can be used to improve system efficiency and reduce energy losses. This can be achieved by using high-performance components, minimizing parasitic interference and designing circuits to minimize energy losses.
- ***Use of renewable energy:*** In electrical systems, renewable energy is energy generated by components that are powered by energy that does not consume vital resources that already exist in the surrounding environment and are traditionally unused (sun, wind, vibration, etc.). This energy can be stored and used to power other components of the system, reducing energy consumption and operating costs.

1.2 Goal of the Thesis

As the aerospace industry develops and expands, the demand for aerospace thrusters test stands is expected to grow significantly. The aim of this PhD thesis is to research and contribute to the development of efficient and reliable solutions for monitoring and controlling the testing process of thrusters used in aircraft and space vehicles. These systems play a crucial role in ensuring safe and efficient operation of the stand and propulsion system, being responsible for controlling the engine speed and other performance elements, as well as monitoring temperature, vibration and other relevant parameters.

In this thesis, the importance of developing and optimizing the control of electrical systems for the automation of an aerospace propulsion test stand is explored. It discusses the various components of these systems, including sensors, actuators and control software, and considers how these can be optimized to improve system performance and efficiency.

1.3 Thesis Content

Chapter 2 presents concepts for automated test stand solutions for space thrusters. Technical aspects of the main automation components for such stands are introduced: sensors (instrumentation), actuators, infrastructure elements (cables, cabinets, etc.), monitoring and control system, software aspects and data acquisition. Shortcomings as well as innovations in the field are presented. In addition, 4 examples of stands where I brought important contributions to the development of control systems are presented: a classical propulsion test stand (aviation turbine engines), an air pumping stand for testing combustion chambers, a test stand for an experimental model of electric aerospace propulsion, and a test stand for molecular turbopumps used in rocket engines.

In Chapter 3, aspects related to the operation of one of the stands listed above, namely the molecular turbopump test stand for rocket engines, are presented in more detail. These aspects serve to describe the operation of the application and to outline development requirements for its dedicated automation, including: specific operating requirements, input and output parameters, type of control.

Chapter 4 describes the development of the automation, with a focus on the automatic control system of the stand: controller, signals, software. Identified instrumentation solutions for this automation are also presented. Furthermore, a study on innovative instrumentation technologies is presented. In it, I studied possibilities of converting energy dissipated by vibration into usable electrical energy. I studied aspects such as: structure and characteristics of piezoelectric generators, harvesting networks, their applicability and optimization. Regarding control system development, I presented an architecture for an autonomous instrumentation system with wireless transmission, powered by energy from vibration. I also studied, at a theoretical level, optical sensors and wireless sensors, analyzing their application in turbine engine applications. Beyond this, I presented the final and functional solution for a control system developed specifically for this stand. System testing was carried out using both classical methods and the Hardware-in-the-Loop method, an additional, innovative method of testing the controller and control software by simulating the equipment under test before it is physically available. I developed this simulation following research into its application to similar applications worldwide.

Chapter 5 presents conclusions, original contributions and prospects for further development.

Chapter 2

Automated Stands for Aerospace Propulsion

2.1 Concept of Automation

Automation is a concept that refers to the use of electromechanical systems to perform tasks without human intervention or with as little human intervention as possible. This concept has become increasingly important with the advancement of technology and the need to streamline industrial processes and other activities requiring repetitive and precise processes.

Automation systems are used to perform a variety of tasks, such as temperature and pressure control, plant control, loading and unloading, equipment condition monitoring and more. One of the great advantages of automation is that it can reduce costs and improve the efficiency of the system as a whole. Automation systems can run non-stop, without breaks or human error, which can reduce processing time and increase production. Automation can also reduce costs by reducing the number of employees needed to perform a particular task.

Automation can be achieved by using a control system that monitors and controls activities. Automated control systems consist of a central processing unit, sensors and actuators. The central processing unit takes data from the sensors and uses this data to control the actions of the actuators. Sensors are responsible for measuring physical parameters such as temperature, pressure, speed and level. Actuators are responsible for controlling processes such as opening and closing valves, starting and stopping motors, and much more.

Below I describe the main components of a typical test stand automation.

2.1.1 Sensors and Instrumentation

Instrumentation of test stand applications for turboshaft and aerospace engine applications involves the use of a complex set of sensors to measure critical parameters such as pressure, temperature, air or fuel flow, vibration and other important information, in order to assess the performance and reliability of the equipment.

Remotely communicating sensors, connected to the automation system, are an integral part of the system and the closed-loop control logic it can achieve. Based on values transmitted by the sensor to the control system, the software can identify if the measured values exceed the acceptable limits and could trigger sequences to warn the operator, to initiate maneuvers to remove the hazard (e.g., opening an exhaust valve) or to decide to stop the operation of the main equipment.

Sensor limitations may relate to: measurement accuracy, signal resolution or response time, which may contribute to or affect system performance. Also, the interface type must be compatible with the other system interfaces with which the sensor communicates.

Depending on the parameters measured, sensors can be of the following types: pressure, temperature, flow, vibration sensors.

In implementing automation, it is important to consider all relevant technical aspects and choose the right sensors for the test application in question. The choice should be made not only by the type of parameter being measured, but also by the accuracy and interface characteristics that influence the integration of the sensor into the system and the achievement of a measurement at the desired quality. For example, a sensor interface that is compatible with the rest of the measurement line up to the controller optimizes the measurement process by not requiring additional compatibility measures such as signal converters or additional interconnections. These measures are to be avoided because interconnects or any additional electronics can add delays or even additional disturbances to the measurement chain.

It is also important to ensure that the sensors are properly calibrated and to make the necessary adjustments and pre-tests to ensure measurement accuracy.

2.1.2 Actuators

Actuators are pieces of equipment that receive commands from the control system and, using some form of energy, perform physical maneuvers to achieve the objectives of the installation, the stand in this case. Among the most common actuators in test stands for aerospace propulsion systems can be: electric motors, valves, electric pumps (which are also based on electric motors) and electric heaters.

Valves. Most of today's more complex control applications use electrically driven valves. The valve actuator receives the command from the control system and precisely positions the valve in the desired position. Actuators can close and open the valve completely or allow intermediate positions. They may contain switches or other methods of signaling the valve position to the control system.

Electric valve actuator motors are motors specially adapted for such applications. They are required to operate in extreme environmental conditions and have a higher starting torque than conventional motors. Most motors are three-phase, single-phase asynchronous or DC motors. The applications described in this paper mainly use single-phase AC motors. The reasons are both technical (easier to automate the change of direction with two relays) and economic.

The actuator switches signal the ends of travel of a valve. In the case of valves with intermediate positions, the generation of an analogue electrical signal, in the form of a 4-20 mA current or voltage, is required to read the exact position of the valve. Remote control also requires the transmission of an analogue signal from the control system to the valve actuator.

For control and position reading, electrical equipment adequate to the type of actuator is required to acquire and process the feedback or reference signal into a useful signal. They may consist of analogue-to-digital/digital-to-analogue converters, relays, contactors and other elements that interface with the main control device (PLC, operating panel, data acquisition board, etc.). Signal adapters, including signal safety barriers, shall also comply with application-related safety requirements, such as meeting certification in potentially explosive applications, if applicable. This includes galvanic isolation of the signal between the PLC, located in the protected area, and the equipment on the stand, located in the hazardous area.

In *"Electronic Improvements Made for Industrial Valve", C. Nicolescu, B. Varaticeanu,* ***A. Stoicescu****, C. Nechifor, Electrotehnica Electronica Automatica (EEA) Journal, 2020, Vol. 68, nr. 3, pp. 05-12* [8], I participated in a theoretical and practical research campaign on improvements and optimizations that can be made to industrial valves, as part of automation systems for gas installations. The research included:

- testing the replacement of mechanical position limit switches with optical switches;
- using a Pt1000-type sensor for internal temperature monitoring;
- using a humidity sensor to determine condensation;
- considering the opportunity to study other improvements.

Carried out as part of a knowledge transfer project between the COMOTI Institute and the ICPE company, the campaign I coordinated explored the possibilities and limitations of these improvements in an attempt to prototype a valve actuator with additional features to those commonly found. The main remaining constraint was the size of the solution with optical contacts, since in all studied aspects we used existing market components.

Electric motors are particularly important because they can drive mechanical assemblies, machines that can be the focus of research applications, or fluids via electric pumps.

In addition to the motor itself, the main component of the electrical drive system may be a **variable speed drive**, that can drive the motor with a variable speed controlled remotely from the stand control system. The role of the drive is to allow speed adjustment operations according to user command or pre-programmed automatic sequences, and to provide a high level of safety by adding conditions that automatically intervene in the control process. Depending on the application requirements, complex sequences for varying or maintaining motor speed can be implemented according to inputs, calculated parameters or various types of pre-programmed logic using the controller connected to the drive.

In addition to applications where the electric motor drives a thermal machine or other mechanical load, there are also stand setups where the electric motor is used as a generator by a thermal machine. Such a situation has been studied and presented in the paper *„Asynchronous Three-Phase Machine Driven as Generator by a Twin-Screw Expander", C. Borzea, A. Săvescu, I. Vlăducă,* ***A. Stoicescu****, SME'20 (Electric Machines, Materials and Drives Present and Trends / Actualități și Perspective în Domeniul Mașinilor Electrice, 2020* [12]. Here, the operating regimes of a three-phase induction machine, used in an automated stand, driven by compressed air from a screw expander in order to generate electricity to the power grid, were studied.

2.1.3 Infrastructure Elements (cables, cabinets, etc.)

Infrastructure elements are deemed as those elements that do not belong to the above categories, but are indispensable for building a complete stand automation. The infrastructure of an automation system comprises many types of elements, from cables, electrical cabinets and signal converters to the simplest auxiliary elements.

Electrical cables play an important role in stand automation systems, being used to transmit electrical power and control signals between devices in the stand. For example, cables can be used to connect sensors to controllers in order to transmit measurement and process monitoring signals. Cables can also be used to connect the motor to the controller to transmit start, stop and speed control signals.

Electrical cabinets are structures that serve to group and protect electronic components (signal adapters, converters, power supplies, etc.) and cable connectors, and to facilitate the (re)distribution of electrical power and signals according to the architecture and requirements of the system being served and its sub-assemblies.

Signal adapters or converters are used to convert signals from sensors or other equipment into a suitable format for use by other equipment or devices, usually the stand control system. Adapters can be used to convert analogue signals to digital signals, or vice versa, or to convert analogue signals of various types (e.g., 4-20 mA current, 0-10 V voltage, etc.). For example, a signal adapter can be used to convert analog signals from a temperature sensor to a 4-20 mA signal so that they can be used by a PLC with a 4-20 mA input module. This is a very common case in the test stands I contributed to.

Relays are electromechanical devices used to facilitate electrical circuit control by means of an electrical signal. The role of relays in automation and control systems is to connect and disconnect the circuits of various devices, such as motors, valves, heaters, fans and other equipment, following a command. Thus, relays can be used to connect or disconnect power circuits so that the operation of each equipment can be controlled from the control system. For example, a relay may be used to start an oil pump, to open or close a valve or to activate the frequency converter of an electric motor.

2.1.4 Monitoring and Control System. Software. Data Acquisition and Post-Processing

Thruster test stands are used to test and collect data during the testing process. Testing is done under controlled conditions, which allows for the collection of precise and accurate data on the full range of parameters of interest. To collect them, the stands are equipped with data acquisition systems designed and sized according to the application and instrumentation characteristics.

Data acquisition systems acquire, store and process data generated during propulsion tests. This includes data on propulsion performance such as power, fuel consumption, temperature and pressure.

Automated stand control is programmed through software routines, often within the same software application that also performs the data acquisition, since access to the sensor channels is continuously performed for both purposes.

In this thesis (Chapter 4.3.2), I described a software that I developed in its entirety, in order to facilitate and optimize monitoring, automatic control and data logging for a molecular rocket turbopump test stand. Also, other contributions I made to the development of testbed software were described in Chapter 2.2.

2.1.5 Current Problems and Shortcomings

One of the major problems in the optimization and control of electrical systems is a certain deficiency in the clarity and consistency of standards in the electrical and automation industry.

Another problem is related to environmental factors. Propulsion systems under test and their accompanying electrical systems must operate in hostile environments, such as at high altitudes or in space, where they are exposed to ionizing radiation and temperature extremes.

The quality of test data is also an important issue. Test data must be accurate and reliable to ensure that tests are carried out correctly. However, test data can be influenced by a number of factors, such as measurement errors and electromagnetic interference. To avoid these problems, these factors should be considered when developing systems and systems should be designed to minimize interference.

