UNIVERSITY „POLITEHNICA" of BUCHAREST
DOCTORAL SCHOOL OF MECHANICAL AND MECHATRONIC ENGINEERING

Decision no. …….. of ……

THESIS SUMMARY

CONTRIBUTIONS TO ANALYSIS, REALIZATION AND USE OF PULSE-CONTROLLED PROPORTIONAL PNEUMATIC DISTRIBUTORS

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BUCHAREST 2021

Presentation of the doctoral field

The digital world, related to IIoT and Industry 4.0, in which the production of objects is carried out by fully automated production lines, with equipment capable of "conversing" with each other, comprises a series of functional subassemblies within pneumatic systems (complex control systems in which the basic working environment is compressed air).

The field of pneumatics has experienced a rapid development in recent years due to undeniable advantages related to pneumatic components used in the construction of systems in this category:

• a functionally stable construction at a reasonable cost, lower than that of equivalent electronic systems;

• high static and dynamic performance, which gives them an advantage of use in robotic processing industries;

• the use of compressed air gives, in addition to the low price of applications, a preference for use in clean environments (industries such as food or pharmaceuticals);

• the symbiosis between pneumatics and electronics / informatics allowed the elaboration of new solutions for applications to which, until recently, only electronic solutions were dedicated.

Pneutronic systems use high-performance pneumatic components in operating speed, which makes them irreplaceable in many applications, an eloquent example being the automatic assembly lines with industrial robots. It should be emphasized that - at present - the execution elements, from the simplest on / off type to the most complex ones that involve multiple positioning, have - in the pneumatic version - dynamic performances superior to the electronic ones. Consequently, intense research has been carried out to increase the performance of pneumatic devices, the literature dealing in monographs or articles - punctual, smaller - constructive principles, innovative device solutions that minimize nonlinearities and mechanical hysteresis, new constructions of electro-pneumatic components. These aspects explain the extensive list of bibliographic references attached to this paper.

The field of the thesis is part of the effort to find new solutions suitable for the efficiency of pneumatic equipment, especially those that use actuators (execution elements) in which compressed air is the natural working environment.

The purpose of the thesis

The elaborated thesis has as general objective the analysis, construction and use of digital pneumatic distributors on / off controlled in PWM modulated pulses, both theoretically and experimentally, following the stages from conception to physical realization and use in applications.

The achievement of the general objective was done following a series of specific objectives, which involved:

- realization of digital distributors on / off controlled in simple PWM pulses (construction with mobile reinforcement with translation, with good static / dynamic performances for multiple applications);
- analysis of the distributors' performances made with specific assemblies imagined by the thesis author;
- performing experiments consistent with the general purpose (objective);
- application of equipment developed in pneumatic structures that prove to achieve high performances (chapters 5 and 6).

The thesis makes a number of contributions in the field of proportional pneumatics, which are briefly presented in this summary.

A rich bibliography (over 290 references) formed the basis of the documentation, especially the one referring to the summary part of chapters 1 and 2.

The thesis is structured on 8 chapters, the final one being to highlight the personal contributions and the new directions of further development, to which is added a list of three annexes and a bibliography adequate to achieve the general objective and the specific objectives.

Original contributions

The thesis brings a series of contributions in the field of proportional pneumatics, which are presented below, following the content according to the elaborated chapters.

The paper makes a gradual treatment by the integration mechanisms of pneumatic equipment in the process of globalization by the production of material goods, with the advent of the Internet and its use through the development by the concepts of IIoT and Industry 4.0.

Thus, after a review of the concepts of IIoT and Industry 4.0, the paper presents the effort of integrating the Internet into industries, by analyzing current IoT research, key generic technologies, major Internet applications in industries and identifies research trends and challenges. *A major contribution* (Chapter 1) of this paper is that it systematically summarizes current state-of-the-art IoT technology in industry, and how pneumatic developments can be included in IIoT. There are a number of arguments in support of this idea, which can be summarized as follows:

- ♦ the number of IoT devices increases from year to year, the growth rate being exponential, the reason being that it provides comfort in human life and achieves better results than humans;
- ♦ the step towards a fully connected digital world for the production environment, at which the number of required measuring points (sensors) and actively controlled devices (actuators) will increase significantly is Industry 4.0. As a result, intelligent objects can be created with the help of sensors and integrated systems with intensive software;
- ♦ a tree-type IoT architecture has at its root the various categories of sensors (transducers) and actuators, essential components in pneumatic systems, and IoT technologies use as coupling elements with the external environment the two major categories of products;
- ♦ numerous IoT applications are currently being developed and / or implemented in various industries, including environmental monitoring, healthcare, inventory and production management, food supply chain, transportation, workplace and home support, security and surveillance.

