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DESENVOLVIMENTO DE UM SISTEMA DE CONTROLO ATIVO DE FORÇA PARA A INDÚSTRIA – SIMULAÇÃO, SOFTWARE DE OPERAÇÃO REMOTA E TESTE

Dissertação no âmbito do Mestrado Integrado em Engenharia Mecânica, especialidade de Produção e Projeto, orientada pelo Professor Doutor Joaquim Norberto Cardoso Pires da Silva e apresentada ao Departamento de Engenharia Mecânica, da Faculdade de Ciências e Tecnologias da Universidade de Coimbra

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Development of an active force control system to the industry – Simulation, remote control software and testing

Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Mechanical Engineering in the speciality of Production and Project

Desenvolvimento de um sistema de controlo ativo de força para a indústria - Simulação, software de operação remota e teste

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“Art without engineering is dreaming. Engineering without art is calculating.”

Steven K. Roberts

To my late grandfather

Fernando Madeira

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Abstract

Polishing as an industrial process is increasingly getting out of date. The existence of few specialized operators, the dependence on their ability, and the various efficiency limitations are some of its problems.

These are more accentuated by the constant technological and scientific developments, such as the concept of *Industry 4.0*, which is gaining ground in a future where companies will look for solutions in the area of automation and robotics, whether they are new technologies or adaptations of old technologies. In this follow-up of ideas, a group of MIEM students proposed to develop an active force control system from the ground up, consisting of a pneumatic device coupled to a robot and capable of applying a constant force across a surface.

This thesis aims to deepen the issues related to the application of this system. A robotic cell was developed in *RobotStudio* to simulate as accurately as possible the real-life conditions and to show the true potential of the system, by digitally replicating the projected tests, and with the possibility of sending this information directly to the robot controller.

It was also created a GUI with a direct connection to the simulation software and to the force control component, the *Arduino*, via TCP/IP to allow the remote control of the entire operation both in a virtual or real environment.

The development of this dissertation was also based on a theoretical contextualization of the industry where this tool could be useful and on a complete study of the works and investigations which once tried to create a solution like this one.

The robot was capable of coursing through the path using the active force control components in the simulation, the communication protocols and the software proved to be adequate, and the entire system was feasible from an experimental point of view, with enormous potential for success. Everything was suitably ready to work according to the intended objectives.

Keywords Polishing, Automation, *RobotStudio*, *Industry 4.0*, Robotics, Simulation

Resumo

O polimento enquanto processo industrial está cada vez mais desatualizado. A existência de poucos operadores especializados, a grande dependência pela aptidão dos mesmos e as várias limitações do ponto de vista da eficiência são alguns dos seus problemas.

Estes são ainda mais acentuados pelas constantes evoluções tecnológicas e científicas, como o conceito da Indústria 4.0 que vai ganhando cada vez mais peso num futuro onde as empresas irão procurar mais soluções na área da automação e robótica, sejam elas novas tecnologias ou adaptações de tecnologias antigas. Neste seguimento de ideias, um grupo de alunos do MIEM propôs-se a desenvolver de raiz um sistema de controlo ativo de força, constituído por um dispositivo pneumático acoplado num robot e capaz de exercer uma força constante ao longo de uma superfície.

Esta tese tem como objetivo aprofundar as questões relacionadas com a aplicação desse sistema. Foi desenvolvida uma célula robótica em *RobotStudio* que permitisse simular com a maior exatidão as condições reais e replicar digitalmente os testes projetados, com a possibilidade de enviar essa informação diretamente para o controlador do robot. Foi também criado um GUI com conexão direta ao *RobotStudio* e à componente de controlo da força, o *Arduino,* com ligação Wi-Fi de modo a que o controlo remoto de toda a operação fosse possível tanto em ambiente virtual ou ambiente real.

O desenvolvimento desta dissertação foi assente numa contextualização teórica das necessidades da indústria onde esta ferramenta poderia vir a ser útil, e também num estudo completo dos trabalhos e investigações que outrora tentaram construir uma solução semelhante a esta.

O robot foi capaz de seguir a trajetória corretamente com o dispositivo na simulação, os protocolos de comunicação e o software utilizados revelaram-se adequados e todo o sistema demonstrou-se exequível do ponto de vista experimental. Estavam reunidas todas as condições para o sistema funcionar com enorme potencial para vir a ser bem-sucedido.

Palavras-chave: Polimento, Automação, *RobotStudio*, Indústria 4.0, Robótica, Simulação

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LIST OF ACRONYMS / ABREVIATIONS

Acronyms/Abbreviations

CAD – Computer Aided Design

CFM – Constant Force Mechanism

CL – Cutter Location

DH – Denavit Hartenberg

DoF – Degrees of Freedom

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

GUI – Graphical User Interface

I/O – Input/Output

IDE – Integrated Development Environment

IoT – Internet of Things

MIEM – Mestrado Integrado em Engenharia Mecânica

PID – Proportional Integral Derivative

SMC – Sliding Mode Control

TCP/IP – Transmission Control Protocol/Internet Protocol

1. INTRODUCTION

The industrial environment has been changing for the last 3 centuries to keep up with technological and scientific progression. These evolutions carried intrinsic social, political, and economic changes, culminating in new perspectives, ways to see life, and to live. But before looking forward, it is important to contextualize the important industrial marks of our past.

If we scrutinize our history, it is easy to identify the 1st Industrial Revolution: it occurred in the 18th century with the introduction of steam power and the concept of factory. The economy started to shift from agriculture to mechanization, speeding up urbanization.

By the 19th century, the development of iron and metal productions alongside an early appearance of electricity brought the 2nd Industrial Revolution and a major technologic advancement. It allowed the concept of “line of production” and “mass production” to emerge.

Then, the 3rd Industrial Revolution took place closer to our reality, in the 60´s/70´s, through the arising of computers, industrial automation, sensors, actuators, several hardware and software evolutions. It helped greatly the exchange of information, allowed higher indexes of process efficiency and increased automation.

(D’Souza et al., 2020) As referred before, these three revolutions followed as a result of the scientific/technologic progression and were only acknowledge as such years later. On the other hand, the 4th and current Industrial Revolution has already been announced in 2015 as an answer to a need in technological boost, to connect and digitalize all industrial, manufacture, and logistics processes. It was an announced digital ecosystem strategy to fight the low values of productivity and growth felt all around the world in the last decades.

Stated by (Vaidya et al., 2018), a new level of organization and control was proposed to the complete life cycle of a product. According to the German Federal Government, the pretension was to create fully integrated, automated, and optimized production cells.

Another difference to other industrial revolutions is the usage of existing technologies. However, the twist here was the need for an investment to enable their usability by mainstream industries.

Thus, the *Industry 4.0* is only as viable as the evolution and reinforcement of its base technologies, like additive manufacturing, advanced robotics, virtual/augmented reality, cloud and cybersecurity, simulation mechanisms, data analytics, etc.

It is suitable to include an automated decision-making component to complete this insight because artificial intelligence is crucial to predict and solve problems, leading to an increasingly higher production flow and efficiency.

(Pires, 2020) Intelligent factories are also a proposed hyper-flexible model, through programming, automation, industrial computation, and embedded systems with shorter work time cycles, better optimization mechanisms, much greater efficiency, connectivity, and fewer general costs.

The idea of smart factories gains ground in this current reality to smooth and speed up production by covering the usage of digital sources, allowing a decision-making element, and connecting different environments.

Therefore, there'll be a change in the old centralized supply-chain, replaced by a digital information distributing model through various sources. The system can have the power and knowledge to autonomously know what order to give for the machines to execute.

Introducing cyber-physical systems could also help to mature this concept, explained in Figure 1.1. These systems enabled a greater efficiency, decision-making/problem-solving capacity by communication mechanisms as IoT (Pires, 2020).

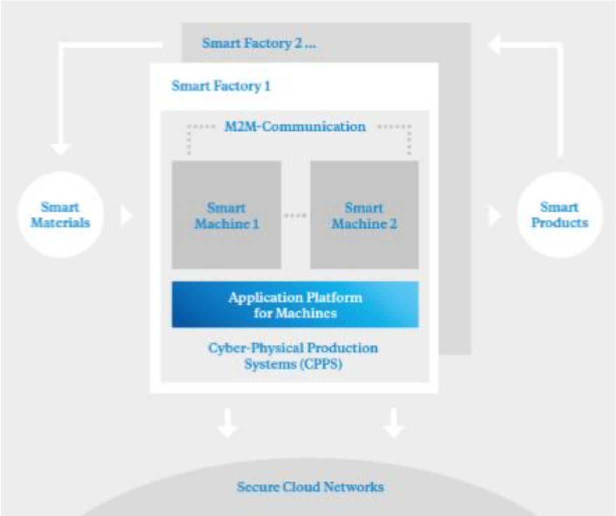
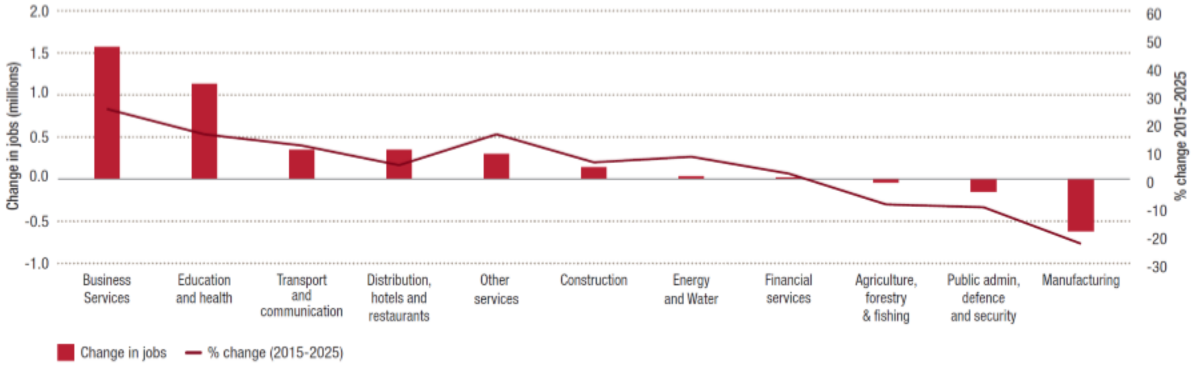


Figure 1.1. Schematic representation of Cyber-Physical systems (Pires, 2020).