In this thesis, I presented several specific cases of applications where I brought contributions and how the requirements and aforementioned problems were solved.

2.1.6 Innovations

The most important innovations in automatic control systems are:

1. **Real-time testing**

A practical case in this field is the use of sensors with short response times (in the ms range) to monitor flow, pressure and other relevant parameters in real time. This data is then processed by control algorithms that automatically adjust parameters according to changes in test parameters. Such applications where the detection and response time of the control system is very important to be short are applications where rapid phenomena such as ignitions (combustion of a propellant) or harmonic components of the vibration of a high-speed machine can be anticipated, where the event is desired to be captured by the instrumentation and recorded in detail, but also where certain control processes are desired to be triggered extremely quickly.

2. **Artificial intelligence systems**

Intelligent test systems can be used to analyse data collected during tests and identify patterns and trends that can be used to improve test processes. These systems can also be used to improve test efficiency by reducing the time taken to complete tests and increasing the accuracy and precision of measurements.

Over the last decade, research has been carried out in the field of intelligent control of turbine engines. In [14], the authors studied a combination of two techniques: fuzzy logic and evolutionary algorithms. The control parameters included inlet vane opening and nozzle area. Similar research was conducted in [15] in the design and evaluation of two types of fuzzy controllers by regulating the combustion pressure. In [16], a neural network-based controller for gas turbines was presented. Although traditional control techniques are well-established and reliable, modern control techniques promise to provide improved control and increased performance [1], [17]. In recent decades, most control problems have been formulated by objective knowledge of given systems (e.g. mathematical models). Most of these approaches based on mathematical models have found their way into practice and have proven to be satisfactory solutions for the spectrum of complex systems [18]. Intelligent systems can be trained to identify faults in an engine based on data and images captured during testing.

In October 2018, I published a scientific paper on a concept of a self-adaptive control system:

“Self-Learning Control System Concept for APU Test Cells”, R. Ciobanu, ***A. Stoicescu****, C. Nechifor, A. Ţăranu, MATEC Web of Conferences, 2018, Vol. 210* [19].

In the paper, together with the other co-authors, an innovative control system was proposed, compatible with an existing test stand for aircraft auxiliary power unit systems for turbine engines. The system identifies the needs and efficiently distributes power to the aircraft subsystems, based on actual parameters and parameters generated by mathematical models of the aircraft.

3. **Using Hardware-in-the-Loop simulation**

Hardware-in-the-Loop simulation is another important innovation in the field of test stands for aerospace thrusters. This innovation involves the use of mathematical models to simulate thruster behavior under different test conditions. Simulation can be used to test different scenarios and operating conditions before physical tests are carried out. This helps to reduce the cost and time needed to complete tests and can ensure that tests are carried out safely.

As part of this thesis later shows, I performed and tested such a simulation for an aerospace turbopump test stand (see chapter 4.3.3).

4. **Use of innovative sensors**

In the field of sensors used for aerospace thruster test stands, various technologies are gaining interest. Technical typologies differ from case to case and several examples have been studied in the chapters 4.2.1 and 4.2.2, where I have conducted a review of fiber optic sensor technology, wireless sensors and their extent of use in turbine engine applications.

In chapter 4.2.3, I conducted a theoretical and experimental study on vibration energy harvesting solutions, to power autonomous sensors.

2.2 Automation of Test Stands for Aerospace Propulsion Elements

In this chapter I described four test stands for various elements of aerospace propulsion. From aircraft engines to innovative space thrusters, these test stands cover a wide range of examples where automation was developed and where I had contributions on the development of monitoring and control systems that facilitate and optimize the way thrusters or their sub-assemblies are tested.

2.2.1 Test Stand for Classical Propulsion (aviation turbine engine)

Aviation turbine engines are complex machines, and the larger the engine, the more sophisticated the stand will be. In this example, I show the developed system for the control of the combustion process in a multimodular postcombustion plant type ST18, where I developed a station (computer) software that takes data from the PLC in order to monitor and log data during tests.

The sensors transmit the signals to the PLC, from which they are displayed on the operating panel and the monitoring station, which also logs the data. The controls are performed from the control console, via the PLC, to the actuators on the stand. The air fans are also controlled from the console.

The design of the software for the monitoring and data logging station that I developed followed the following ideas and steps:

- I created a graphic diagram of the stand, which the operator can easily get familiar with;

- I placed the sensor data on the graphical schematic in an intuitive way, similar to the position of the sensors in the stand, so that its parameters can be easily spotted and read;

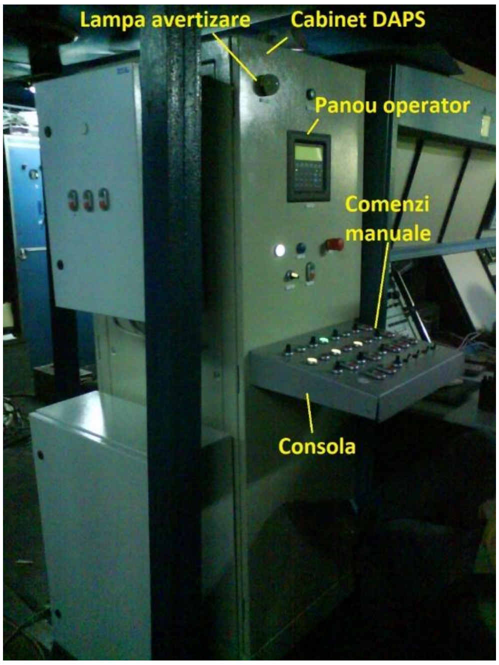


Fig. 1. The cabinet for turbine engine stand automation

- I distributed the parameters on the graphic diagram so that the operator can easily identify the 4 main monitoring areas: the fuel gas supply circuit (yellow), the primary air (fresh air) circuit, the secondary air (postcombustor air) circuit and the postcombustion chamber exhaust area - Fig. 2;

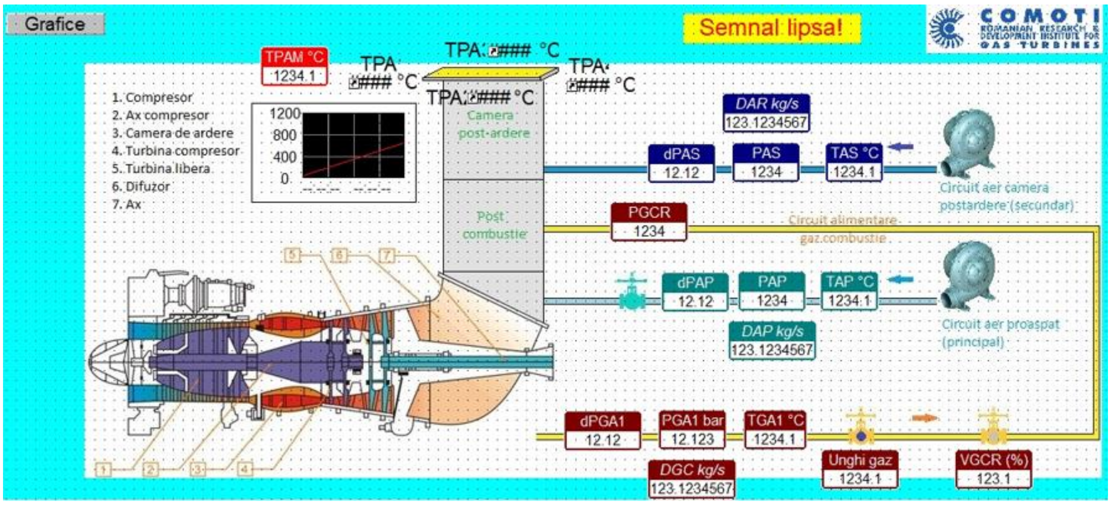


Fig. 2. Schema grafică a unui stand pe software de interfață postardere

- I implemented a "Missing Signal!" led to warn the operator of the disconnection of any of the signals;
- I implemented data logging in *csv* format for all parameters on the screen at a frequency of 1 Hz, as required;

- I made a chart for the average of the postcombustion temperatures, which is of high interest: *TPAM* = average(TPA1...TPA4);
- I made a separate screen with the enlarged graph of *TPAM* variation and flow values, these ones calculated in PLC from the values of pressures, differential pressures and pipe cross-sections.

The software I developed for monitoring and logging the parameters of COMOTI's turbine engine test stand optimized the processes of evaluating the performance of the tested turbines, providing specialists with accurate data for post-analysis of the plant's operation.

2.2.2 Air Pumping Stand for Combustion Chamber Testing

This stand is used to generate compressed air to a facility for testing combustion chambers for small turbine engines, including aviation engines. The stand uses a centrifugal air compressor that provides varying levels of flow and pressure, which can be adjusted to simulate the flow of air from a turbine engine to its combustion chamber.

This stand was a prototype, designed and built for the first time in this configuration to meet the specific requirements of the users of the combustion chamber test bed. The innovation of the compressor stand, as well as its control system, is the possibility to perform the operation of the compressor within a wide range of operating regimes.

My contributions to this stand, further described in this chapter, are:

- I developed entirely, the software-based automatic control and monitoring system, via PLC and operating panel, as detailed below;
- This control system optimizes the stand by performing mathematical calculations in the PLC, to calculate the compressor operating curves without using an airflow transducer;
- I created a program to connect a laptop to the PLC and record data from experiments;
- I participated in on-site tests in the stand, in order to test its operation and improve the control and optimization algorithms;
- I published the development and results of the control method in a scientific paper.

In this chapter of the thesis, I present a brief description of the stand, and towards the end of the chapter the software and control logic I used for the stand.

Description of the stand

After the air is compressed in the compressor, it is routed through the discharge line into the combustion chamber via a valve called EV (short for *Exhaust Valve*). The purpose of EV is to open up access for the compressed air into the combustion chamber test facility. At the same time, the proportional discharge valve DV is responsible for releasing part of the air flow into the atmosphere and maintaining the pressure needed for the combustion chamber system to be tested. To start the combustion chamber experiments, the first step is to start the compressor, which is first run at a minimum steady state with the EV valve in the closed position. When the EV is open, the DV must be automatically adjusted so that it can maintain the required pressure and operating regime.

The power required to compress the air is about 260 kW and the speed variation is done by the frequency converter. For these reasons, a 315-kW engine with a rated speed of 2970 rpm was chosen.

The stand includes: mechanical assembly; electrical cabinet comprising the power part - the variable speed drive; electrical control equipment and the connecting cables between them; control (automation) part comprising the programmable logic controller (PLC) which receives data from the instrumentation equipment (sensors of the various parameters) and transmits commands to the actuators via electrical cables.

The drive powers and controls the asynchronous motor used to drive the compressor, is responsible for varying the motor speed according to the software command, protecting the motor from sudden movements, etc.

The controller is a VersaMax programmable logic controller (PLC) from General Electric, which includes the following components:

- Power supply;
- 128K CPU;
- 1 x Analogue Input (AI) module, 15 channels / 15-bit;
- 1 x Analogue Output (AO) module, 4 channels / 12-bit;
- 1 x Digital Input (DI) module, 32 channels, 24 Vdc;
- 1 x Digital Output (DO) module, 32 channels, 24 Vdc 0.5A;
- 4 x Input/Output (I/O) chassis.

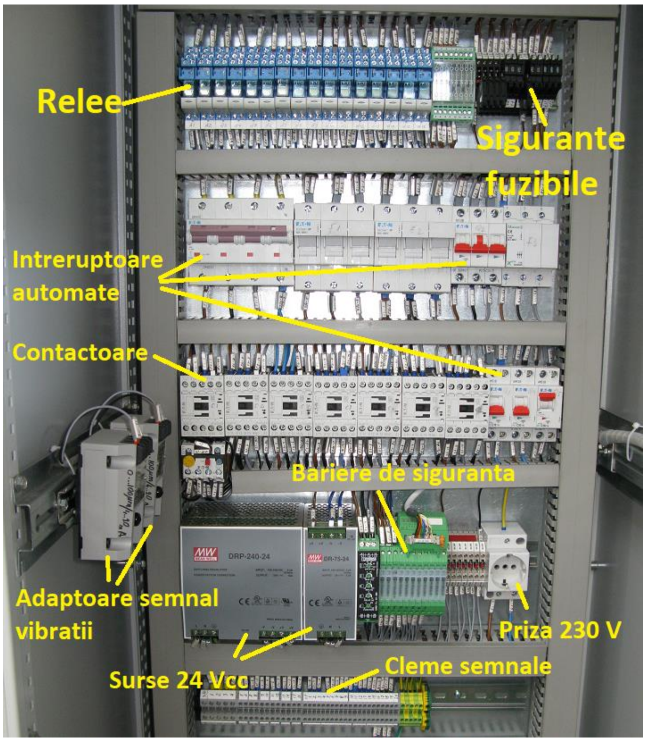


Fig. 3. The interior of the control cabinet

The main software display screen (Fig. 4) shows the values of the monitored sensors.