Another contribution concerns the analysis of future trends in IoT research, which highlights a number of challenges related to:

- ♦ network architecture, but especially the interconnection through different communication technologies;
- ♦ standardization within the IoT, which aims to reduce entry barriers for new service providers and users, improve the interoperability of different applications / systems and enable products or services to function better at a higher level;
- ♦ information security and privacy protection;
- ♦ integration of social networks with IoT solutions, development of IoT energy technologies, computing techniques based on artificial intelligence;
- ♦ combining IoT and Cloud Computing to develop new models or platforms that offer "perception as a service" on the cloud.

Mechatronic systems are - without a doubt - compatible with the new industrial revolution, as mechatronics involves a chain of applications in the field of mechanics with those of electronics and computer systems, so that the products obtained bear the endorsement of these large industries, being characterized by high quality, with state-of-the-art electronic structures, capable of performing operations with a high degree of difficulty, which allowed the migration to smart products. A mechatronic system can be considered with automatic regulation, in the sense that it reacts - in real time - to various external stimuli (situations), so it involves the existence of sensors / transducers to take external information, and actuators to apply commands.

At present, the pneumatics is placed among the top technologies, the research efforts being directed towards solving the shortcomings related to the viscosity and compressibility of the working environment. It should be noted that, in some applications, pneumatic structures are preferred exclusively to electrical, hydraulic, or mechanical ones.

By defining the notion of intelligent technical system, implemented by different techniques, algorithms or methods, able to emulate functions specific to human beings or other systems in different fields, whose operation is based on the 4 pillars of intelligent process management represented by expert systems, fuzzy crowds, neural networks and genetic algorithms, it was possible to associate real-world pneutronic systems with great complexity, assimilable to intelligent technical systems, which have configurations adapted to the application in which they are used. However, it should be noted that their structure is oriented according to a hierarchical design concept - from process to application server - which is an optimal combination between hardware and software applications. The objective function includes the task that the pneumatic system must perform. To achieve the goal, it must be correctly described and defined. Appropriate methods of communication with the system are usually used, the most common variant involving the use of an appropriate language to describe the objective to be achieved.

In Chapter 2, a careful assessment was made of the field of proportional pneumatic equipment, which led to the identification of the main trends and perspectives, namely:

- strong development of tires in the future;
- incorporation of informatics in pneumatic driving systems and equipment, which contributes to the development of pneumatic systems;
- increasing the reliability, functional accuracy and static and dynamic performance of real pneumatic devices;
- development and construction of new types of high performance pneumatic equipment.

Through the study of an extensive bibliography it was possible to show as irreversible trends the integration of sensors and transducers, as well as related electronics, in the construction of the latest equipment, miniaturization of constructions, increasing interest in environmental safety, switching to equipment recycling at the end of their life cycle, the construction of low-energy equipment.

In order to set the framework for research on proportional pneumatic distributors, their constructive-functional aspects were presented, starting from the simplest configuration of a 2/2 distributor (with two positions and 2 holes), in the most used constructive variant - the with cylindrical drawer with translational movement. Digital pneumatic on / off distributors are preferred in many applications compared to proportional analog equipment, because the latter are expensive and have - in general - a hysteresis of high values, the feature can have areas with different slopes, performance is given by precision with which are made of the constructive elements of the equipment, of the mechanical frictions, of the existing games, of the existence or non-existence of the automatic control of the position of the mobile armature of the actuator. By comparison, proportional equipment controlled in modulated pulses, in which a continuous adjustment of the instantaneous flow is not possible, but performs a

control of the average flow, have a number of advantages such as: high response speed, acceptable cost price (equipment is simple constructive and do not impose special conditions of execution and assembly), elimination of hysteresis and its undesirable effects, obtaining a very good repeatability. At the same time, a drive system in which such equipment is integrated can be controlled with a microprocessor / microcontroller, which greatly simplifies the structure of the control system.