However, from another point of view, the working relationship between humans and robots could bring paradigm changes in such a way it could cause fear within the worker's community, either for personal safety or anxiety of being replaced.

Still, (Vaidya et al., 2018) refers that the suggestion of the whole revolution is not to replace all humans with robots. Instead, it is ambitioned to include humans in the robot's control, creating an intelligent and open platform where all data is exchanged and monitored in real-time. It emphasizes the intention to modulate the working reality and not to replace it.

(Pires, 2020) stated that about 35% of current jobs would be replaced by robots, and business services 56% will have the biggest change percentage, as showed in Figure 1.2.



Source: PwC projections based on historical ONS data

Figure 1.2. Changes in jobs in the UK industry sector between 2015 and 2025 (Pires, 2020).

(Dautovic, 2019) Another interesting study carried out by the World Economic Forum also suggests that 71% of the current task-hours are completed by humans but in four years that percentage will drop to 58%, so there's a 13% increase in machine task-hours. On the other hand, 70% of workers believe that automation will offer them an opportunity to qualify for more highly skilled work.

So, although it is vital to reflect carefully on how to manage this process, there is a clear opportunity capable of impacting our working ways. The evolution is expected to be conducted across the world of robotics and automation, with a constant pursuit for maximum efficiency and connected productivity.

1.1. Motivation

This new reality introduced a change in the industrial paradigm and created a demand to automatize more processes, and if in normal circumstances this need was evident, now it is almost mandatory since the whole world is forcibly changing.

The covid 19 pandemic claimed a startling number of victims and will forever be remembered as the genesis of one of the most devastating financial crises ever. It is a period of uncertainty and volatility, when many companies have stopped their activities indefinitely and, as a result, several economic, financial and social problems have arisen. It enforced people and companies to completely reformulate their working scheme if they wanted to remain relevant in their activities, and it emphasizes the existing flaws of several systems.

This way, there is an enhancement and validation of the advantages of a new connected industrialization. The constrains in social distancing and changes on working habits forced industries to find innovative new solutions to stay afloat. It is a new and different life, where a lot of workers are forced to do their tasks from home. Telecommuting is obligatorily more popular.

On the other hand, it is the perfect opportunity to implement new intelligent cells whose nature allows humans to control operations at the distance and reducing substantially the number of workers around each other.

(Shepherd, 2020) Recent studies prove the feasibility of this new environment by presenting the potential annual savings from employers offering telecommuting flexibility. For example, in 2015 the savings ascended to 44 billion US dollars. Studies also report 2/3 of managers found that employees who work from home are more productive, data also corroborated by 86% of the employees themselves.

Also, in the new *Industry 4.0* reality, there is a need for quick and constant information exchange. Most manufacturing companies whose connectivity resources hasn't evolved enough are limited to success, mainly now that competitivity is higher than ever.

Another barrier to some companies' development is the ancient nature of most industrial processes, making them time-consuming and not efficient. There are still many manual labour jobs whose evolution of the working techniques through technological advancements are not enough to reach the point of perfect harmony with the new concept of a fully optimized work cell. Therefore, improvements in the productivity and efficiency departments are increasingly more important.

This thesis is based on the application side of a big project: the development of a cost-effective cell, with an integrated pneumatic end-effector capable of actively controlling the contact force. This way, those goals could be achieved while preserving the workers' health and replacing tedious jobs, as a cost-effective solution even for companies with a lesser stable financial situation.

But then rises another important question: is there an industry where a device like this is needed?

An early research showed the diversity of tasks where a constant force application was crucial, from the automotive to the aeronautic industries. For example, car assembly lines have processes like fitting-in panels, collage procedures, and detection of irregularities (dents, finishing defects, force tests, etc.), which are mainly done by humans and could be automatized in some way.

Yet, there is a bigger opportunity to embrace several different branches of the market: the surface finish industry. After the manufacturing process, the great majority of parts requires a final treatment to improve the surface finish (for looks, to adjust the tolerances, etc).

This process has a massive market and is full of potential revenue, from small parts to the blades of wind turbines, where the airflow is critical. So the goal is to develop this device and prepare the early stages of its implementation into the vast world of robotic and automated polishing systems, where there are loads of chances to improve and innovate.

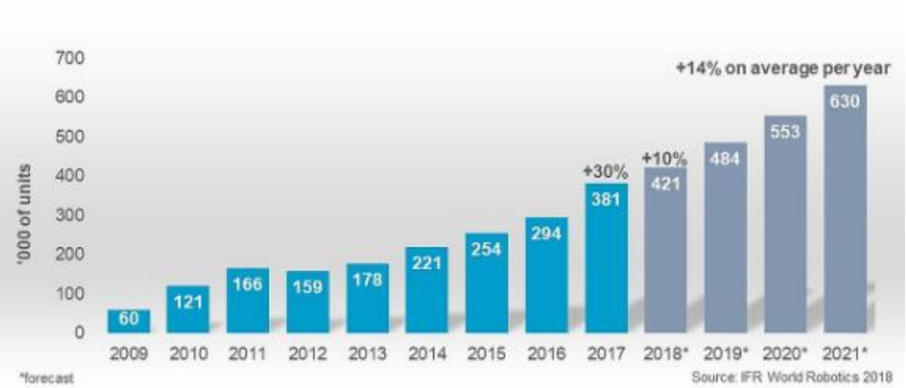


Figure 1.3. Estimated annual worldwide supply of industrial robots (Milenkovic, 2020).

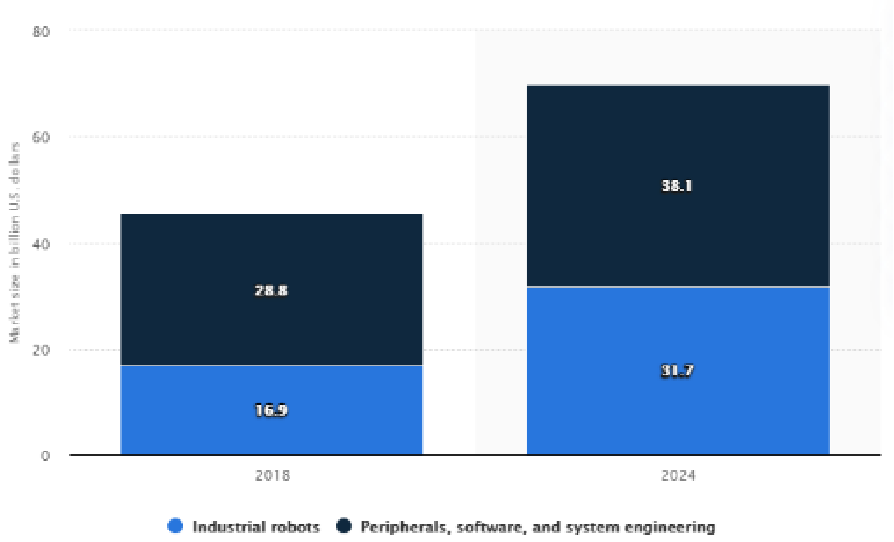


Figure 1.4. Industrial robots' market size (Wagner, 2020).

(Milenkovic, 2020) said that it was expected to see over 2 million new industrial robots entering service between 2018 and 2021, with a 14% annual growth (Figure 1.3). Plus, (Wagner, 2020) added that the industrial robot's market is hugely substantial, as we can see in Figure 1.4.

Throughout my literature review (in-depth on the next chapter), many projects had different approaches on how to solve the main problems of the surface finish industry. However, the awareness of those problems is common to all of them, and the obstacles are well known.

(Xudong Zhang et al., 2017) state that the industries' standards are getting higher and higher, so it is imperative to solve all the manual labour issues in the surface finish industry, from the need of highly qualified operators (and even then, the risks of human error/fatigue is high), to its low efficiency and consistency.

Another problem raised by (Kalt et al., 2016) is that some manual techniques are very difficult to automate on complex parts or with high precision requirements, ensuing in not using robots to execute these tasks.

There is also unanimity on the advantages. (Miao & Fang, 2017) state that the benefits of the robot's usage are flexibility, low price operation, and a bigger workplace. More benefits referred by (Márquez et al., 2005) are the minimization of time, cost and maximization of efficiency.

To sum it up, the keywords for whatever industries are: Better, Quicker, Efficient, Cheaper. It is agreed that the need lies in the lack of repeatability, the immense amount of time it takes for an operator to do all the work from start to finish (including the training time), the high probability of physical failure during that period, and also the health issues this job can bring (caused by dust particles and vibrations).