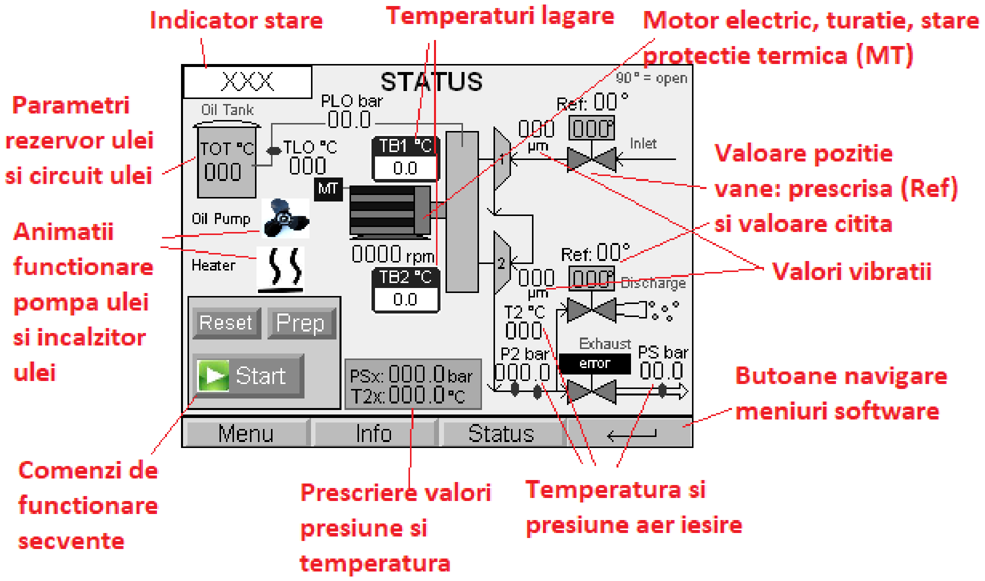


Fig. 4. Main control panel software display

Implement control logic into the software

In order to outline the main logic, it was necessary to study control methods for the surge phenomena in compressors. A preventive approach in reaching the surge limit parameters is ideal. This approach can be done by an automatic system capable of running real-time calculations based on monitored parameters and implemented algorithms. When a surge event occurs, the system can be controlled and stabilized using a PID (Proportional Integral Derivative) controller. Moreover, this conventional controller can be replaced by a fuzzy controller. Various papers have analyzed such technology [24, 25] and it turned out that the performance of fuzzy controllers is similar to the PID controller.

In this application I implemented a multi-reference control method, in the sense that the same compressor is controlled (*P2* output pressure control) by adjusting two parameters: the speed of the electric motor and the opening/closing degree of the DV discharge valve. From the operator's point of view, he has to input, before start-up, only the desired *P2* pressure given by the compressor to the combustion chamber, and select one of the three automatic operating curves, depending on the flow and pressure preferences for the chamber.

Despite the fact that air flow was used in defining the performance graph, the control method was developed so that the compressor does not require direct flow input data, thus not requiring a dedicated flow transducer. This leads to an **optimization** of sensor and measurement line costs, after familiarizing the developer with determining performance graphs for such compressors.

The adjustment sequence of the DV valve is done by continuously comparing the measured pressure *P2* with the reference pressure *P2ref* every 3 seconds, and if the difference is more than 0.1 bar, the valve is closed or opened by 1° as appropriate.

In Fig. 5 an example of the results obtained can be seen graphically, which were also published by the author of the thesis in the paper [26]: *"Automated Multi-Reference Control for Centrifugal Compressor", **A. Stoicescu**, O. Dumitrescu, G. Fetea, 9th International Conference on Energy and Environment (CIEM 2019), 17-18 Oct 2019, Proceedings IEEE, Timișoara, Romania.*

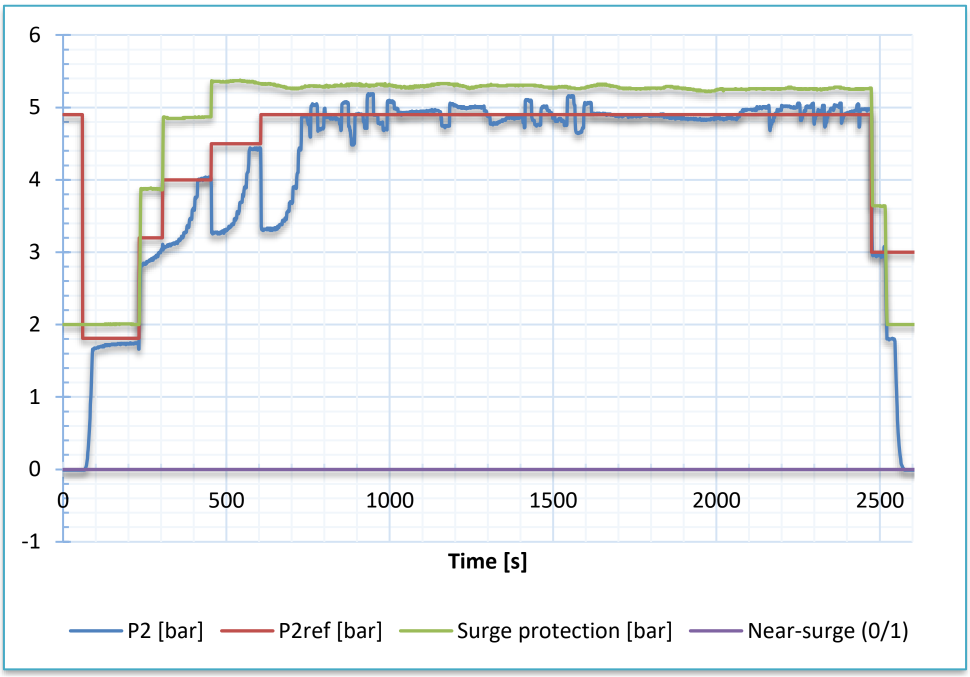


Fig. 5. Performance of the control system on the pressure delivered by the air compressor [26]: Blue – measured pressure (*P2*), red – reference pressure (*P2ref*), green – surge protection limit, which was not exceeded

During this test in the example above, the pressure (blue) following the reference (red) never exceeded the surge protection line (green), even when operating close to it, with the control system successfully avoiding any such situation and maintaining a control accuracy of ±0.3 bar, which fit the technical requirement.

Thus, we were able to demonstrate the success of this electrical and software system in achieving and maintaining, through automation and software control sequences, the compressor outlet pressure without the need for a flow transducer, with effective protection against surge phenomena.

In conclusion, the optimizations we have made through the development of this control system have concerned both the interface and the sequences of operation implementation.

2.2.3 Test Stand for Electric Propulsion

Electric space propulsion is considered to be that in which the thruster uses electrical and potentially magnetic means to generate the thrust required for motion. The chosen application is based around a Helicon radio frequency (RF) thruster. This is an innovative technology that was the subject of the research project "*Assessments to Prepare and De-Risk Technology Development: Helicon Plasma Thruster*", won by COMOTI and funded by the European Space Agency.

The thruster (Fig. 6) consists of a cylindrical discharge enclosure made of dielectric material, where the plasma is generated, an RF antenna wrapped around the discharge tube, and a magnetic nozzle. Stand testing is done in a vacuum chamber, simulating near-space environmental conditions. RF power is supplied to the antenna using an external generation system. The fuel (argon) is supplied via a power supply system attached to the vacuum chamber. A set of magnets surrounding the discharge tube also generates the necessary magnetic field, both in the magnetic discharge area and in the plasma expansion area, forming a magnetic nozzle.

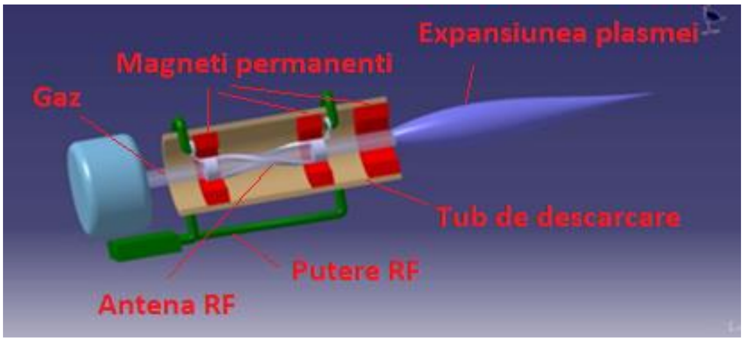


Fig. 6. RF thruster 3D model

The following elements are highlighted in Fig. 7:

- **PC station** (1) – laptop with software for equipment control and data logging;
- **Vacuum pumping system** (2) - delivers vacuum to the vacuum chamber;
- **RF system** (3) – delivers RF power to the thruster at 13.56 MHz and power levels up to 800 W;
- **Flow controller** (4) – gas flow controller;
- **Pressure gauge** (5).

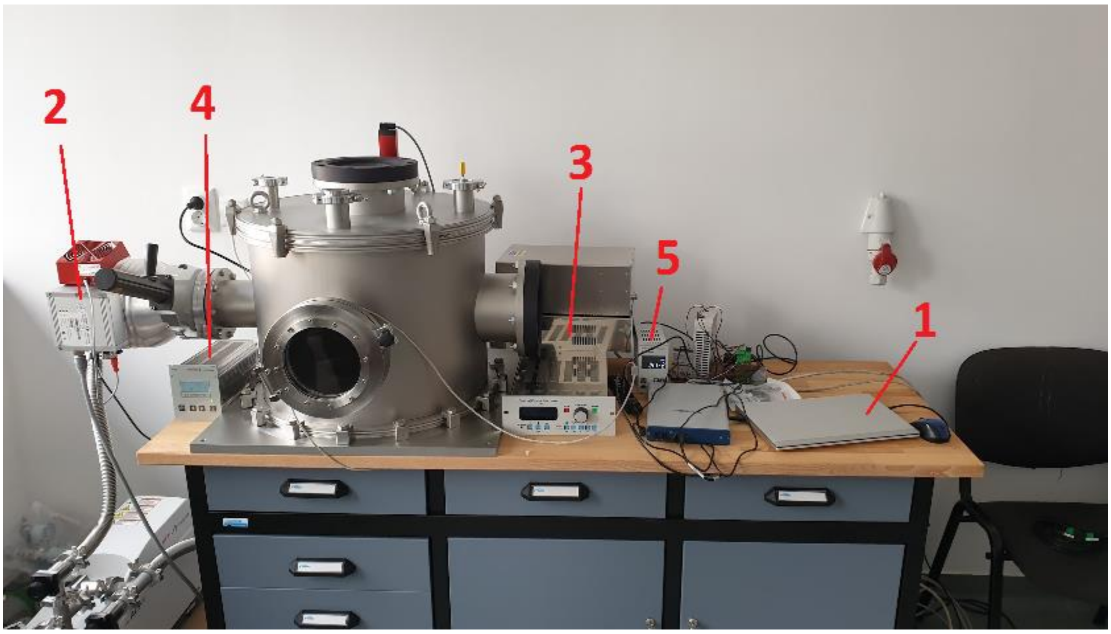


Fig. 7. Overview – Helicon thruster test ministand, built within the Helicon Plasma Thruster project, at COMOTI Măgurele

My contribution in the development team was the interconnection of the systems with the control and data acquisition system, the development of the control and data logging software, as well as in the selection and study of the efficiency of the RF power generation system.

The **RF generator** belongs to a range of models specifically designed for plasma processing applications. During the experiments, the generator was positioned outside the vacuum chamber and connected to the load (plasma) via special cable seals designed for vacuum enclosures. For its choice, it was necessary to know several aspects, therefore below my contribution to their study is detailed.

RF generators can operate at different frequencies. They determine the behavior of plasma ions. For example, at lower frequencies longer wavelengths are created, which cause the ions to have higher kinetic energies. At the same time, a higher density of ions is created, so more plasma particles per unit volume. The higher the frequency, the shorter the wavelength, leading to faster processes, but requiring more operating energy.