The thesis makes an *important contribution* by presenting the pulse-modulated driving techniques for controlling digital on / off distributors, classified into two main categories:

- ♣ flow control methods using modulated control signals, which include the PFM ("Pulse Frequency Modulation") method and the PWM ("Pulse Width Modulation") method,
- ♣ flow control methods based on the coupling of several distributors, such as the PNM method ("Pulse Number Modulation") and the PCM method ("Pulse Code Modulation").

However, it should be noted that, regardless of the pulse control mode, driving techniques take into account the dynamic characteristics of the process, so a regulation law consistent with the process dynamics must be applied, doubled by ensuring static performance imposed by the physical reality of the application. The thesis combined the concepts developed by the theory of automatic systems (regulation theory) with electronic schemes for obtaining control signals, so as to ensure performance according to the objective function assumed.

The thesis makes *a significant contribution* by analyzing company products for high-performance pneumatic drive systems for flow and pressure control. From the scanning of the products identified by the company we found the use of analog regulation schemes in open loop and closed loop, respectively, the introduction of digital technology by using state-of-the-art DSPs or microcontrollers (essentially for digital regulation, but also for communication with dispatchers for complex automations); a widely used technique in the control of the electromechanical part is based on PWM, which involves the generation of rectangular pulses of frequency much higher than the maximum frequency of the electromechanical part, the pulse width being proportional to the control signal, the average pulse per fundamental period being proportional with order. Also, an analysis of the specialized works in the field shows the preoccupations of the specialists regarding the proportional pneumatic distributor channeled - mainly - on:

- ● analysis of the constructive elements that enter the configuration of the distributor and the ways to increase the performances by optimizing them;
- ● developing new (particular) solutions for products in this category, which meet the performance requirements, in particular by reducing equipment costs;
- ● the realization of innovative solutions regarding the automation strategies, which would allow the increase of the dynamic performances of the pneumatic structures in which proportional pneumatic distributors controlled in impulses are used;
- ● the use of structures based on pulse-controlled distributors to obtain high positioning accuracies.

A special contribution is made in Chapter 3 by the design of the proportional pneumatic distributor controlled in pulses with movable reinforcement with translational movement. The basic idea from which the distributor was conceived was that the closing of the magnetic field lines should be done by ferromagnetic material characterized by a relative magnetic permeability $\mu_r \gg \mu_{aer}$. If this principle is maintained, then the developed electromagnetic force will be large enough to attract the mobile armature to the fixed magnetic core, an operation that can be performed with a high frequency. The dimensions of

the dispenser were calculated so that its components were assembled into a normal syringe body.

Continuing the idea presented above, *an improved variant of the distributor* was designed, which has the possibility of easy modification of the flow section, fast coupling (without modifications) of several distributors, constructive simplification by adopting symmetrical landmarks. Also, the model designed with the Inverter program, allows a quality operation regarding the way of processing the flow through the distributor.

The chapter includes *an important section of dimensional design* of the previously developed categories of distributors, establishing - by mathematical formalization - the flow dimensions (diameter, stroke of the mobile valve) depending on the shape of the valve and the direction of fluid flow through the distributor. An important component is given to the sizing of the electromagnet by designing its components so that they fit spatially into the desired shapes.

Also, *a significant contribution* is made to the electronic block of acquisition and order, designed and developed by the author of the thesis, which deals with the design and construction of ways to generate order signals, as well as acquisition of analog and digital signals from the schemes developed. It is specified that the basic technique consists in using the LabVIEW development environment, in which the connection with the external environment is made through the NI USB 6001 module. Also, the final control stage of the distributors used in the experimental lifts is presented.

Chapter 4 analyzes - both theoretically and experimentally - the mathematical models of the proposed pneumatic systems, which use digital distributors controlled by pulses. The original contributions made in this section relate to:

- mathematical modeling of pneumatic systems; thus, starting from the flow continuity equation, we proceed to the pressure variation equation in a working volume, which is followed by the flow expression in a given section and the equation of motion by which the balance of forces acting on the moving elements in pneumatic equipment;
- modeling of the proportional pneumatic distributor controlled in impulses with movable reinforcement with translation, at which the related subsystems are analyzed in detail (electromagnetic and mechano-fluidic), establishing the analytical relations that describe their operation, and determining the nominal flow diameter and stroke furniture for the category of distributors designed in Chapter 3;
- simulation of the distributor when the electromagnetic relay is triggered / triggered; starting from the theoretical ideas expressed in the dynamics of the distributor in chapter 3, the response in time to the activation of the electromagnet coil is treated - using the technique of the direct and inverse Laplace transform. The detailed theoretical analysis was done to study the total trigger time, which is a critical part in establishing the maximum working frequency for the distributor. It is specified that the theoretical assumptions assumed in this paragraph have been verified experimentally by determinations made with the digital oscilloscope. Also, a simulation program was developed in LabVIEW for this component, which allows the rapid determination of the parameters used in mathematical formalization.
- for the triggering part it was theoretically demonstrated and experimentally confirmed that the closing time of the distributor valve is much reduced compared to the opening time due to the pulse extinguishing diode placed in parallel with the coil of the electromagnetic relay.
- in order to demonstrate the advantages of the “speed up” technique, a suitable assembly was carried out using a high-speed electronic switch controlled by a monostable, so that it was possible to apply a maintenance signal with an amplitude of

25% of the normal one, which led, both to the increase of the operating frequency and to the considerable decrease of the energy consumption.

● for the development of a distributor model regarding the instantaneous mass flow, the theoretical concepts in §.4.3.2.1 were exposed, which were verified by experimental surveys.

● for the verification of the maximum modulation ratio of the distributor operation, theoretically exposed in §.4.3.2.3, experiments were performed that present the instantaneous flow depending on the inlet pressure, with a variable restriction on outlet output, data presented in tables and graphs being in accordance with the theoretical behavior in stationary and dynamic regime.

● the instantaneous mass flow model, which is established by the mathematical reproduction of the modulation process of the distributor. The equivalent mass flow model and the maximum modulation ratio of the operation shall also be established.

● Numerical simulation of the distributor operation used two different environments, namely: AMESim environment (Advanced Modeling Environment for performing Simulations) and Matlab Simulink environment. From the analysis of the results obtained by simulation it can be concluded that the average flow can be controlled by means of the filling factor parameter as well as by means of the frequency of control pulses. The model developed in the Simulinik environment was made on the basis of the relationships set out in paragraph 4.2.2. The two simulation methods were the subject of a comparative analysis.

● the experimental analysis of the proposed models was performed, for the designed distributor performing experiments to highlight the behavior of the distributor in restricted frequency, the behavior of the distributor in frequency without restriction, the behavior of the distributor at variable filling factor, the behavior of the distributor at variable filling factor, pressure input 2 ... 4 bar, restriction of 1 bar in output.

● a comparative analysis of the theoretical and experimental results in direct connection with the equipment used, in terms of their static and dynamic performance.

In chapters 5 and 6 are analyzed - both theoretically and experimentally - two case studies to highlight the advantages of digital distributors on / off. The original contributions made in the first section relate to:

♣ with reference to Chapter 5, entitled Control of pneumatic actuators with pulse-controlled distributors, we start from an adequate theoretical support for the control of pneumatic motors, insisting on the accuracy of positioning the solutions presented in the technical literature.

♣ in the paragraph Mathematical modeling of the electro-pneumatic system a model of the electro-pneumatic system is studied which includes on / off distributors and a cylinder with double action without rod. Thus, it is presented: modeling of the on / off distributor, modeling of the cylinder with double action without rod, mediated model of continuous input using an adequate mathematical support. It highlights the connection between the pressure in the cylinder chambers and travel, but also the way in which digital on / off distributors can be used in positioning problems.

♣ in the paragraph entitled Designing the controller for the electro-pneumatic system, it is proposed to use PWM signals with modifiable phases to improve the regulation performance. In this sense, the seven switching modes of the four distributors used in the position control are analyzed, resulting in the effects presented on the positive direction called "advance", respectively the negative direction called "withdrawal". These modes, classified in Table 5.A.1 according to the logic commands of the distributors, have different effects and may influence the performance of the control under different pressure conditions.

♣ the phase change PWM strategy is proposed, in which the switching from x mode to y mode ($1 \leq x \leq 7$, $1 \leq y \leq 7$) in a PWM period is defined as M_{xy} mode, where x represents the main mode of control (as long as the pulse width is active = "1" logic) and the y mode represents the auxiliary control mode (as long as the pulse width is inactive = "0" logic). The phase-shifted PWM strategy is implemented with the slider (tracking) controller, in addition, two T_{PS} and T_{PD} pressure transducers are allocated to measure the pressure of both chambers.