The main goal is to innovate at the heart of the polishing sector, within the *Industry 4.0* main goals. Building the basis for a highly sensitive system, supervised and controlled by humans is an opportunity to bring something new that will not only be functional but also financially accessible to many companies.

This brings us to another key question: cost. The known solutions available in the market are force sensors integrated into the robotic arm's movement control. They act as a force controller to the movement against the workpiece and provide constant communication with the robot, so it is possible to exchange data and maintain a constant force.

Figure 1.5. Examples of force sensors. Source: https://www.te.com/usa-en/products/sensors/force-sensors/force-sensor-elements.html?tab=pgp-story

However, the problem is the limitation in the operation's precision and it requires a more complex geometrical model for the robot to follow. To make things worse, to achieve the level of precision and forces that we want, they would very expensive and so wouldn't be a viable solution for all companies.

1.2. Objetives

This thesis promised to develop the application matters of the active control force system, more specifically the complete simulation and respective test, able of representing the capability of maintaining a constant force requested throughout a surface, with a remote-control component.

To justify its application into the industry, this solution could help to make a way to decrease the manufacturing costs and to increase productivity and efficiency, making it a viable and sustainable solution as an automated system.

To achieve those propositions, the whole system should be capable of executing several tasks, so this sub-chapter will review those objectives hoping to see them accomplished later on.

Firstly, it was planned for the operator to be able to start and cancel the operation both in the virtual and real environments, to select the required force, to activate different modes of the system (for example, to bring the robot and the device to the home position or a zero voltage state) and analyse feedback data in real-time, all this remotely via Wi-Fi.

For those movements, the robot needed to locate itself and move accordingly to the required positions, like the working space to detect the workpiece and execute its task, or the home position. It required the calculation of tolerances and automatic calibration between the virtual simulation and the real-world workspace to harmonize the whole system.

It was considered crucial for the system to interpret the operator’s input, to transform that numeric force into a voltage signal, then into the correspondent pressure, and finally into the movement and the intended force through the wanted path.

As it was important to maintain a constant force application even through irregularities in the workpiece, the system needed to be designed to automatically readjust the pressure inside the pneumatic system.

After the robotic arm succeeds in following the most appropriate path with a constant force application, and depending on the operator’s intention, it must return home and finalize the task.

For demonstration purposes, it was important for the robot and the end-effector to be able to counteract external stresses while keeping the contact force constant, and to send the output data to prove it at every given moment.

The simulations should be as resembling as possible to the real world, and the projected experimental test should be able of demonstrating the capabilities of the system.

1.3. Initial Thoughts

To achieve the objectives referred in the last sub-chapter, it was important to create a well-established plan with the means needed to accomplish them, making sure there were anchor points along the way to check and to anticipate issues likely to appear. Therefore, it would be possible to adjust parameters and review data individually if required.

Choosing the components for the device was important based on the application needs and the electrical circuit designed for this purpose. After the skeleton pieces were projected in CAD and 3D printed, the assembly should start to ensure all clearances and fitments were perfect. The pneumatic lines and air pressure supply should be taken into consideration throughout this stage.

The robot needed to know what to do, how to do it, and when to do it. It would be necessary to create a working protocol for all routines of the robot and end-effector movements and their respective corrective actions when required.

It was pre-assumed that all robotic tasks would be simulated via *RobotStudio* software to study and manipulate various aspects of the tests before putting them into real-life. Afterwards, this data could be introduced directly into the robot controller, which at that point would already be connected by communication protocols to the *Arduino*, the components, and the user himself. That would mean the system was ready to work in real life.

To enable the constant connections and data transfer between the end-effector's components, and between the whole end-effector and the robot, it would only be possible by the creation of a graphical user interface, capable of compiling all the commands and bridging both software.

Also, it would act as a link between the operator and the robotic cell, allowing him to select various poses for the system, start or cancel the operation, manipulate several parameters and analyse output data from the system's feedback, with a remote-control component embracing the *Industry 4.0* goals.

The force corrections through the end-effector should be in line with the robot's arm movement, that is, the workpiece shape can induct an action in the end-effector to maintain the force constant, but it may not be enough. An idea to mitigate this problem would be the use of the workpiece in a CAD format to be directly inserted in the trajectories programming procedure, while creating a virtual environment as well, created by CAD models of the real-world workspace.

This way, it would be easier to reconcile all movements and achieve the desired finish with the best possible efficiency, both in the virtual simulation and later in the real world.

Following this reasoning, there should be a need to develop a path protocol using the CAD workpiece as a basis through the *RobotStudio* software

As a brief note, and to make sure the reader understands perfectly the dynamic of this project, it was developed by three engineering students, all with different tasks and inspiring each other's thesis, but with the same purpose of developing this device from the ground up. So, it is recommended to read both of these thesis of (Carvalho, 2020) and (Fernandes, 2020).

1.4. Chapter Organization

To enable a clear understanding of this thesis, its structure was divided into 6 chapters:

- 1st Chapter: Primary approach to the whole project, including the motivation, objectives, and initial thoughts;
- 2nd Chapter: Study of relevant topics and in-depth investigation of the previous work developed by other authors, incorporated with the purpose of the thesis;
- 3rd Chapter: Demonstration of the hardware used in this work;
- 4th Chapter: Presentation of the software used in this work;
- 5th Chapter: Development of the experimental work and obtainment of results to support it;
- 6th Chapter: Conclusions and proposition of future work to be developed.

2. STATE OF THE ART

This chapter serves as a theoretical and comprehensive basis for the investigation, a brief overview of what's already been made about this topic. It is also a support in the search to where is the so intended opportunity for innovation and how it can be achieved. On top, it is a great aid to understand the background of the technologies under study and serves as an inspiration to guide us.

It was divided into the robot itself, some complete polishing systems, where it is included the force/path control and polishing process analysis, and finally force controllers in general applied to other industries.

Primarily the work focused on the basic preparation and early steps of the usage of an industrial robot in cooperation with a unique device as an end-effector to provide a constant force application across the entire surface of a given part. This thesis was more directed on the application area, and choosing the right usage for this product was not easy because there are hundreds of utilities for it.

Nevertheless, and considering our engineering background, the most appropriate practical application is the polishing world, where its problems are unanimous and this device would bring an added value as this state of art reflects.

However, the pretention was not to build a complete polishing system. Instead, the main objective was to prove it was possible to create such system, and to provide the needed tools as the basis to implement a polishing feature onto the system or for other researchers to continue developing further areas of our specific work.

Subsequently, it was vital to concentrate on the key points of this thesis.

2.1. Robot

According to (Simon, 2020), it isn't easy to clarify a robot's definition. It can be defined as a programmable machine whose purpose is to satisfy or replace a human action, by analysing, thinking and executing tasks autonomously.

But not just any machine. They are ingenious precision devices moved by its creator's ambition and controlled by programmed and disciplined tasks.

(Minner, 2019) notes the huge variety of circumstances where they can be used, from aerospace and panic response, to the final consumer for entertainment.

In this case, it is important to study the industrial robots for production or assistance to human tasks, and as they share the working space with humans, they're named collaborative. Their main features are a monitored and safe stop, manual guidance during the operation, an easy built-in programming process, and constant scanning of speed, force, and torque.

There are five main ramifications of this concept: cartesian, polar, scara, delta, cylinder, and articulated. This last one is the most interesting type of robot for the given application.

They're shaped with several rigid elements and each pair is connected by rotative joints. Generally, their six degrees of freedom give them high rates of moving flexibility, dexterity, and reach. However, they are not cheap or light, so they aren't the most suitable solution to high-speed operations.

The project used an articulated industrial robot from *ABB*, a well-renowned company with years of experience. (ABB, n.d.) they have been developing and improving robotics technology by targeting and building fast, efficient, precise, and flawless machines.

The model used was the *ABB IRB 140 M2004 TypeA* and it will be studied in the Chapter **Erro! A origem da referência não foi encontrada.**

2.2. Automated Polishing System

This dissertation focuses on the study of a purpose for this system where maintaining a constant contact force between a pneumatic device and a workpiece is essential, not forgetting the cost restrictions defined the project's accessibility.

Although many articles delved deeper into this subject, the great majority of them used such kind of force control linked to a polishing/deburring system of some sort. And as already have been discussed, the polishing industry is an environment where the contact force is vital. Over the years, there've been multiple efforts to automatize polishing processes, and this section reviews those attempts.

For example, (Almeida et al., 2018) linked the usage of an automated robotic polishing solution as an enhancement for reproducibility and precision in the manufacturing industry, while bettering tolerances and production times.

To (Tian et al., 2016), this was particularly relevant now that the manufacturing industry has higher quality requirements and more complex parts in the production of moulds, for example.

However, according to (Kalt et al., 2016) and a few years later to (Mohsin et al., 2019), the main complications sited on the limited flexibility and inspection difficulties.

(NAGATA et al., 2008) mentioned again there wasn't enough flexibility for the force controllers to be implemented and the systems could not undertake a smooth position control because they weren't developed enough to achieve good results on complex surfaces.

Yet, despite all these adversities, they weren't as disadvantageous as the limitations of the manual polishing process itself.

As have been said before, (Mohsin et al., 2019) described polishing as a very error-prone, time-consuming, and expensive manual task. (NAGATA et al., 2008) related that polishing depended mostly on the operator's skill (dexterous in force and trajectory control). Plus, (Mohsin et al., 2019) added there was a real health issue caused by vibrations and by small particles released in the polishing process.