13.56 MHz is one of the internationally designated frequencies for **I**ndustrial, **S**cientific and **M**edical applications (the so-called ISM band). It allows for certain power applications without disturbing any surrounding communications.

The selected generator generates an RF frequency of 13.56 MHz, at a maximum power of 600 W. It still however considers load impedance as 50 Ω resistive, as this is the industry standard for measuring and transferring high-frequency electrical power. However, plasma is not such a load. RF discharge models have been proposed by researchers for many years, leading to equivalent circuit models for plasma [30-33], in order to quantify its nature (resistive, resistive-inductive, resistive-capacitive) and impedance amplitude. It is also certain that a type of plasma enclosure, such as the one in the present case, possesses characteristics that are not only different from a "standard" load, but also dynamic [34]. On a macro-temporal scale, plasma is considered a nonlinear electrical object [35]. In order for the power transfer from the source to the plasma to be optimal, all interactions between the two must be considered. Tuning the impedance of the plasma to the output impedance of the RF generator requires additional circuitry to counteract the inductive and/or capacitive components of the chamber and tune them to a purely resistive 50 Ω impedance. If the tuning is not complete, some of the RF power will be reflected back to the power source. Thus, the whole system is less efficient and situations may arise that lead to overheating, equipment failure, etc.

To solve the situation, I introduced a circuit to eliminate the impedance difference, a device called a "**Matching Box**". This has automatic impedance adjustment over a wider range. It is basically an air-cooled unit with stepper motors that automatically adjusts its capacitors according to the required impedance values.

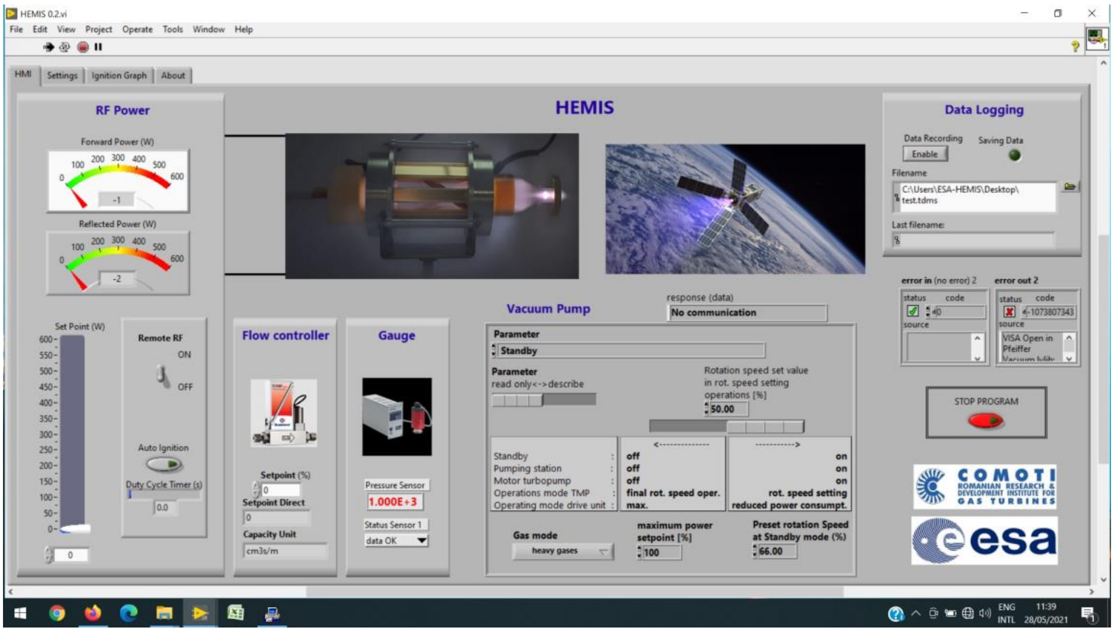
To transmit RF power, we decided to use coaxial cable, consisting of a central conductor surrounded by a dielectric insulation, which in turn is surrounded by an outer conductor. With this type of cable, RF power propagates through the dielectric material between the inner and outer conductor.

Special attention had to be paid to EMC (electromagnetic compatibility) issues. A plasma chamber, with RF and magnetic phenomena, should be treated as an application that requires special attention in this respect, in order to ensure adequate signal and power transfer between system elements.

For RF power transmission, the RF cable must form an unbalanced coaxial line, allowing a grounded return path. In this way, the magnetic and electric fields radiating from the cable will be largely eliminated, due to the fact that the only live conductor would be the inner one. Also, the dielectric between the inner and outer conductor makes the impedance relatively constant along the cable.

Good shielding was required for all communication paths to prevent RF power transmission on the signal cables.

The software interface that I made in LabVIEW is in Fig. 8.



Forward Power (W): -1
Reflected Power (W): -2
Set Point (W): 0
Remote RF: ON / OFF
Auto Ignition
Duty Cycle Timer (s): 0.0
Setpoint (%): 0
Setpoint Direct: 0
Capacity Unit: cm3s/m
Pressure Sensor: 1.000E+3
Status Sensor 1: data OK
response (data): No communication
Parameter: Standby
Parameter read only<->describe
Rotation speed set value in rot. speed setting operations [%]: 50.00

	<-------------	----------->
Standby :	off	on
Pumping station :	off	on
Motor turbopump :	off	on
Operations mode TMP :	final rot. speed oper.	rot. speed setting
Operating mode drive unit :	max.	reduced power consumpt.

Gas mode: heavy gases
maximum power setpoint [%]: 100
Preset rotation Speed at Standby mode (%): 66.00
Data Recording: Enable
Saving Data
Filename: C:\Users\ESA-HEMIS\Desktop\test.tdms
Last filename:
error in (no error) 2: status ☑ code 0 source
error out 2: status ☒ code -1073807343 source VISA Open in Pfeiffer Vacuum.lvlib:
ENG INTL 11:39 28/05/2021

Fig. 8. Main software interface for the thruster test ministand

To facilitate operation in a pulsed regime, I created a software routine that automatically controls RF power and gas flow according to a duty-cycle template. The cycle includes an Off timer (**toff**), during which both RF power ("*Power*") and gas flow ("*Flow*") are turned off (or set to a minimum value), an On timer (**ton**) during which RF power and gas are turned on (or set to a maximum value) simultaneously, and a delay (**tdelay**) between the moment the gas is turned on and the moment the RF is turned on, as shown in the graph.

In the test campaign (Fig. 9, 10) various values were tested in order to maximize the thruster performance. In Fig. 9, the mini-thruster, inside the vacuum chamber, is observed to be ignited from the software control, and the white jet is visible on the right side.

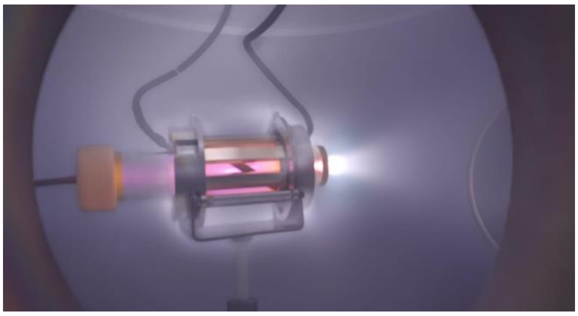


Fig. 9. Thruster ignition testing in vacuum chamber

Maximizing the thruster performance is meant by a reflected power (*Pref*) as low as possible in relation to the active power (*Pfwd*), as well as reaching the Helicon mode, shown in the graph in Fig. 10 by a power step higher than the initial ignition step. Helicon mode implies charging oscillated particles by an electric field, and achieving it was one of the project's objectives. In this test, the maximum power was increased to a level close to 600 W.

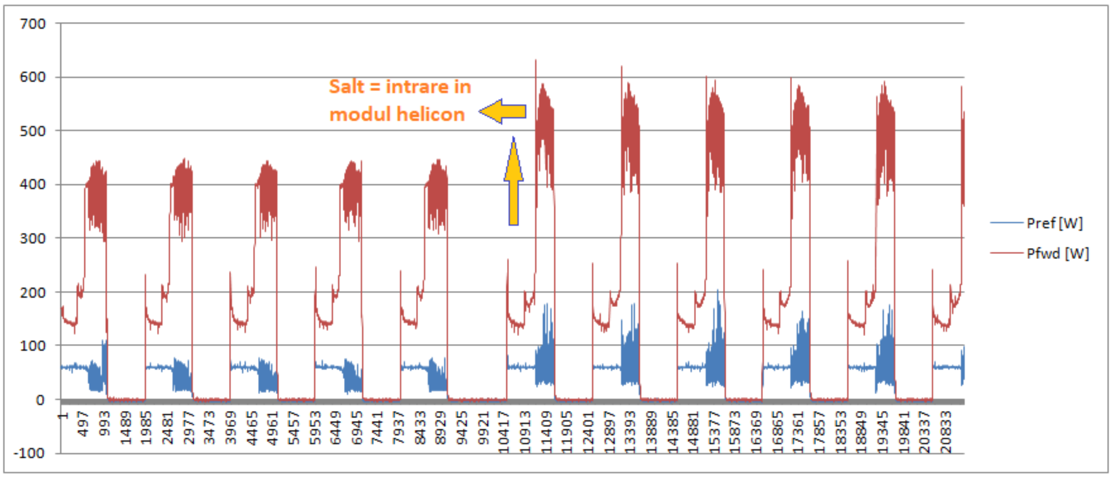


Fig. 10. Graph of thruster power performance at one of the tests; *Pfwd* - active RF power induced in the thruster, *Pref* - power reflected by the thruster; on the horizontal side is the time axis (in ms), with sampling rate of 1 ms

Achieving these goals would not have been possible without ignition optimization measures, such as the use of the "Matching Box" device or the short duration multi-cycle control sequence shown above, which I programmed and tested with different values until the desired performance was achieved.

2.2.4 Test Stand for Rocket Engine Molecular Turbopump

The main purpose of the so-called "TPO Test Rig" (Fig. 11) is to develop an experimental platform to evaluate the performance of the VEGA-E turbopump based on the similarity of real conditions with the stand conditions. I contributed to this development by configuring a controller and developing software for the automatic control system and logging of the stand data, as well as researching and performing test procedures that are described throughout the thesis.

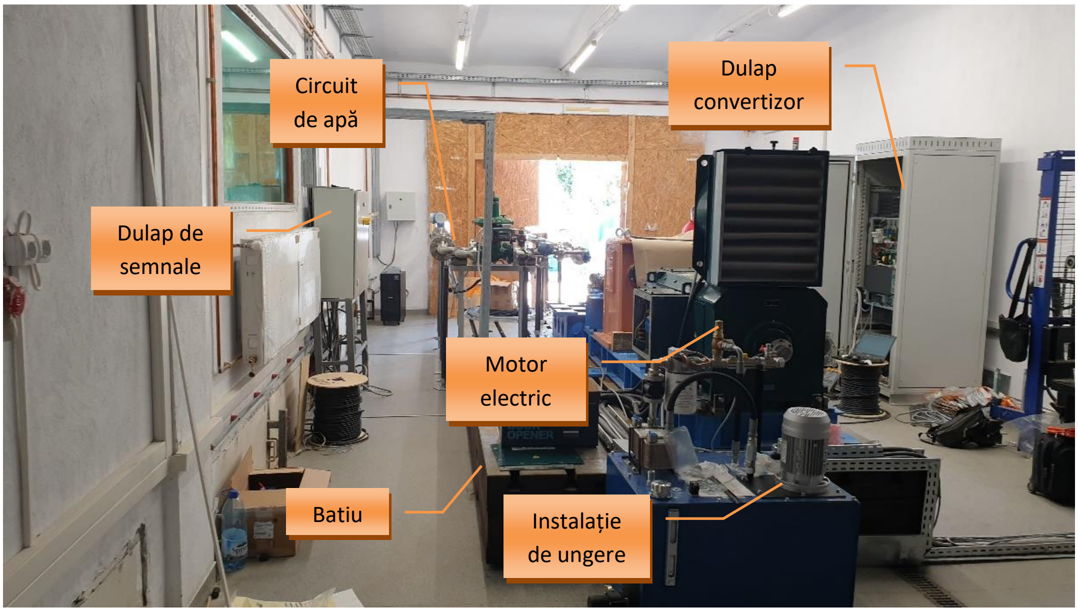


Fig. 11. Standul de testare turbopompe în curs de execuție, la COMOTI Măgurele

To meet the objectives, appropriate instrumentation was chosen to determine the stand parameters.