♣ a special analysis is assigned to the parameter selection section, in which several suitable methods are presented to select the pressure difference parameter, the sliding function parameters α, β, χ and other critical parameters from the sliding mode controller. The choice of these parameters is made - mainly - based on the position error.

♣ the processing of data from the incremental position transducer was an important problem of positioning, as it involves taking over - without loss or addition of impulses - the movement made by the moving mass of the pneumatic motor. An innovative solution was used, based on the property of the NI USB 6001 pulse counting module, which led to an exceptional practical achievement, in the sense that the LabVIEW program aims to move from the incremental position transducer without loss / addition of pulses.

♣ with the general configuration of the electro-pneumatic system, having detailed the pneumatic component as well as the electronic one, we proceeded to perform the experiments, which involved several situations set out in detail in the thesis. All the results show the solidity of the proposed controller against the uncertainties in the model and the reliability of the PWM phase change strategy.

The second case study - presented in Chapter 6 - refers to regulating the pressure in a tank with variable losses using pulse-controlled distributors. The original contributions made in this section relate to:

■ use of the ball valve presented in Chapter 3. This equipment, integrated in the structure of the system, is a valve controlled in modulated pulses, small (D_n = 2 mm), with preferential position, type 2/2, electrically controlled, with an electromagnet that can operate at high operating frequencies, thus obtaining, at the consumer orifice, an air flow that corresponds to the average value of the effective flow that crosses the internal circuit of the equipment.

■ elaboration of the mathematical model for the constant volume enclosure, starting from the pressure variation in the constant volume enclosure V - depending on its supply flow. Thus, relationships are established that allow the analysis of the operation of the automatic pressure regulation system both in an analytical and in an experimental way.

■ distinct treatment of the three cases corresponding to the three operating situations (details on notations in the thesis, chapter 6). The relationships for the three cases were integrated in a program developed in the LabVIEW 2011 environment, and the results confirmed the theoretical assumptions.

■ in the paragraph intended for the experimental determination of the pressure variation in the constant volume enclosure, experiments with an assembly developed by the thesis author were presented, which demonstrated the validity of the theoretical analysis in paragraph 6.3, as well as other properties related to pulse control of digital distributors. The experiments aimed to highlight the behavior of the pulse-controlled distributor in regulating the pressure using digital controls with different frequencies and filling factor, as well as changing the thresholds P_p, P_r and the exhaust flow through the pneumatic throttle. It was observed that at the same value of losses,

highlighted on the electronic flow meter, the response of the pressure control system is better the higher the filling factor and the higher the frequency of the control pulses (this aspect was expected as it is in line with the theoretical analysis set out in Chapters 3 and 4.

■ in order to perform the pressure adjustment loop in the tank, the assembly from figure 6.4 was performed, at which, for a good performance of the experiment, the value purchased from the pressure transducer was multiplied by the constant factor 10, after which it was passed through the digital smoothing filter. The results of the experiments - with detailed comments - are presented in the thesis, these being in accordance with the theoretical assumptions presented in the first part of chapter 6.

Dissemination of results

Papers presented at international conferences:

1. M Avram, **A I Sgârciu** and C Bucşan - *Trends and perspectives in proportional pneumatics*, Published under licence by IOP Publishing Ltd, IOP Conference Series: Materials Science and Engineering, Volume 997, The 9th International Conference on Advanced Concepts in Mechanical Engineering - ACME 2020 4-5 June 2020, Iaşi, Romania, ISSN: 17578981, DOI: 10.1088/1757-899X/997/1/012034, indexare ISI, SCOPUS.

2. I A Sgârciu, A S Cernian, A M Anghel and V Sgârciu - *Maximum energy efficiency on photovoltaic solar panels by using an innovative solar tracker*, Published under licence by IOP Publishing Ltd, IOP Conference Series: Materials Science and Engineering, Volume 997, The 9th International Conference on Advanced Concepts in Mechanical Engineering - ACME 2020 4-5 June 2020, Iaşi, Romania, indexed ISI, SCOPUS.

3. Nedelcu A., Nedelcu B., **Sgarciu A.I.**, Sgarciu V. - *Mining Data for Human Resources*, 2019, Proceedings of the 11th International Conference on Electronics, Computers and Artificial Intelligence, ECAI 2019, DOI: 10.1109/ECAI46879.2019.9042148, **ISBN:** 978-1-7281-1624-2, **ISSN:** 2378-7147, WOS:000569985400156, indexed ISI, SCOPUS, IEEE.