Following this logic, a work was guided by (Kalt et al., 2016) with the proposition of building an automated polishing system following a teaching approach. They collected data (force, torque, vibrations, polishing patterns, etc) and studied the polishing parameters through the operator's vision and touch.

The polishing path and force control were aided by the 3D CAD of the workpiece.

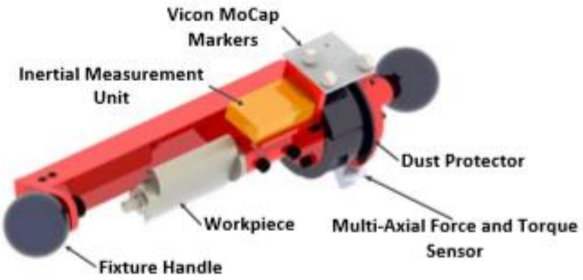


Figure 2.1. Design of the device to capture data as polishing parameters (Kalt et al., 2016).

However, they were only able to conduct this experiment on simple geometry parts, so they concluded it didn't exchange data fast enough. Also, it was hard for the robot to maintain a perpendicular pose regarding the workpiece. There was potential, but the attention should be more focused on including a bigger variety of shapes and improve the communication between devices.

A year later (Kharidege et al., 2017) considered there were enough technological innovations in robotics and automation to make possible the built of an automated polishing cell capable of syntonising a six-DoF robot, a polishing tool, the workspace, and the path planning kinetics model.

As seen before, normally this kind of systems used a learning system, but besides being more user-friendly and easier to program, they were considered very time consuming and error prone.

A differentiating factor was their application of simulations to potentiate the appraisal and prediction of all kinds of situations, problems, and obstacles in real life.

Therefore, they followed a software simulation approach for the path planning, based on CAD data. However, it become crucial to optimize the tolerances by calibrating the cell, decreasing the differences between virtual models and the workpiece. This information was important to this dissertation as it aims at a virtual simulation to control the robotic cell and the tests.

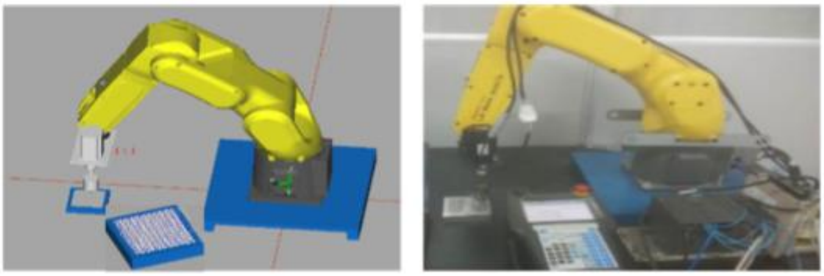


Figure 2.2. Simulation vs Experimental procedure (Kharidege et al., 2017).

Their conclusions awoke the extreme importance of the kinetics model accuracy to maximize the robot's performance. All these interpretations resulted in an improved system, where the reliability, cost, precision, and safety were directly benefited.

However, the main challenge was to implement this system in complex parts, and because of that, they concluded as well there was a need for another feedback input like a force feedback.

Another interesting approach was (F. Chen et al., 2019) study of vibrations in polishing systems, relating them with variations on the workpiece's superficial quality.

It was mainly designed for plane engine turbines manufacturing, which had very low tolerances and depended immensely on the superficial quality. But the vibrations on the system could affect drastically these parameters.

Other works already tried to compensate these harmful vibrations through mathematical approaches or by simply optimizing the robot's posture to avoid such a phenomenon. Yet, these solutions were cell-dependent and time consuming, and it was more effective to add a specific device to minimize the vibrations.

The solution was a smart end-effector, with active force control (thought force sensors and gravity controllers), tilt sensors, and electromagnetic shock absorbers (to reduce the vibrations).

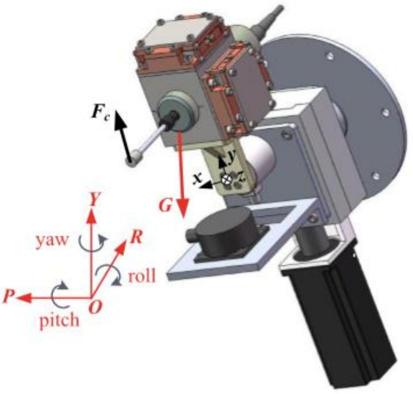


Figure 2.3. Smart end-effector (F. Chen et al., 2019).

There was a constant data exchange between the intended force and the measured force, in compliance with all the working parameters. The vibration suppressor improved the final quality, but by observing the results it was concluded that the force controller worked well only within simple pieces. Therefore, the problem of complex shapes continued.

Filling this geometric blank, (Tian et al., 2016) projected an automated robotic polishing solution for curved surfaces, to reduce costs and improve the parts' quality.

It was followed an innovative four procedures division: a removal distribution model for each polishing path, an algorithm to obtain a suitable path spacing, an effective planning algorithm for the tool location, and finally a polishing control model.

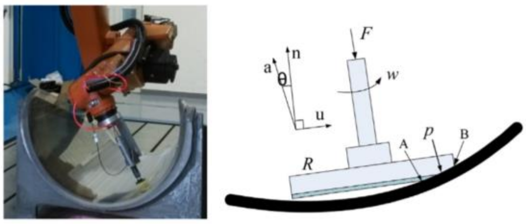


Figure 2.4. Schematic diagram of contact in the simulation (Tian et al., 2016).

This last one was particularly interesting since it was arranged by an active compliance (all control strategies for the active force adjustment in accordance with the sensor input), in the form of a force-position-posture control, and passive compliance (natural compliance of the tool under deformations or external forces), in the form of a spongy tool as shown in Figure 2.4. It was seen as a good way to assist naturally the force control.

Their conclusions verbalized the importance of studying the path spacing because it affected the pressure distribution and material removal rate. For the force control, it was important to compensate the gravitational force to provide stability, precision, and quality.

On a more complete approach, (Márquez et al., 2005) intended to help innovating the mould manufacturing industry for a more efficient, less time consuming and more cost-effective polishing. So, they developed a robotic cell with an *ABB* robot, a force feedback controller, and a device to measure roughness.

Once again, they used a CAD model of the workpiece as a basis for all the processes, so it was a good pattern to be followed. A key innovation was their system's division based on a finishing appraisal model (roughness and shine), as seen in Figure 2.5.

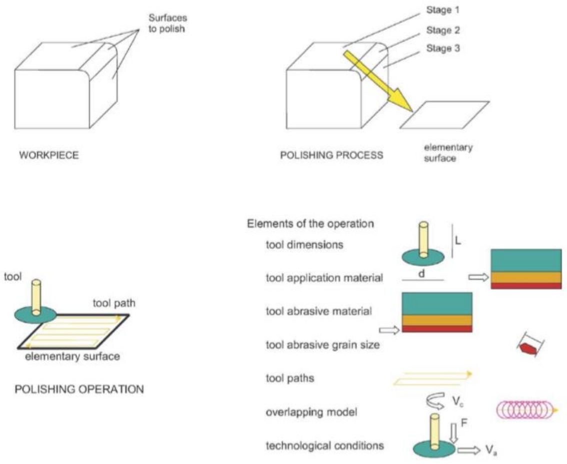


Figure 2.5. Representation of the polishing model (Márquez et al., 2005).

To accomplish the lowest value of roughness, there was a need to execute many tests, and it could cause deviations. So, an inventive way to correct it was the "control operation system", and together with real-time data analysis, it was possible to achieve a higher rate of efficiency and quality.

For each abnormal behaviour, the system anticipated it by checking data and knew exactly how to respond to them.

They concluded this method was perfect for production series with CAD-based geometries, and they managed to reduce 25% of the polishing time, which itself represented 17% to 29% of the total manufacturing time.

2.2.1. Force Control/Paths in Polishing

As seen before in this chapter, some articles developed an entire system, including both the force and path control.

But the ambition was also to take some knowledge individually from the force control and the path planning applied to polishing, because they both need to be in constant and perfect tune throughout the all process.

On a first line, (Miao & Fang, 2017) developed dynamic equations to keep the contact force constant. The data from the process was analysed in real time and compared with the force and roughness values predefined. There were two sources of feedback: vision feedback in the form of a camera to evaluate the workpiece and force feedback as a force controller.

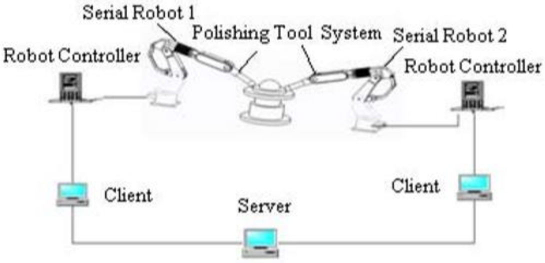


Figure 2.6. Representation of the polishing model (Miao & Fang, 2017).

Another interesting point was their modal study of the robot's rigidity to ensure all the components endured the stress in work (fitting parts, tool, flange).

Conclusions said the quality and efficiency of the work depended on the real time comparison between the pre-set values and the read ones. The visual and force feedback were enough for the force maintenance.

Another proof of the importance of the polishing force was (Xudong Zhang et al., 2017)’s work. Keeping the contact force continually monitored and controlled was the most important factor to industrialize robots in the polishing sector, more specifically the normal component. So, it was imperative to retain the force perpendicular to the workpiece, in this case through pneumatics.