To validate the methane pump, a series of tests will be carried out beforehand by similarity with water for all operating regimes including start-up, low flow and high flow shutdown. To carry out these tests, an electric motor already installed and coupled to a gearbox multiplier is used, which provides the necessary power to the pump for operation.

The automatic control system is understood under this objective as that part of automation which includes: the control and data acquisition system consisting of the industrial computer and its modules, the software which runs the automatic control logic, the instrumentation and control lines, including the interfaces on their path. Since this control system is, at least in terms of number of measurement lines and controlled equipment, the most complex of those described in this paper and one to which I brought a substantial contribution, it is dealt with at length in the following chapters, 3 and 4.

Chapter 3

Application Operation

3.1 Specific Requirements

We have identified those requirements with relevance to the design, sizing and development of the control system, including software:

- Number of parameters
- Parameter type (input, output, analogue, digital);
- Control type.

First of all, I studied the list of equipment that must be in the stand, mainly equipment that communicates with the automation system.

The turbopump to be served by this stand was determined to be driven by a DC motor with compensation winding, with a maximum power of 601 kW. The maximum speed of the motor is 2600 rpm and the rated speed 1736 rpm. The motor is connected to the shaft by an elastic coupling which attenuates the high torque during start-up. The advantage of DC drives is that the speed is quickly and precisely controlled by the variable speed drive. Also, the risks of electromagnetic disturbances on signals are lower in DC drives and motors, as opposed to AC drives.

The motor is of type RP 280 KS from Sicmemotori and the variable speed drive is of type TPD-32 from Gefran S.p.a., with an input voltage of 500 V, output voltage of 520 V and output current of 1400 A. It has analogue signal inputs and outputs, an important aspect being the remote monitoring and automatic control of the speed from the central computer in the control room.

3.2 Input Parameters

Based on the equipment tables in chap. 3.1 of the thesis, I analyzed their components and structured the list of parameters as presented in the tables in the thesis.

According to this list I determined the inputs and outputs to and from the controller (the "brain" of the control system), and together with the electrical designer I was able to outline the electrical signal paths (cables, cable routes), the peripheral modules of the controller and the software channels allocated to the parameters used in the automatic control logic and in the monitoring and logging of data.

These signals are transmitted, depending on the type of signal and the amplitude of the measured parameter, either by electric current between 4 (0 for faulty) and 20 mA, or by voltage between 0 and 10 V, or by IEPE (Integrated Electronics Piezo-Electric) complex signal. Digital signals are binary signals (0/24V) provided by the contacts of certain equipment to determine either the position (closed/open), the operating state (on/off) or the reaching of certain thresholds according to which the respective contact is switched.

3.3 Output Parameters

The output parameters represent the commands generated by the controller (by the software) to the stand, more precisely to each equipment in the stand controlled by the automatic system. Parameters are controlled by the software as virtual physical quantities (e.g. speed in rpm, opening degree in % or binary states), and generated electrically by the controller's peripheral modules, through proportional analogue (4...20 mA) or digital (0/24 V) electrical signals, as appropriate. Depending on these signals, the equipment can perform actions such as: speed change, open/close, start/stop, etc.

3.4 Control Type

Broadly speaking, the software logic had to allow for two types of control:

- *“Manual” control* – the execution elements of the stand (motor, valves, pumps, heaters, etc.) are controlled by direct commands, without following a complex operating sequence, the main purpose being to test their individual functionality;
- *Automatic control*, by which more complex sequences of actuator operation can be launched following a software routine.

It was possible to outline 6 types of tests, designed to study each of the subsystems of the test stand:

1. Electric motor and gearbox tests;
2. (Turbo)pump oil circuit tests;
3. Tests for water circuit at atmospheric pressure;
4. Tests for water circuit under vacuum conditions;
5. Tests for water circuit under overpressure conditions;
6. Tightness for the water tank.

Chapter 4

Automation Development and Researched Aspects

4.1 Identification of Instrumentation Solutions

The instrumentation solutions for the turbopump test stand were identified following an analysis by an interdisciplinary team of which I was part, in order to achieve the following goals:

- The sensors were chosen to provide a common, reliable, easy-to-use interface that allows using peripheral modules with a considerable number of inputs per module. Of all the possible analogue signals, the 4-20 mA standard offers the following advantages:
    - powering can be done directly through the signal loop;
    - by the difference between 0 and 4 mA, signal interruption can be easily detected. Thus current values below 3.5 mA or above 20.5 mA can lead to warning or automatic shutdown conditions;
    - the signal is not affected by the voltage drop along the path length;
    - has relatively high immunity to electromagnetic interference.

  Acquisition modules with this standard have 32 analogue input channels each;
- If the 4-20 mA interface is not available, the signal can also be 0-10 V;
- In the case of 2 dynamic pressure sensors, due to the high requirements for the signal acquisition rate (16 kHz), sensors with IEPE type signals were chosen, which is a standard for such sensors containing integrated impedance conversion electronics via BNC cable;
- For instrumentation where only binary information is required (e.g. closed/open, on/off or over/under, or depending also on availability trade-offs, 24 V contact signal interfaces have been chosen;
- The sensors have been chosen so that their measuring range covers the range within which physical quantities can vary;
- All commands from the controller are performed either by 4-20 mA current variable signal or by relays;
- Other considerations: economic, expertise in use, brand, etc.

Thus, the instrumentation that consists the purpose of the case study is distributed as follows:

- 25 sensors with 4-20 mA output signal (7 temperatures, 8 pressures, 4 flows, 1 level, 2 differential pressures, 2 vibrations, 1 torque);
- 2 dynamic pressure sensors with IEPE output signal;
- 1 turbopump speed sensor with 0-10 V output signal;
- 1 valve with 4-20 mA output signal and 4-20 mA control signal;
- 2 valves with 0-10 V output signal and 4-20 mA control signal;
- 3 valves with digital output signals (2 end contacts) and relay control;
- 2 temperature sensors with 2 contacts;
- 1 level sensor with 2 contacts;
- 3 oil heaters with contacts and relay control;
- 2 electric motors for pumps, with contacts and relay control from contactors;
- 2 special pumps (recirculation and vacuum), with contacts and relay control from contactors;
- 1 emergency stop button (kill switch), with normally closed contact;
- 1 main electric motor variable speed drive, with 4-20 mA output signal, 4-20 mA control signal, 2 contacts and relay activation;
- 1 oil clogging indicator with 2 contacts.

4.2 Study of Innovative Instrumentation Solutions

Within this sub-chapter, I integrated a research campaign on innovative types of instrumentation that I have studied and analyzed for optimizing various types of stand applications in the field of machine testing, and beyond. The study of instrumentation types used in such applications contributes to the development of knowledge in the field of innovative control systems for engine test stands.

4.2.1 Fiber-Optic Sensors

Fiber optic sensors are of interest as a possible alternative to traditional sensors, with advantages that make them suitable for harsh environmental conditions such as high temperatures, explosive environments, electromagnetic disturbances, noise, humidity and vibration. These advantages include [20]:

- immunity to electromagnetic interference;
- electrical passivity, suitable for use in potentially explosive environments;
- data transmission over relatively long distances;
- long lifetime in various environments

The sensor emits and receives a light, which is converted into an electrical signal. Fibre-optic cables transmit the light to and from areas that are difficult to access (small) or hostile to the sensor. The cable consists of a plastic or glass core surrounded by a layer of armour [36], which reflects the light so that it travels the full distance of the cable.

Some types of cable can withstand high flexibility without affecting its structure, making it suitable for cramped spaces, such as in avionics.

Beyond generalities, the exact types of fiber optic sensors are distinguished by many variations in their architecture and operation. In the case of temperature alone, at least four measurement techniques can be distinguished, and accuracies can be ±0.1

°C and sometimes much higher [40]. These techniques include: remote pyrometry, Fabry-Perot interferometry, fluorescent emission, etc.

In order to get a true picture of the combustion process, an example of the use of optical sensors is to place them in direct locations where thermocouples have a harder time, such as in the combustion chamber or at its immediate outlet. This eliminates the need to draw additional algorithms to determine conditions there based on temperatures at more remote positions where thermocouples would be mounted.

The field of aviation flight testing presents numerous challenges for instrumentation, including scale, environmental, and regulatory requirements [74, 75]. On aircraft such as the Airbus A380, measurements can be made from areas of the aircraft that are up to 100 m away from the hardware and processor housings [76]. Electromagnetic compatibility (EMC) requirements are specified in certification standards such as CS-23 or CS-25, and the nature of some of these instruments can be problematic in terms of their incorporation into the aircraft [75]. The immunity of FBGs to electromagnetic interference, the low mass of the sensor elements, the possibility to embed the optical fiber in composite materials or mount it on the surface of metals, the possibility to multiplex a sensor array into a single optical fiber and to monitor multiple arrays simultaneously using a properly configured demodulation system, are major benefits of their use in aircraft turboshaft applications. Their potential for aeronautical applications including wind tunnel or structural monitoring has also been highlighted in [77-81].

The study concludes that the immunity of FBG fiber optic sensors to electromagnetic interference, their low mass, the possibility to embed the optical fiber in composite materials or to mount it on the surface of metals, the possibility to multiplex a sensor array into a single optical fiber and to monitor multiple arrays simultaneously using an appropriately configured demodulation system, are major benefits of their use in aero-engine applications. On the other hand, these systems are costly and require more testing and standardization before really breaking into the field.

4.2.2 Autonomous/Wireless Sensors

The use of wireless technology for instrumentation systems would bring the following advantages:

- substantial increase in the complexity of the data that can be sent to the ECU;
- allowing for more sophisticated monitoring of engine condition;
- replacing cables with wireless transmission reduces system mass, resulting in lower fuel consumption and reduced carbon emissions;
- online statistical analysis of data from such a system can allow a better understanding of engine and aircraft health.

However, the integration of wireless technology into aerospace or industrial turbine applications faces very significant challenges, particularly in aerospace engines, where a high level of safety and certification is required. Temperatures on an engine casing can exceed 250 °C, eliminating the use of conventional silicon-based electronics. In addition, maintaining the integrity of an RF signal transmission in a largely metal environment without interfering with other electronic equipment can be a major obstacle. Powering sensors is also a significant challenge, which may require various means of harvesting energy.

4.2.3 Energy Solutions from Clean Technologies. Practical Case Study

Among the types of renewables, a less publicised but growing interest is piezoelectric power. This technology is gaining interest because of its ability to generate energy from vibrations and mechanical shocks, which are present in many applications in the field, including test stands for turbine engines and other aerospace thrusters. For this reason, I conducted theoretical and experimental research into the potential use of this technology in these types of applications.

In order to obtain a proper sizing of a vibration harvesting network, it is necessary to have an understanding of the vibration spectrum of the machine in normal operation. The electrical power generated by the harvester will depend on its inertial mass m, the attenuation factor of the damper, the resonant frequency (which should match the vibration frequency as closely as possible), the vibration amplitude and the vibration frequency. Therefore, a sizing that matches the characteristics of the machine considerably increases the resulting energy.

In order to determine the complex vibration characteristics of a turbine engine, it is necessary to use specially designed equipment. With the help of this equipment, under my coordination, the team of the Acoustics and Vibration Laboratory of COMOTI carried out vibration analyses on TV3, Rolls-Royce Tyne, Cogenerare Suplacu de Barcău etc. turbine engines. The vibration measurements were carried out with acceleration transducers of the PCB 352C33 type and with an 01dB-Metravib Orchestra acquisition system, and an FFT function was applied to them.

Vibration spectra were extracted from the TV2 turbine engine compressor under test at the COMOTI stand. From the spectrum it can be seen that the dominant vibration frequency is around 240 Hz, where it has an amplitude of 6500 mm/s^2, but there are also spectral components exceeding 500 mm/s^2 in amplitude at frequencies of 450, 600, 900 Hz and higher.

For maximum efficiency, the piezoelectric device should be chosen and configured so that its resonant frequency coincides with the fundamental component of the vibration, where its amplitude is greatest.