4. Nedelcu, A., Nedelcu, B., **Sgarciu, A.I.**, Sgarciu, V. - Data Mining Techniques for Employee Evaluation, Proceedings of the 12th International Conference on Electronics, Computers and Artificial Intelligence, ECAI 2020, **ISBN:** 978-172816843-2, **DOI:** 10.1109/ECAI50035.2020.9223165, indexed ISI, SCOPUS, IEEE.

Patent of invention:

5. Inventor(s): Sgarciu I.A., Sgarciu V. - ANTI-THEFT PROTECTION DEVICE, **Patent Number(s):**RO131336-A2, **Derwent Primary Accession Number:** 2016-525372, International Patent Classification: B60R-025/02; B60R-025/04; B60R-025/06; B60R-025/10; E05B-013/10; E05B-065/10, Derwent Class Code(s): Q47 (Locks, window and door fittings (E05)); X22 (Automotive Electrics), Derwent Manual Code(s): Q47-A; Q47-U; X22-D01; X22-D03A; X22-F04; X22-X06X, RO131336-A2 , 30 Aug 2016.

Papers published in journals:

6. B.Nedelcu, A.Nedelcu and **A.I.Sgarciu** - *Cybersecurity - The Cloud and Government Intervention within Cyberspace*, International Journal of Progressive Sciences and Technologies (IJPSAT), ISSN: 2509-0119. © 2020 International Journals of Sciences and High Technologies, Vol. 23 No. 1 October 2020, pp. 468-472, http://ijpsat.ijsht-journals.org

Works in progress:

7. V.Sgârciu, A.S.Cernian, M.A.Anghel, C.Chițu, D.Floarea, A.Năstase, **A.I.Sgârciu** - *Process Control using Cloud Computing Architectures***,** in book *Big Data Platforms and*

Applications; Case Studies, Methods, Techniques, and Performance Evaluation, **Editors:** Pop**, Florin,** Neagu**, Gabriel (Eds.),** appearance September 2021.

Papers submitted for publication:
8. I.A.Sgârciu, A.A.Năstase, A.Nedelcu, B.Nedelcu, V.Sgârciu - *Theoretical and experimental analyzing on digital pneumatic valves*, CSCS-23, may 2021.

Perspectives for further development

The perspectives of further development in the field of proportional pneumatics, as well as my research activity, will follow the directions started in the thesis, whose common point is the digital on / off distributors ordered in impulses, by:

- Conception, design and realization of equipment with high performance / price ratio, having simple and safe configurations in operation;
- Integration of pneumatic systems in hybrid architectures;
- The process of harmonization with IIoT architectures;
- Application of developed solutions to complex pneumatic systems.

Regarding the research in this field, I consider that there are still opportunities related to new technologies, even operating principles, so I will have the opportunity to focus on finding specific ways to solve them. At the same time, based on the experience gained in doctoral training, I will try to imagine configurations of digital distributors on / off, with a minimum number of parts, which can be made with equipment from the laboratory of the department of Mechatronics and Precision Mechanics.

Regarding the integration of pneumatic systems in hybrid architectures, I believe that the realization of integrated solutions that use Arduino or Rasberry Pi type microcontrollers with pulse-controlled digital distributors will be frequently used in the future.

Another area in which future research will be channeled is related to the development of flexible solutions for various automations, related to the use of high frequency digital on / off distributors (ultrafast), by typing subassemblies, thus ensuring easy installation in parallel with a special miniaturization.

An important share of research - in the coming years - will focus on smart objects, as integrated IoT products, in complex cloud interconnected networks. Consequently, there will be problems of indexing them, as well as their efficient organization and management. Mechatronic products, in particular proportional pneumatic distributors, cannot be missing from this vast innovative technological process. New challenges will arise in data management in these complex networks, the synchronization of IoT transactions, their security and confidentiality.

Intense, innovative research will take place in the field of pneumatic products and systems. I believe that many of the current solutions, which use well-established electronic structures, will be taken over by hybrid configurations (pneumo-electronic), in which compressed air will be the working environment, especially where microbiological requirements require clean and energy-efficient working environments. reduced.

I believe that the efforts made to complete this thesis will open new opportunities for the field studied, which will include research related to mine, potentially applicable in the field of material production.