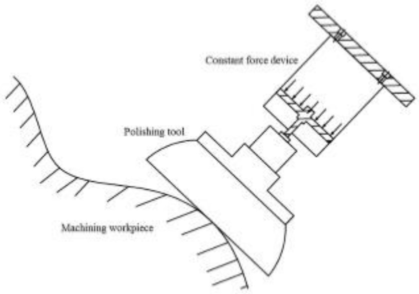


Figure 2.7. Diagram of the pneumatic actuator’s action (Xudong Zhang et al., 2017).

Once again, the sensor adjusted the force by making immediate calculations between the measured values and the wanted values, then sending data directly for the actuator to perform accordingly. The force control was composed by the components showed in Figure 2.8 and the constant flow of data was considered crucial.

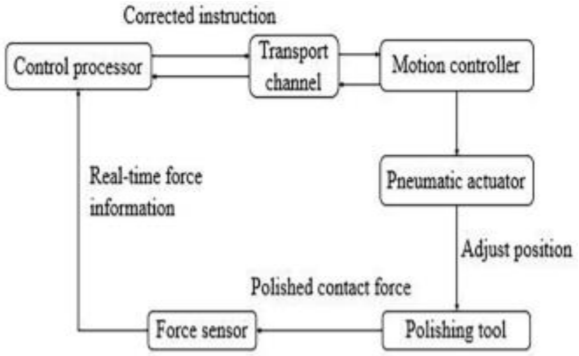


Figure 2.8. Communication protocol (Xudong Zhang et al., 2017).

(NAGATA et al., 2008) specified the main difficulties in automated polishing systems: the non-accessibility of teaching processes for curved surfaces, lack of kinematics/servo control knowledge, and few well-succeeded control strategies.

To correct this, were followed two separate loops. The force control loop controlled the polishing force based on the contact force and kinetic friction force, and the position feedback loop controlled the cartesian space to keep the tool in the desired path.

It resulted in the following communication protocol represented in Figure 2.9.

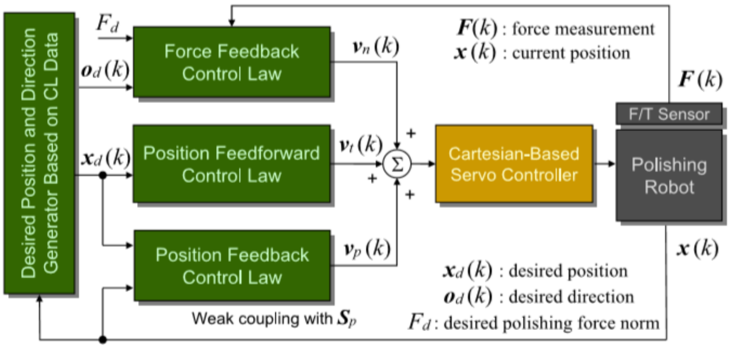


Figure 2.9. Block diagram of the position/force controller (NAGATA et al., 2008)

All movement characteristics were based on CL data from CAD (normal vectors, path planning, translation movement, and contact directions). Once again, this allowed a much quicker non-thought operation.

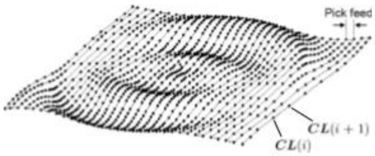


Figure 2.10. Example of CL data (NAGATA et al., 2008).

The results achieved a 0.2mm tolerance for a polishing force of 20N. The force controllability was a bit worst compared to a manual procedure, but it could take those forces for longer periods. Once more, the data exchange was crucial and was noted the need for constantly updated CL data to smooth the feed motion.

Regarding the path component, there were also several works developed. (Feng-Yun & Tian-Sheng, 2005) automated polishing system used CAD software to control the path, which meant it didn’t need a learning process as well.

Thus, CL data was again the basis for the path planning and the study of the workpiece surface.

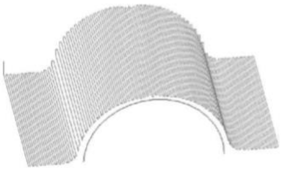


Figure 2.11. CL data for a test workpiece (NAGATA et al., 2008).

Also founded on CL data were made several interpolations to smooth the transition between orientations and poses of the robot or even to compensate zones in need of more smoothness (for example, interferences or sudden direction changes).

With assistance from the pose controller and CL data, it was aimed for the tool's axle to be always in contact with the surface. This point turned out to be crucial in the conclusions. The results showed an effective system, so an algorithm of this kind was a viable solution to follow.

On another direction, (Mohsin et al., 2019) presented a very well laid out structure of what they thought a path planning should be (Figure 2.13). For the displacement of the system, were studied two different circumstances: if the workpiece to be polished was heavy and big, it should be fixed and the movement would be made by the tool. Otherwise, if the part was light and small, it could be used for the movement against a fixed tool

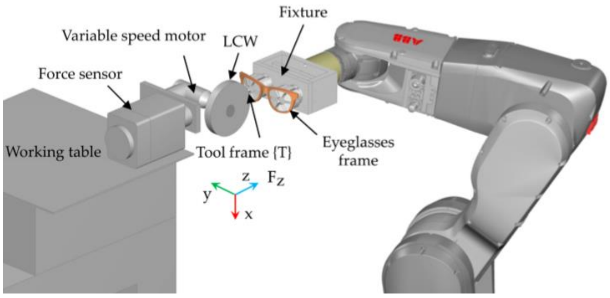


Figure 2.12. Setup for the robotic polishing (Mohsin et al., 2019).

There were three steps believed to be essential for the tool path planning: firstly, the workpiece was divided into several smaller parts until it covered 100% of the surface, reaching a non-stop smooth path. Then it was required for each part to investigate all the important parameters that could affect the path planning (singularities, joint limits, etc).

Finally, all the segments were "stitched" together to connect them and create a homogeneous finish.

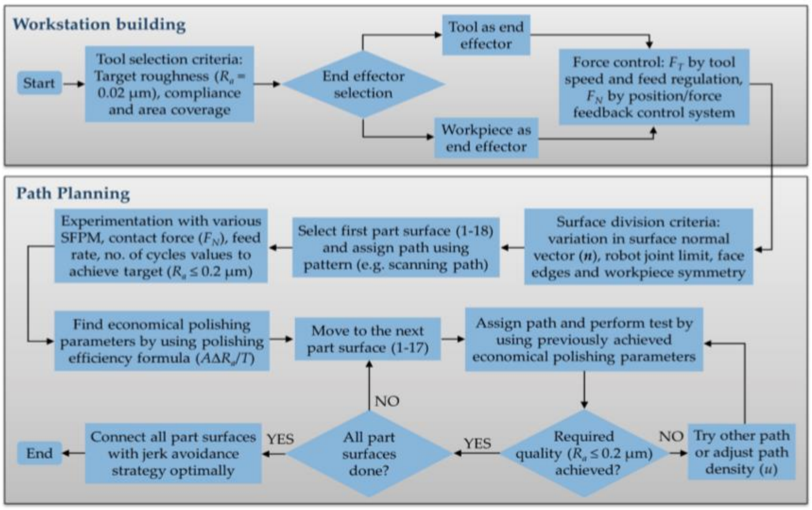


Figure 2.13. Diagram for an automated polishing system (Mohsin et al., 2019).

The force control was divided into two separate modules: the tangential control based on tool parameters, and the normal control which used a pneumatic force feedback controller because of its quick response.

Again, a comparison model between a measured force and the pre-set one was the source of the force control (Figure 2.14), and then the system could implement automatically corrective actions on the movement and the force.

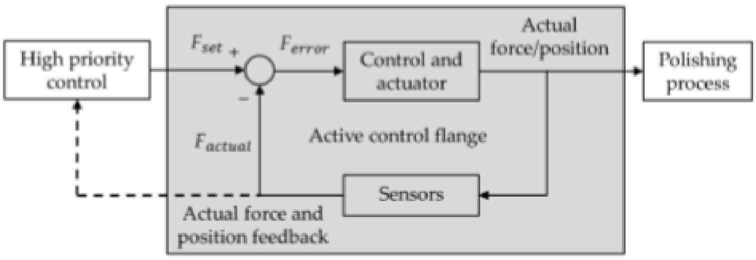


Figure 2.14. Force control working protocol (Mohsin et al., 2019).

For a polishing system to be successful, they concluded that it was important to control the surface area coverage, to test the best suitable polishing parameters for the circumstances, and to guarantee a stable contact force.

If these parameters were controlled, the system should be effective. The surface division and the study of the joint's limits also proved to be indispensable. Once more, it was mentioned that a good polishing system required constant communication and a perfect tune between all the components, protocols, and data.

2.2.2. Parameters Optimization

Despite the inspiration was not to assemble a polishing system, it was important to scrutinise the application environment parameters (like the importance of an evaluation of polishing parameters) for understanding purposes and to develop a complete work. As with the other themes, all topics addressed in this state of art were connected in some way. Thus, bonding them in perfect line was very important.

Roughness was a widely used feature to appraise the surface finish in the course of the polishing process. Towards corroborating it, (de Agustina et al., 2018) used a camera to acquire data related to the piece's shape and to define the path. It was applied a pneumatic force actuator/feedback system to define and study the force variations. Along these lines, the surface roughness was estimated via force signals to guess when the polishing process was finished.