Two scientific articles capture a research campaign with practical tests of piezoelectric systems that I coordinated:

- *"Piezoelectric Harvester Performance Analysis for Vibrations Harnessing", C. Borzea, D. Comeagă,* ***Adrian Stoicescu****, C. Nechifor, UPB Scientific Bulletin, Series C (Electrical Engineering and Computer Science), Vol. 81, Issue 3, 2019* [99];
- *"Vibration Energy Harvesting Potential for Turbomachinery Applications",* ***Adrian Stoicescu****, Marius Deaconu, Romeo Dorin Hrițcu, Cristian Valentin Nechifor, Valeriu Alexandru Vilag, Aerospace Europe CEAS 2017 Conference, 16th-20th October 2017, Bucharest, Technical session Propulsion II*; publicat în *INCAS Bulletin Volume 10 Issue 1, March 2018.*

The campaign involved attaching the piezoelectric device to the Klimov TV2 turboshaft in the COMOTI turbine engine test stand, connecting the device to an electronic harvesting board and measuring the voltage generated during operation. Four accelerometers were also mounted on the engine casing to study resonance points and to correlate them with the electrical power generation performance (Fig. 12). The piezoelectric device we chose is a MIDE PPA-4011 type, with a resonance frequency set at 183 Hz.

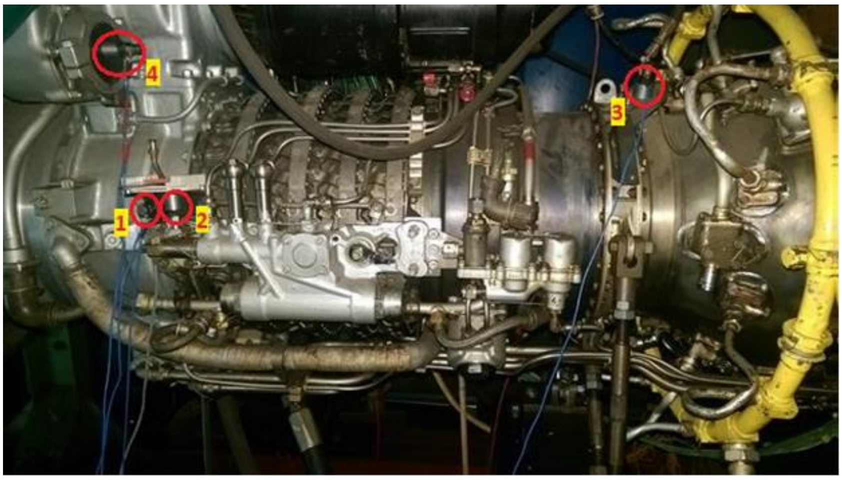


Fig. 12. Position of accelerometers on the TV2 turbine engine: **(1)** axial-horizontal near the harvester, **(2)** axial-vertical near the harvester, **(3)** at compressor end, **(4)** on the engine starter [100]

The engine operated between 10,500 and 12,000 rpm, at various regimes and speed levels, while the generated voltage, rotational speed (frequency) and engine vibration data was continuously monitored.

A vibration of approximately 0.9 g was measured at a frequency of 190 Hz (11,400 rpm). At the resonant frequency, the voltage recorded was between 3 and 3.5 V, above the level of a small electric battery. During transient regime, a voltage of 4 V was obtained at 190 Hz.

In order to develop a system that wirelessly transmits the data values from the sensors, I coordinated a laboratory study using the "Microchip" evaluation kit P2110-EVAL-01 (Fig. 13). It contains a data acquisition module, built with the PIC24F16KA102 microcontroller, which takes data from local sensors (which could be temperature, brightness, humidity) and wirelessly sends it using a second module built with the MRF24J40 specialized in 2.4 GHz communications according to the IEEE Std 802.15.4™-2011 "Low-Rate Wireless Personal AreaNetworks" (LR-WPANs) standard.

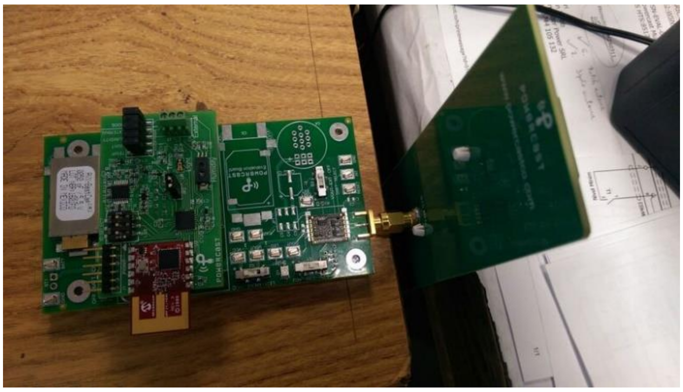


Fig. 13. P2110 evaluation kit

In order to study the possibility of using the energy obtained from the vibrations of a turbine engine, I purchased a demonstration circuit for piezoelectric harvesting and coordinated the team of electronics engineers to study its operation potential. The "Demo circuit 1459B" from Linear Technology uses the specialized

LTC3588EMSE-1 chip. The PIC24F16KA102 chip is a 16-bit, general-purpose, flash-memory microcontroller developed in "nanoWatt" technology.

The specific consumptions for these power saving modes are:

- current consumption in *Run* mode is typically less than 8 µA/MIPS (Mega Instructions/s);
- in standby modes (*Doze*, *Idle* or *Sleep*) the current consumption is less than 2 µA;
- *Deep Sleep* mode typically goes down to 20 nA.

The consumptions that are fixed in any regime are those of continuously operating components:

- Real time clock and calendar (RTCC) consume 490 nA at f = 32 kHz and Vdc = 1.8 V;
- Watchdog Timer consumes 350 nA at Vdc = 1.8 V.

In the last mode (Deep Sleep) the power consumption is the lowest but the 'wake-up' is slow, which may affect the need for timely transmission of data packets. For this reason, we have chosen "Sleep" mode to relax standby consumption and to allow enough energy to be built up for use in the "Run" mode. A reduction in consumption is observed inversely proportional to the supply voltage (Vcc), which according to the specifications is in the range 1.8V...3.6V. The consumption is also reduced proportional to the decrease in processor clock frequency.

The solution was to program the instrumentation and data transmission board so that it goes to sleep and periodically activates for wireless data transmission.

The conclusions of this sub-chapter are that by whatever method and however much we maximize the energy gained by harvester, it is very important to find ways to rationalize and reduce consumption for useful activities. To this end, the consumption of the acquisition and transmission system must be optimized by scheduling work modes and timing the activity in accordance with the rate and timing of energy extraction from the source.

Future studies in this field can be carried out to find methods to model the consumption in order to use the energy obtained by harvester economically and efficiently - control, commands, timing, optimization.

These objectives can be achieved by modifying the structure and content of the firmware of the equipment, which represents 80% of the composition of any current system built with a microcontroller network, as well as by setting time periods for useful consumption / pause for energy accumulation from the environment.

4.3 Automated Control of the Application

4.3.1 Hardware Solution

The hardware solution focuses on the architecture of the controller and its input and output modules for the signals it receives from sensors and equipment, as well as those it generates to control the actuators of the stand.

To facilitate and optimize the process of controlling and monitoring the system, I chose to centralize the sensors and execution elements in the same controller. This approach involved the implementation of a complex control and monitoring algorithm (see chapter 4.3.2), allowing efficient interaction between sensors and actuators. In addition, I chose to implement a data logging system (also chapter 4.3.2), allowing continuous monitoring of system operation and identification of possible problems.

The controller is positioned in a separate room adjacent to the stand, as it is sensitive to aggressive environmental factors (water vapor, oil vapor, electromagnetic interference from the variable speed drive, vibration, mechanical hazards, etc.).

From a hardware point of view, I configured the PXI system (Fig. 14) based on the resources needed to run the software smoothly and log data at the required frequencies. I also sized its components to interface with all types of stand input and output signals.

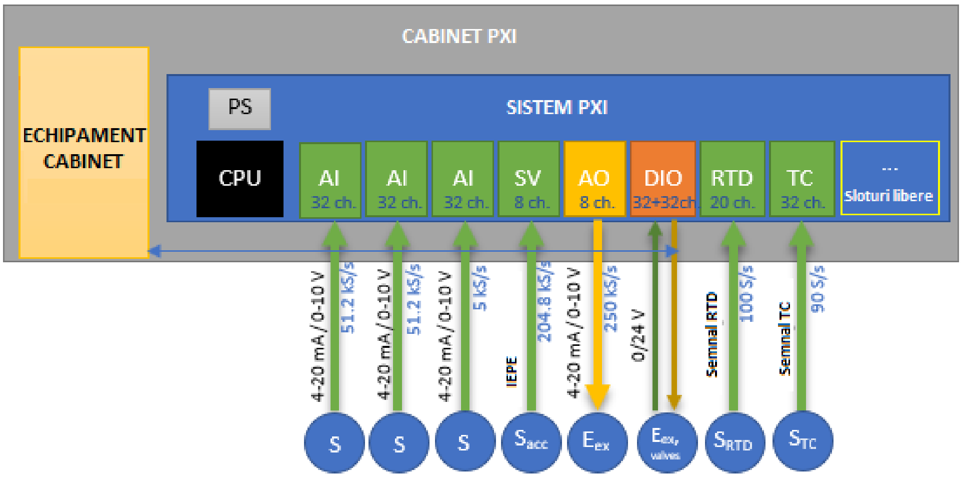


Fig. 14. PXI system architecture, highlighting input/output modules

LEGEND:

PS – Power Supply
CPU – Controller with CPU (processor), RAM, SSD, operating system;
AI – Analog Input mode;
SV – sound/vibration mode for IEPE signals;
AO – Analog Output mode;
DIO – Digital Input/Output module;
RTD – Resistance Temperature Detector (RTD) input module;
TC – Thermocouple mode;
S – Sensors;
S_{acc} – Accelerometer or other IEPE sensors;
E_{ex} – Actuators – motor on/off converter, on/off valves, electrical circuit connection/disconnection, etc.;
S_{RTD} – RTD sensors
S_{TC} – Thermocouple Sensors.

AI modules are mostly dedicated to pressure, flow, temperature and vibration sensors that have 4-20 mA or 0-10 V output signal, the same type of feedback signals from valves, speed feedback from motor's variable speed drive, torque transducer signal.

The SV module is by default dedicated to accelerometers, due to the large dynamic range. However, two changes occurred: the accelerometers (the two vibration sensors) were later equipped with 4-20 mA converters and passed to the AI modules. Dynamic pressure sensors were connected to the SV modules instead, because their IEPE standard is compatible with the SV module, and the high frequency acquisition requirements make the connection of these sensors to this module (allowing for 204.8 kHz) a suitable one.

AO modules are dedicated to variable signal generation for electric motor control (via its converter) and variable position valves.

The DIO modules are dedicated to 24V control signal output (on/off) for switching on/off electrical circuits, valves and other circuits, and for reading the presence of 24V feedback contacts.

The RTD and TC modules are designed to cover temperature sensors (resistance thermometers and thermocouples respectively) without conversion to another type of analogue signal. This is currently a fallback solution as all temperature sensors installed so far generate 4-20 mA signals.

In addition, there are free slots where additional modules can be inserted to extend the measurement range for future needs.

Fig. 15 shows the monitors interfacing with the operator in the control room of the stand.

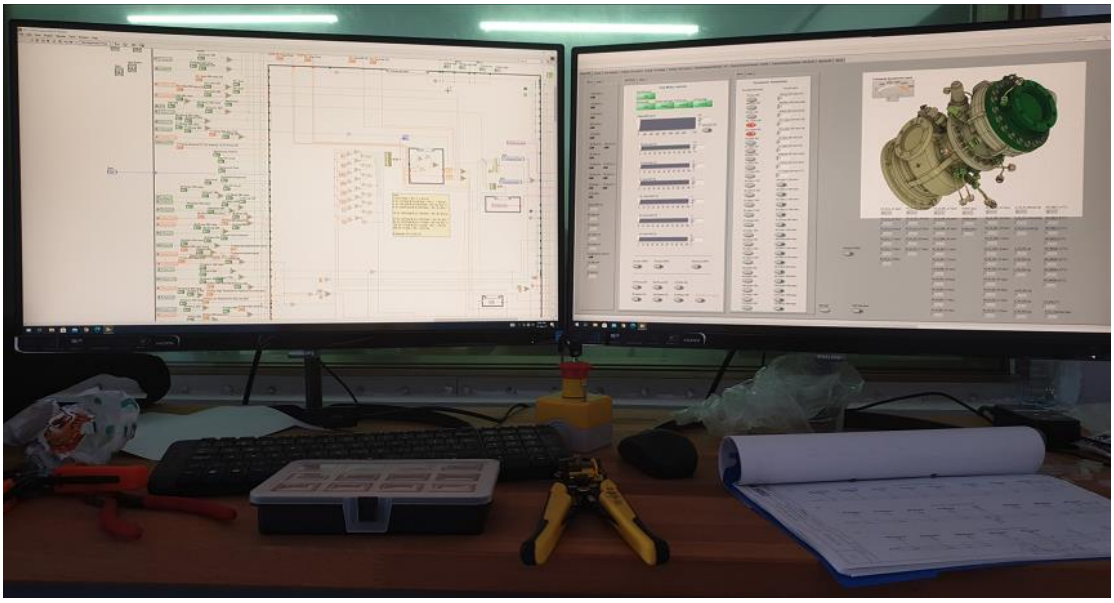


Fig. 15. Software interface displays for the molecular turbopump test stand control system, COMOTI Măgurele

4.3.2 Software Development

I developed the software according to the requirements and in order to monitor and record all data received from the stand. Also, through the approach described below I have further achieved considerable optimization in the use of algorithms and resources, so that the whole system works safely, efficiently and intuitively, taking into account the complexity of the instrumentation and routine operation requirements.

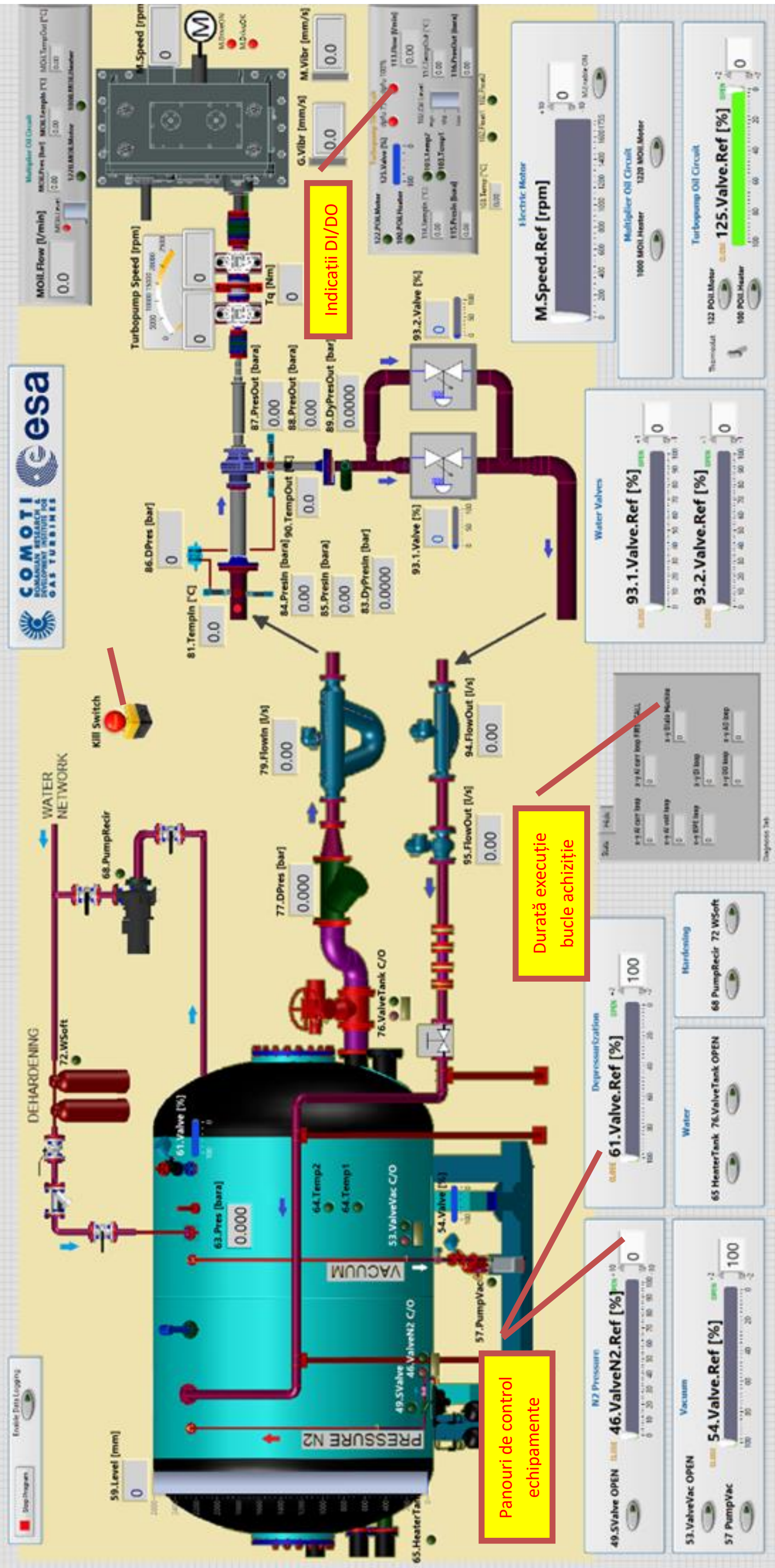


Fig. 16. Main software interface for the turbopump test stand

Fig. 16 illustrates the main interface of the control system, with a synoptic diagram of the stand, sensor indications and manual controls of the controlled actuators. The indications from the sensors, and from the other equipment transmitting signals to the control system, are laid out on the synoptic diagram according to the location of the respective equipment within the stand.

Manual controls are grouped at the bottom of the screen.

The programming of the analogue channels (current, voltage) in the LabVIEW development environment was carried out as shown in Fig. 17. The approach facilitates the initial as well as the later setting of the channels by entering directly from the interface: the scale ends for the electrical signal as well as for the physical size represented, the channel address and the shunt resistor value. Thus, I brought a major optimization of the subsequent channel setting process performed by the operators, without them needing to be familiar with the programming language.

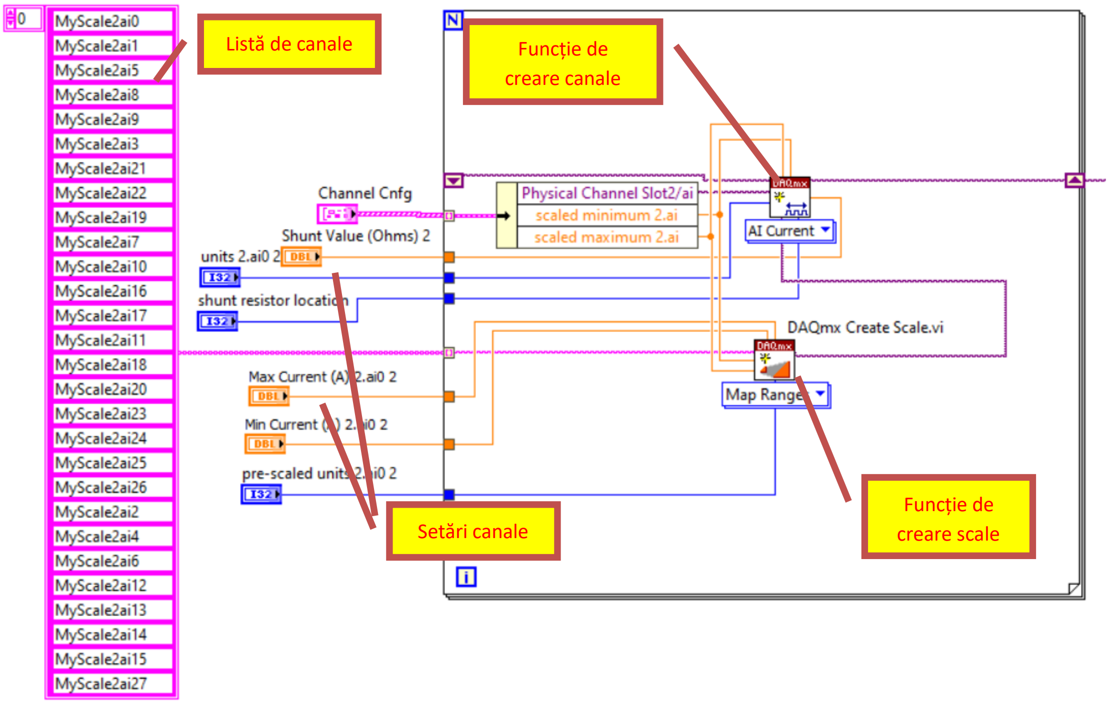


Fig. 17. Programming 4-20 mA current input channels

In processing and logging the data I took into account two important aspects. The first is the optimization of hardware and software resources, which is particularly important since some of the parameters are logged at fairly high frequencies (kHz) and reliability and operational control safety must be maintained for all control loops. The second issue relates to requirements for recording parameters at different frequencies in the same data file, in addition to which: the creation of the time stamp for each recording and its synchronization with the hardware timer recording loop, as well as display considerations, such as setting a different number of decimal places.

To achieve this, I implemented a complex data logging algorithm that allows data to be logged at different frequencies and in the same data file.

For logical decision making and for externally generated commands within the program, I used a state machine, optimizing the programming of control sequences compared to the method using only binary conditionals (*If...Else*). The state machine is an algorithm that contains: a number of defined states, a causal relation of transition from one state to another, input parameters, output parameters, and routines that differ by state and cause the value of output parameters to change according to input parameters and predefined algorithms within the routines. In essence, the state machine can be considered as a mathematical model that predictably describes an outcome as a function of inputs.

The states corresponding to automatic operation are as follows:

- ***Init*** – default system state;
- ***Test Mode*** – individual equipment test state;
- ***Pre*** (preparation);
- ***Work*** – the actual operation of the stand, which revolves around the control of the main electric motor and valves 93.1 and 93.2, in order to simulate the conditions necessary for testing the central object of study (the turbopump);
- ***Stop*** (normal stop);
- ***Emergency Stop***.

4.3.3 Automation Testing. HIL (Hardware-in-the-Loop) Method

Beyond the standard vital steps, I also studied and put into practice a new type of testing for the control system, the so-called Hardware-in-the-Loop testing or simulation. With this test, using as a reference principles studied in similar fields, I verified the functionality of the software sequences before the test stand (engine, gas circuits, equipment, sensors, etc.) was ready for operation. Afterwards, I performed final, physical testing.

During HIL testing, the physical system (e.g., engine, machine, controlled plant) interfacing with a control system is simulated on a hardware system, and the outputs of the simulator mimic real outputs of the physical system. In this way, the control system (or controller) considers the simulated system as a real system and a wide variety of possible scenarios can be carried out.

For the physical HIL platform, I provided a National Instruments data acquisition and control system (CompactRIO) for the physical acquisition and generation of analog and digital signals in a HIL loop, which contains the following:

- a controller for running the simulation model;
- a module with 8 analogue inputs of 0-20 mA current, which takes 4-20 mA analogue control signals from the PXI;
- 3 modules with 8 analogue 0-20 mA outputs, generating signals to the PXI based on the simulated parameters;
- two modules each with 16 digital 0-20 mA outputs, which transmit simulated signals instead of physical sensors to the PXI;
- digital input and output modules, which take digital 24 V relay control signals from the PXI, and transmit simulated signals (closing contacts) instead of physical equipment to the PXI;
- software developed in LabVIEW, shown below, which simulates the reaction of the physical parameters of the stand (pressures, flow rates, vibrations, equipment status) according to the commands received from the PXI controller;
- a visual interface;
- physical interconnections (cables) between PXI and CompactRIO.

As software, I used the LabVIEW platform to run the mathematical model (Fig. 18).

The testing was done by simulating the inputs, analyzing the outputs, evaluating the time response, evaluating the functionality and safety, applying different scenarios, as detailed later. Before implementing this solution, I studied the extent and the way of its implementation in similar applications. In this endeavor, I coordinated and published the paper *"Hardware in the Loop Test Platform Concept for Adaptive Turbine Engine Controller", **A. Stoicescu**, R. Ciobanu, A. Țăranu, C. Nechifor, F. Niculescu, TURBO Scientific Journal, Vol. VI, 2019*. In this paper I described the concept of an HIL system for testing an innovative (ECU-like) controller for turboshaft engines based on neural networks [122]. To the best of the authors' knowledge, this is the first time that such a HIL has been proposed for controllers of this type.