Following the same principle, (H. Chen et al., 2018) established a “surface roughness model for free curved surface”. The importance of the polishing parameters control was studied in to optimize them and achieve higher surface quality. This example was based on a semi-empirical model to analyse and correlate data, and on a generical algorithm to optimize the iterative search algorithm.

Delving deeper into this subject, were tested the direct connections between the roughness and the control parameters (normal pressure, rotational velocity of the tool, velocity rate, inserted and converted by *C++*). Concluding, the most effective way to improve the parameters was based on the curvature equivalent radius.

(Almeida et al., 2018) noticed that the injected parts quality depended immensely on the mould where they were manufactured. Thus, it was analysed the quality of the moulds surface finish to ensure it was perfectly levelled. With that in mind, these were the key parameters mainly studied: applied force, angular velocity, and feed rate.

Spec-wise, their algorithm was based on optical and tactile measurements to analyse the wanted shape and the polishing path, which meant they used measurement machines in link with the CL data to shape a “point cloud” representative of the piece. The higher the density of the points, the lower the dot pitch and the higher the precision of the correction profile.

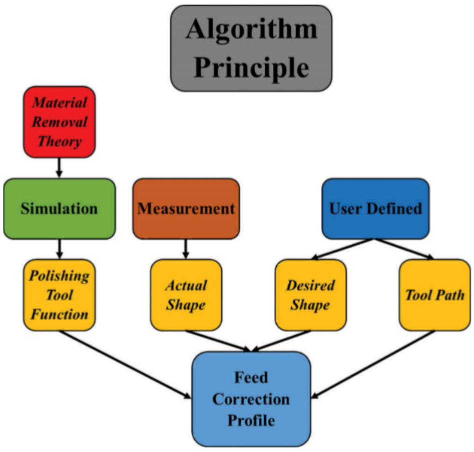


Figure 2.15. Algorithm to calculate the correction profile (Almeida et al., 2018).

The removal rate was based on the time needed to pass from the actual shape to the intended one. Then, and thanks to the software, every time there was a variation on the feed rate the tool adjusted its position to increase the material removal at that point.

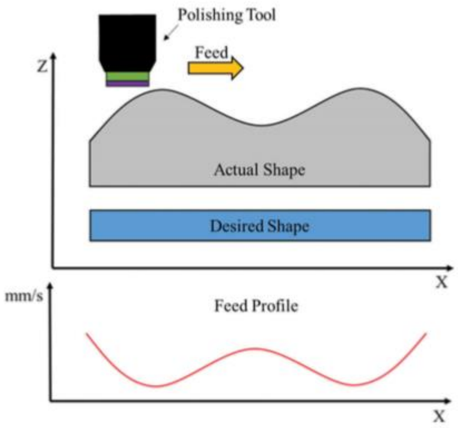


Figure 2.16. Polishing correction technique (Almeida et al., 2018).

To achieve a uniform correction profile, every point on the surface needed to be machined with the same number of path points. To avoid a non-homogeneous finish on the edges, the path extended its movement beyond the limits of the shape, and the number of passages was defined by the operator. It was achieved a 68% improvement in roughness, with an error of 4.9nm (0.72%).

2.3. Force Controllers

The usage of force controllers wasn't restricted to the polishing sector. As we're going to perceive throughout this sub-chapter, there have been some devices and procedures embraced on different branches of the industry, even if in smaller numbers. So this section wanted to stretch the knowledge of force controllers beyond the polishing barrier and to study the pneumatic system itself.

For starters, (Ruihua et al., 2006) followed an SMC approach in a pneumatic force control servo system instead of a conventional PID controller, which according to them had uncertainties on the sensitivity to external disturbances.

For instance, PID control algorithms have been successfully employed in electrical drive systems control but it was very difficult for pneumatic actuator systems to achieve the desired performance while using only a conventional PID controller.

Since pneumatics systems played a significant role in the industrial automation systems, it was a technology used in robotics, contact task applications and spot-welding machines for example. The reasons behind this were the component's cost and ease in power transfer.

The Figure 2.17 represents the pneumatic servo system:

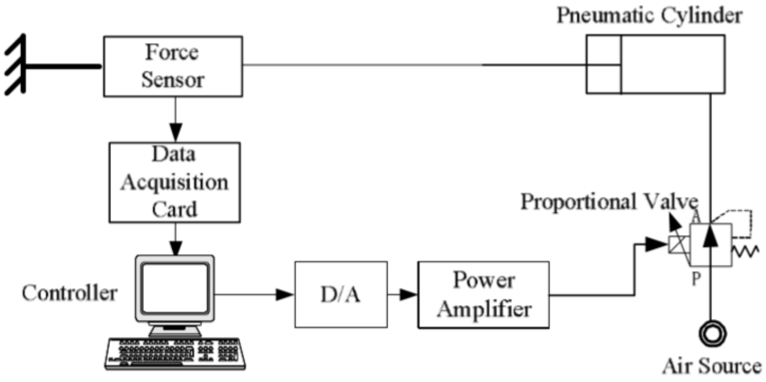


Figure 2.17. Work diagram (Ruihua et al., 2006).

In this specific case, it was used a pressure proportional valve as the electro-pneumatic converter to construct the electro-pneumatic force loading servo system. Due to the friction dead area, non-linearity of the pressure proportional valve, and the non-linearity of the air cylinder, it was difficult to get an accurate and linearized mathematical model.

Because of this, the simulated results indicated SMC had a better control performance in comparison with the traditional PID controller. The response of SMC was faster and the force control error was smaller. It could satisfy the need for a pneumatic force loading system.

Again, (Kazerooni, 2004) developed an exact model of a simple pneumatic system consisting of a double-acting cylinder and a servo-valve, intending to provide an insight into the design and control requirements for pneumatically actuated systems.

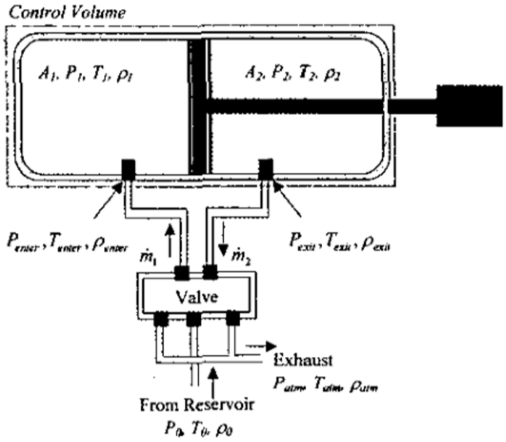


Figure 2.18. Work diagram (Ruihua et al., 2006).

Using this model, they studied derivations of a control algorithm that converted a pneumatic actuator into a force generator for robotic control applications. This concept was originated from a practice because most high-performance robotic systems were designed to be powered by electric actuators, but there were difficulties in transforming pneumatic actuators into force or torque generators.

As seen before, this was caused by the compressibility of air and nonlinearities in the servo-valves. Then, the early applications of pneumatic actuators were limited to simple and non-precise positioning applications, where actuators were controlled using on/off directional valves.

The goal was to derive a control algorithm that converted a pneumatic actuator into a regulated force generator, or in other words, an actuator that used feedback to impose a precise force application as a function of an input command signal.

On a different interpretation of this topic, (Xiaozhi Zhang & Xu, 2019) presented the design, analysis, and testing of a novel and innovating mechanical three-DoF parallel kinematic constant-force end-effector.

It was intended to create a solution whose nature allowed them to get rid of force sensors and reduce the hardware cost. To achieve a constant-force application without extra fixing support, were adopted “symmetrical bistable flexure hinges”. Then to reduce the constant-force value was introduced a preloading CFM.

To ease the fabrication, the three-DoF parallel end effector was designed in a modular way. The constant-force property was obtained by balancing the negative-stiffness mechanisms and the positive stiffness of five decoupling flexure hinges, as seen in Figure 2.19:

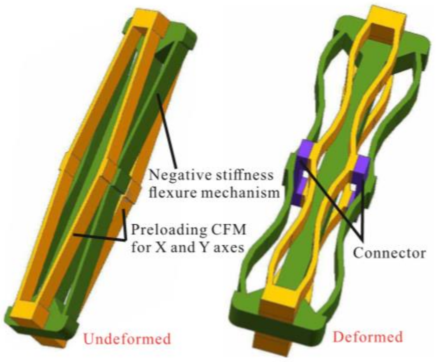


Figure 2.19. CAD model of the device (Xiaozhi Zhang & Xu, 2019).

Besides this, the constant force was 3.4 N with the fluctuation of ±8.8%. With the preloading CFM, the constant force along the X-axis was reduced by 2.7 N.

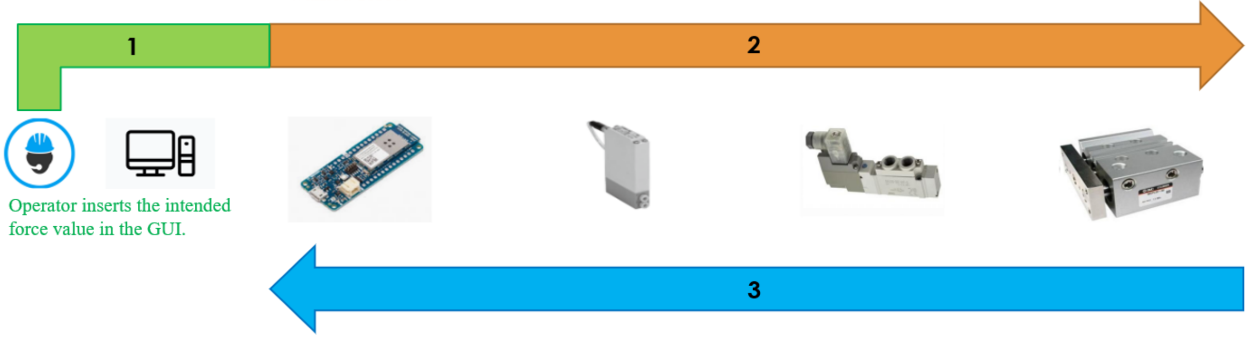
This property enabled a safe interaction between the end effector and the object without using a force sensor, demonstrating the cost reduction on hardware implementation.