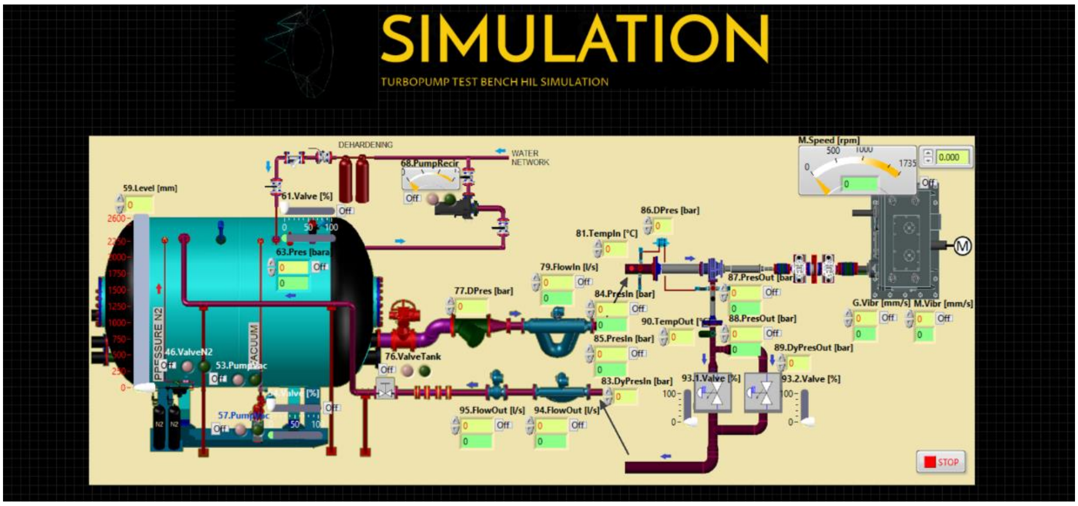


Fig. 18. HIL simulation interface for the turbopump test stand at COMOTI Măgurele

The interface of the stand simulation is in Fig. 18. The operating logic is based on the mathematical model of the stand. The transfer functions are determined or estimated with the help of the stand design team, based on computations and gas-dynamic simulations taking into account the fluids and geometry of the pipe sections and crossing elements. Certain functions could eventually be tested, improved and reintegrated into the simulation, such as the variation of pressures and flow rates with commands to pumps or valves, or the variation of vibrations as a function of speed, engine speed as a function of the speed reference.

The transfer functions used are based on mathematical calculations, logical conditioning, as well as time variations of other parameters; as input data I used: parameters measured by other sensors, valve positions, pump operating status, motor speeds, timing, etc.

With the help of the simulation, I was able to perform especially tests of control loops that I had implemented in various versions of the control software, such as pressure maintenance regulators 86 using the two regulating valves, 93.1 and 93.2. This regulating sequence also involved reaching and maintaining, consecutively, 27 pressure levels, with an estimated response time of maximum 2 seconds between levels, as well as exiting the regulation and switching to the stop sequence, if other predetermined conditions lead to this.

In this respect, I was able to simulate with HIL, pressure, temperature, vibration or flow values both within normal limits and especially outside the predetermined limits. Beyond this, I was able to simulate the effects of controlling equipment, such as valves, on pressures and flows in the plant. Using HIL, I was able to simulate the coarse and fine tuning of the working fluid, using valves 93.1 and 93.2, without using the actual installations on the stand. This allowed the project team to refine the principles of stand testing and the final software logic by which the stand operation should be governed, for both the current and future development phases.

The HIL method ultimately helped to raise the level of completion of the control system software for the turbopump test stand, by being able to test several aspects of operation prior to the physical preparation of the facilities, as well as high-risk scenarios for the facility without putting it at risk. In terms of implementation and testing times, it is estimated that these have been reduced by approximately two months compared to the original estimates, time that has been used for the implementation of other projects.

Chapter 5

Conclusions

Although the optimization of automation systems for aerospace thruster test stands is a complex subject and depends on many variables, some general conclusions can be drawn:

1. Full automation of test systems can significantly improve productivity and process accuracy, reducing the time and cost required to test aerospace thrusters.
2. The use of sensors and continuous monitoring systems can help detect problems quickly and prevent costly failures.
3. The integration of telemetry and wireless communications can improve data transfer and communication between different components of the test system.
4. Various technologies such as piezoelectric devices or fiber optic sensors can bring benefits for certain applications where conventional power supply or transmission require optimization.
5. The use of control algorithms and closed-loop tuning can improve control and accuracy of the test system, reducing human error and increasing efficiency.
6. The use of well-integrated and well-documented software can improve the management and storage of test data, allowing for easier and more accurate analysis of aerospace thruster performance.
7. It is important to conduct rigorous testing of automation systems in order to verify and validate their performance and identify potential problems.
8. Simulated testing and the use of mathematical models can be used to improve the testing process and reduce the costs associated with control logic testing. The use of accurate mathematical models can help reduce the number of physical tests required and ensure an improvement in the quality of the testing process.

In terms of building an automatic control system for the molecular turbopump test stand, this has proven to be a complex and important process that can be successfully achieved by following a set of well-defined steps. The process of building such an automatic control system must include the selection of appropriate sensors, the development of accurate and reliable control software, the integration of the control system with the test stand, and the testing and validation of the control system.

5.1 Results

In the first chapter, I provided an introduction to automation stands for aerospace thrusters. I explained the main difference between the thrusters addressed in this thesis, as well as the challenges the field brings.

In Chapter 2, I explained in detail the features, components and operation of automated stands for aerospace propulsion. I conducted a review of the concept of automation and the components of a stand automation, with examples and personal contributions in studying them. I also carried out a review of four types of test stands for aerospace propulsion elements, where I had various theoretical or practical contributions in their development (see chapter 5.2).

In Chapter 3, I chose one of these stands to explain in more detail the operation of the application and its requirements for the development of its automation. The molecular turbopump test stand for a rocket engine was chosen, within this thesis, due to its high complexity and my possibility to make significant contributions in its development and optimization.

In Chapter 4, I have presented the development of the automation of this stand, as well as aspects I investigated on various innovative instrumentation solutions: optical sensors, wireless sensors, piezoelectric devices. Finally, an automated molecular turbopump test stand with central controller, monitoring software, data logging and automatic control was achieved. In addition, I developed a procedure for testing the controller, using stand simulation software.

In Chapter 5, I presented the main conclusions resulting from the theoretical and practical study campaign, and personal contributions. The findings provided contributions to the field that can be used in other applications, which is also highlighted in the sub-chapter on perspectives for further development.

5.2 Original Contributions

In this PhD thesis, I have made a number of original contributions to the study and development of electrical systems for the automation of aerospace propulsion test stands. These contributions include:

1. Implementation of the software for acquiring, monitoring and logging the data taken from the afterburner installation at the test stand of a turbine engine (chapter 2.2.1). This software has contributed to several campaigns of turbine engine testing in the test stand.
2. Development of automatic control software for the air pumping stand for combustion chamber testing (chapter 2.2.2). With this control I achieved the control and optimization of the air supply at high pressures in safe conditions.
3. Implementation of the automation network and software for automatic monitoring and control of the test stand for an experimental space thruster operated by plasma ionization (chapter 2.2.3). Through this control I accomplished ignition optimization using cyclic sequences of gas and radio frequency power control.
4. Implementation of the control system for a molecular turbopump test stand for a European Space Agency rocket engine (chapter 4.3.2). With this control system more than 50 signal lines were monitored and about 20 pieces of equipment in the test stand were controlled. The control software sequences include a 6-state state machine and data logging at different frequencies.

5. Development of a molecular turbopump test stand simulator, consisting of a controller with interfaces and software, which connected to the stand controller allows hardware-in-the-loop tests to be performed in order to test and validate the performance of the stand control system (chapter 4.3.3). This achieved an important optimization in the development and testing of control scenarios without the need for physical stand availability.
6. A theoretical and practical study on vibration energy harvesting systems (piezoelectric) applied to turbine engine stands (chapter 4.2.3). I tested such systems using the vibrations obtained from the turbine engine stand.

5.3 List of Original Articles

[3] F. Niculescu, M.L. Vasile, **A. Stoicescu**, C. Nechifor, “Comparative Analysis between Gas Turbine and Electric Combined Propulsion”, EV 2019 (Electric Vehicles International Conference & Show), Bucharest, 3-4 Oct 2019 (conferinta); Added to IEEE Xplore: 11 Nov 2019; INSPEC Accession Number: 19136016;

[8] C. Nicolescu, B. Varaticeanu, **A. Stoicescu**, C. Nechifor, “Electronic Improvements Made for Industrial Valve”, Electrotehnica Electronica Automatica (EEA) Journal, Vol. 68 (2020), no. 3, pp. 05-12;

[12] C. Borzea, A. Savescu, I. Vladuca, **A. Stoicescu**, “Asynchronous Three-Phase Machine Driven as Generator by a Twin-Screw Expander”, SME’20 (Electric Machines, Materials and Drives Present and Trends / Actualităţi Şi Perspective În Domeniul Maşinilor Electrice), 2020, ISSN/ISSN-L 1843-5912, https://www.doi.org/10.36801/apme.2020.1.5 ;

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C. Nechifor, V. Năvrăpescu, S. Tomescu, C. Săvescu, M. Roman, R. Conțiu, **A. Stoicescu**, “Optimizing the Electronic Control of Suction Valves for Gas Compression Units”, Revue Roumaine des Sciences Techniques – Série Électrotechnique et Énergétique, Vol. 2, No. 2 (2023), pp. 182-187, ISSN 0035–4066.

C. Săvescu, D. Comeagă, **A. Stoicescu**, "Triangular Shape Optimization of Piezoelectric Harvester with Material Reduction Using Finite Element Analysis", Sensors (MDPI), Special Issue "Piezoelectric Energy Harvesting System", 2023 (în curs de reevaluare după primul review).

5.4 Prospects for Future Development

The field of automation for aerospace thruster test stands continues to evolve significantly as experimental models, prototypes or limited series of thrusters appear in more and more variants. Both turbine engines and space thrusters are constrained by the current environment and limitations to adopt new and improved technologies, and their testing to capture all scenarios that may be encountered in their operation. Thus, test stands can develop their capabilities in the following directions:

1. **Improving the control software.**
   Although it sounds generic, measures to improve test system control software vary from one system to another. By rigorously testing sequences of operation, by taking measures to optimize the resources employed, by using data logging in a way that serves not only to investigate the propellant, but also to identify problems and methods of optimizing the control logic, we can achieve better performance and accuracy of the tests performed, thus providing better control over the process. For example, for the further development of the Turbopump Test Stand with the planned nitrogen circuit, I am considering a solution to manage large volume records by generating separate files at time intervals, instead of one large file that is difficult to store and manage. I am also considering the use of PID regulators to achieve and maintain constant pressures or flow rates at the turbopump inlet, using valves.
2. **Increased automation.**
   An increase in the degree of automation implies more initial costs in I/O channels, programming time, infrastructure and hardware resources. However, a high degree of automation increases operational safety and allows for automated measures to be taken to prevent, rectify and diagnose operational problems. This optimizes the easy, long-term and reliable operation of the stand, increasing its performance in delivering fast and accurate test results. For example, manual valves remaining in the stand can also be replaced by electrically operated valves controlled from software. Also, to increase reliability in more sensitive stand operations, a redundant control system structure can be imagined, with a SIL 3 compliant CompactRIO PLC to manage any risk of control system failure.
3. **Using artificial intelligence and self-learning.**
   By implementing machine learning and artificial intelligence, we can improve our ability to anticipate and prevent problems before they occur, making the testing process more efficient and accurate.
4. **Hardware-in-the-Loop simulation-based testing.**
   Hardware-in-the-Loop simulation allows testing of the control system using a mathematical model of the machine, stand or sub-assemblies to try out various scenarios when the simulated equipment is not available or to test extreme scenarios. Applying this simulation to any type of stand can

bring significant optimizations in development time and testing costs. I plan to continue research to develop a hardware-in-the-loop simulator that can be easily adapted and transferred to multiple applications where mathematical models of the controlled systems exist or can be created.

5. **Increasing intuitiveness.**
   A control system however complex must be intuitive to program, use and operate. The more intuitive it is, the more optimized its use and troubleshooting is, leading to longer operating time and less downtime. Along with increasing the degree of automation, I have been constantly striving to make control systems more intuitive and robust.
6. **Harvesting energy from vibrations.**
   Methods to make excess energy useful can reduce energy costs and improve the competitiveness of users as economic entities. Harvesting energy from vibration not only contributes to minimizing plant losses, but also raises the technological bar, paving the way for cutting-edge technologies such as compact or autonomous control systems. The technology of converting mechanical energy from machine vibration into electrical energy is not yet very mature. It was shown in the paper that there are prospects for the development of control systems integrating piezoelectric sources. Their adoption in the field of thrusters implies advantages such as the optimization of automation systems through energy efficiency, which is one of the important objectives of these decades. This optimization results not only from the adoption of energy supply from unconventional, alternative sources, but also from the tendency to minimize, to compact (dimensionally and energetically) elements of the plant, such as instrumentation and electronic circuits.

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