Even though this is an ingenious way to guarantee a constant force value, this thesis's requirements and conditions are discouraging for this kind of device.

3. HARDWARE AND SOFTWARE

While deeming the knowledge about all the components that make up the device, this chapter was separated in two parts: the robot as an entire piece and the end-effector deconstructed into its various parts.

The following scheme represents the main functions and relations between those physical components:



Working Task: The *Arduino* board reads the force value introduced by the operator and converts into a signal to the pressure regulator, which controls the opening or closing of the eletrovalve, and due to the correspondent pressure in the system, the cylinder is moved exactly the right amount to apply the wanted force.

Operator inserts the intended force value in the GUI.

Corrective Task: When the pressure regulator senses a variation on the system's pressure coming from the eletrovalve or cylinder (for example, due to a depression in the piece which causes a deviation on the cylinder's stroke), it sends that data for the *Arduino* board to correct it and reach the desired values again

Figure 3.1. Scheme about the device.

3.1. Pneumatic Device

It was the main tool developed in this project, with the main purpose of providing human-like sensitivity to a senseless machine, targeting the improvement of all kinds of finishing operations by controlling the force application.

It was mounted on the last link of the robot and acted as a last joint with one translational DoF. So, it was possible to acquire and maintain a constant force solicitation due to pneumatics and to the constant flow of data in both directions. Thus, the harmony between all the following components was preserved.

These components were all chosen with cost restrictions in mind to provide a cheaper solution compared to those in the market.

3.1.1. *Arduino MKR 1000 Wi-Fi*

Arduino is a functional, cheap, easy to program and user-friendly single-board microcontroller (Arduino, n.d.). It exists to create, develop and control an electronic device, founded on sets of digital and analog I/O connected to various circuits.

It was used to control the pressure regulator through the induction of electrical voltages and to analyse the data passed throughout the components (like the air pressure and force translated into a voltage), to subsequently perform tasks and act according to that data.

Based on the specs given by (Arduino, n.d.), this specific model was chosen because it offered a cost-effective alternative in the Wi-Fi connectivity range, with the characteristics showed in Table A.2. The tasks would then be called via a *Visual Studio* interface as required by the operator and it would also serve as a foundation to show output data to corroborate the usefulness of the system.

Due to different voltages of the electrical circuit and some bad initial tests, were studied some possibilities along the way to correct it and the solution was the addition of a shield and a breakout board.

Figure 3.2. *Arduino MKR 1000 Wi-Fi*. Source: https://store.arduino.cc/arduino-mkr1000-wifi

3.1.2. Pressure Regulator *ITV 0050-3BL*

This component was the main link between the *Arduino* and the eletrovalve, and it was responsible for data reading and data exchange in both directions.

Essentially it transformed an electrical input signal coming from the *Arduino* (corresponding to the intended force by the operator) into a pressure output data capable of being read by the eletrovalve, ordering its opening or closing and achieving the intended air pressure in the system.

Figure 3.3.Pressure Regulator *ITV 0050-3BL*. Source: https://www.alliedelec.com/product/smc-corporation/itv0050-3bl/70072890/

It could also detect unintended airflow variations in the chamber (it could indicate surface variations, for example) and sent that data for the *Arduino* to make a correction. Its specs are showed in Table A.3.

3.1.3. Eletrovalve *SY5120-5DZ-01F*

With its two working positions, it controlled the airflow coming from the pressure regulator and entering the cylinder chamber. When the intended pressure was achieved, the eletrovalve opened or closed by order of the pressure regulator to reach the corresponding cylinder's translational position (Table A.4).

Figure 3.4. Eletrovalve *SY5120-5DZ-01F*. Source: https://ro.rsdelivers.com/product/smc/sy5120-5dz-01f-q/smc-5-2-pneumatic-control-valve-solenoid-pilot-g/6862668

3.1.4. Cylinder *MGP L40 TF-25AZ*

The cylinder was responsible for the movement of the device and it was the last link of the end-effector's chain. It was directly controlled by the eletrovalve but it was also dependent on data from the *Arduino* and the regulator (Table A.5)

Figure 3.5. Cylinder *MGP L40 TF-25AZ*. Source: https://automationdistribution.com/smc-mgpa40tf-250/

3.1.5. Skeleton Parts

All the parts composing the device's skeleton were developed with the purpose to couple the mechanical components described above like a carcass.

Firstly, were created 3D models through a CAD software in conformity with the mechanical component's sizes and tolerances. If necessary, the models could be improved in some details, creating new optimized prototypes. Then these parts were all 3D printed, later checked the clearances and assembled.

This process was mainly developed in my colleague thesis (Carvalho, 2020).

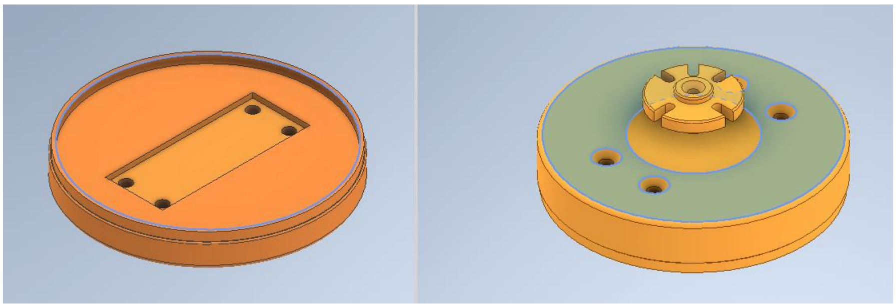


Figure 3.6. Some parts obtained by CAD and 3D printing (Carvalho, 2020).

3.2. Robot

It is a small yet fast and powerful six-axis robot whose compactness allows it to be flexible and robust at the same time. It has an integrated pneumatic source to power the device, also bringing reliability and safety to the system,

All the characteristics described in Table A.1 were taken into consideration, justifying the preference for the 140 model for the simulation process.

Figure 3.7. *ABB 140* articulated robot. Source: https://new.abb.com/products/robotics/pt/robos-industriais/irb-14

3.3. Software

To bring this device to life and to succeed in the projected work, it was mandatory not only to pick the correct hardware but also the right software. The perfect compatibility between the components and between the software could be a deciding factor on the device success.

Within this thesis proposed work, this sub-chapter will investigate and scrutinize the best-suited software for it.

3.3.1. Autodesk Inventor

It is a CAD 2D/3D design and simulation application responsible for the development of most parts that make up our device.

Its features guaranteed an accurate computational model of the workpiece and the whole environment (table for the workspace, robot's support, etc), and it could be used as a crucial aid in the operation itself to create a virtual atmosphere as resembling as possible to the real world.

Furthermore, its resultant CL data could be introduced later into the *RobotStudio* software to plan the end-effector path or to predict the robot's behaviour through the workpiece.

3.3.2. Microsoft Visual Studio

It is an IDE written in C++ or C# and was used as the basis to build up a GUI capable of acting as a bridge between all components, of compiling the device's functions, controlling the operations required, and exhibiting helpful data.

Its structural functions included several buttons, textboxes, toolbars, and other tools to help to build the most appropriate application interface for the user to control and read the information on the device's and robot's operations.

It was responsible as well for the important communication protocols with the *Arduino* (to call the component's programmed commands) and the *RobotStudio* (to control the simulation or real movements), syncing the different logics and languages of the device.

3.3.3. RobotStudio

It was the right program to use in this thesis since it is an official *ABB* product, specifically developed as a simulation and offline programming software to replicate all the physical parameters associated with the robot.

It was used to create the virtual 3D environment and therefore it was possible to experiment and manipulate the robotic cell before testing it in real life, reducing the possibility of errors or failures and its consequences, and saving a lot of time and money by making those corrections in the virtual environment. This data would later be imported into the robot's controller to conduct the real-life tests if required.

Its *RAPID* programmable functionalities allowed the manipulation of various aspects of the robot and the tuning with the device. Furthermore, it enabled the possibility of connections with other programs by creating sockets and ports via TCP/IP. For example, each button and function of the user interface could be connected directly to this software and have the corresponding action of the robotic cell according to the user's will.

Another great advantage of this program was its geometry importing features from the Inventor, for example to create the virtual model of the complete workspace. Additionally, was appreciated the option of importing and integrating the device as a library tool directly into the program with its functionalities, movement, and kinematics properties, so it was in perfect tune with the robot throughout the whole simulation.

This aptitude for software connectivity was very important, and joining all these advantages together, there were conditions to replicate accurately the whole operation.

4. EXPERIMENTAL WORK

This chapter promised to study the best way of demonstrating the work done and exhibiting tangible data as proof of the product’s feasibility. It was divided into its various stages of preparation and execution.

Were developed two simulations in the *RobotStudio* software and a complete graphical user interface in the *Visual Studio* software, both reasoned by output data like graphs and force values. It was also projected an experimental test to prove that there were conditions to bring these tests to real life, so was ensured that those simulations were as resembling as possible of the reality, that the connection between the user and the machine was good, and that the force application control was correctly made during the whole experiments.

They were performed based on the communication protocols between all the components and languages (Figure 4.1), the GUI, the *RobotStudio* simulations with the imported *Inventor* geometries, and the data transferred to the robot controller.

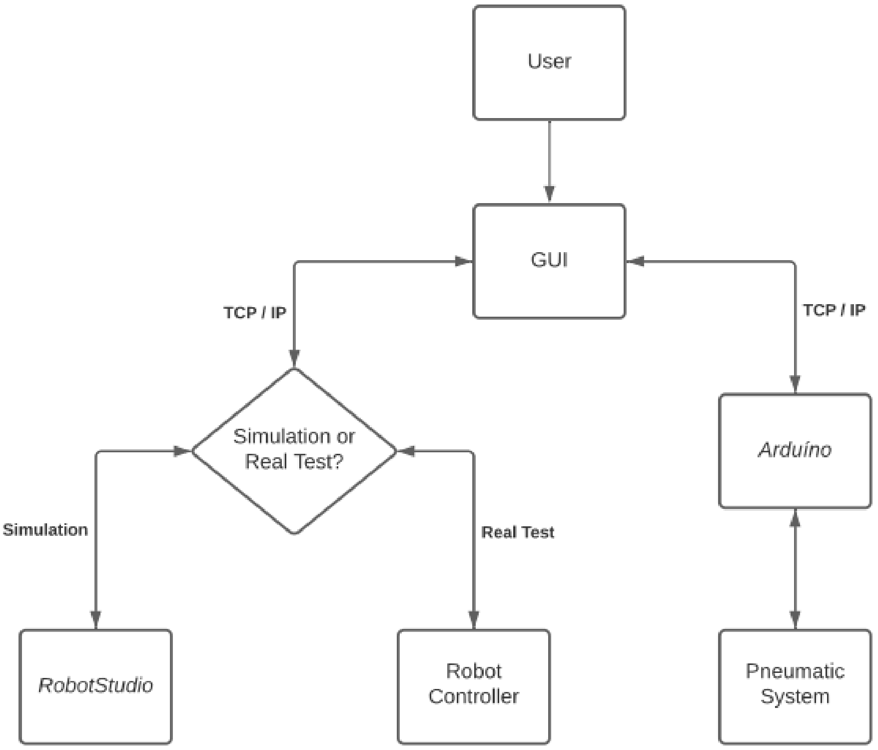


Figure 4.1. Communication scheme of the system.

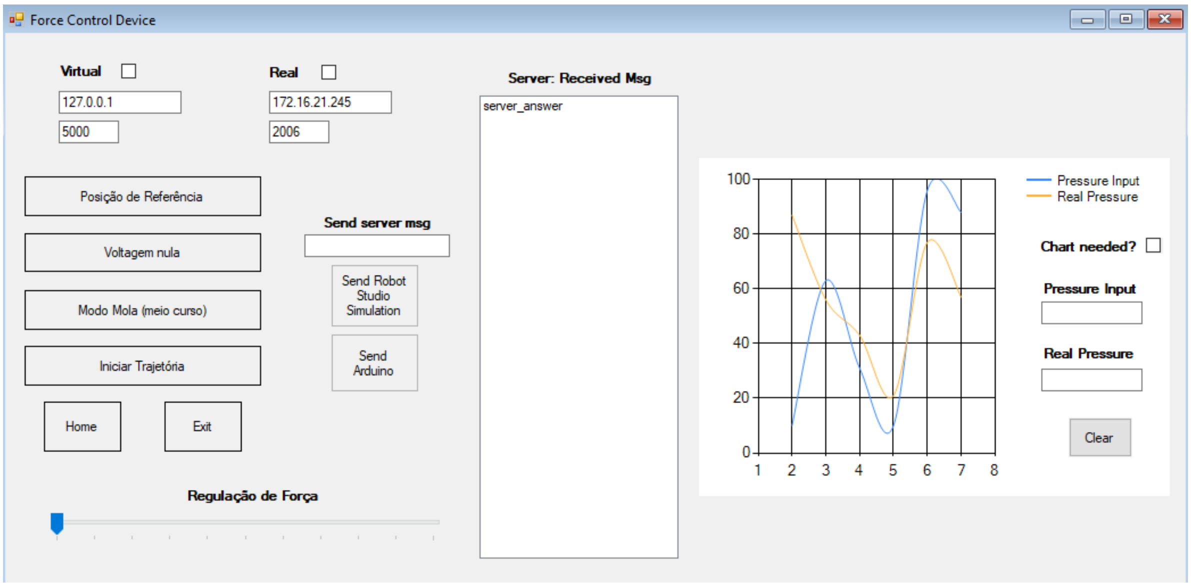
Despite doing the experimental tests in real life or not, the software, the simulations and the system itself were developed to integrate the functionalities of both realities, so that they were ready to work either in the virtual and real world.

4.1. Graphical User Interface

The sum of all components and the corresponding software was not enough to build a complete system because they wouldn't be able to communicate by themselves. So there was a need to create a bridge capable of connecting the device, the robot, and the user.

This job was ensured by the GUI (Figure 4.2), which was developed using the *Visual Studio* software. It had the capacity of controlling both virtual and real tests when required, by ordering certain calls to the *RobotStudio* (simulation) or the robot controller and *Arduino* (reality). To do so, it was organized into those two components, being the simulation discussed in this thesis.

Starting with its structure, was necessary to build an arrangement of buttons, checkboxes, text boxes, and a toolbar to control its multiple functions. Each of them had the purpose of manipulating the motion of the robot and the device.


Force Control Device

Virtual ☐
127.0.0.1
5000

Real ☐
172.16.21.245
2006

Server: Received Msg
server_answer

Chart needed? ☐

Figure 4.2. User interface commands.

The GUI had the ability of controlling both the simulation or the real test through selecting the reality where the test would be conducted, with the corresponding IP address and port to connect to the right software (*Arduino*/robot controller for the real test and

RobotStudio for the simulation). Then, the remote-control functionality was ensured by those connections via Wi-Fi.

According to the environment selected, certain buttons would be available to be pressed:

- Reference position (brings the robot to the working position);
- Null voltage mode (deactivates the device);
- Spring mode with half-stroke (prepares the device to start the working procedure);
- Start (starts the task through the planned trajectory with the possibility of looping it);
- Home (brings the robot and the device to the home position);
- Exit (finishes the simulation).

They were available to both realities with exception of the last one, which only works with the real test and was more suitable to my colleague's Francisco dissertation (Fernandes, 2020). While performing the test, there was a toolbar to control in real-time the intended force (by adjusting the pneumatic pressure inside the system), and there was also the possibility of sending messages to the servers with certain calls. That was exactly the way the buttons were programmed: each time they were pressed, the GUI automatically sent a message to the *RobotStudio* socket where its content was directly associated with a certain movement protocol.

Meeting the user's will, there was also a functionality to allow some of the tasks previously mentioned to be conducted automatically in a sequence, instead of the user manually pressing each button according to the desired task. To finish, there was a text box to receive messages and warnings from both software and the possibility of having a force graph with feedback data to control the force variations.

4.2. Simulation

This sub-chapter concerns the questions resembling the *RobotStudio* configurations and tasks needed to perform the projected experimental tests.

As part of the robotic cell development, the tests were conducted and adjusted in a virtual environment by the hands of this software to prepare them and enable the possibility of modifications before the real test. It was imperative to make sure the simulation environment was as resembling as possible to the real world, saving money and time.

This part of the work was split into two separate simulations, and the first one was built as a more complete virtual experiment connected to the GUI and capable of reproducing accurately the projected test. Selecting the correct robot and controller according to the real hardware used was easy through the *ABB* library. It ensured the tasks transition to the physical devices were precise.

Using once more the CAD software, were imported the 3D models of the workspace (the table and the robot's support), with the possibility of adjusting their relative position accordingly as the experimental test unfolds, to obtain the best possible conditions.

Then was ensured that its dimensions and tolerances were admissible.

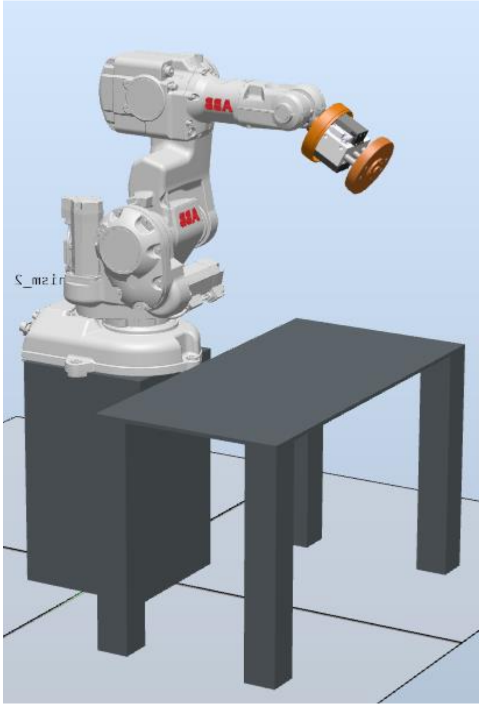
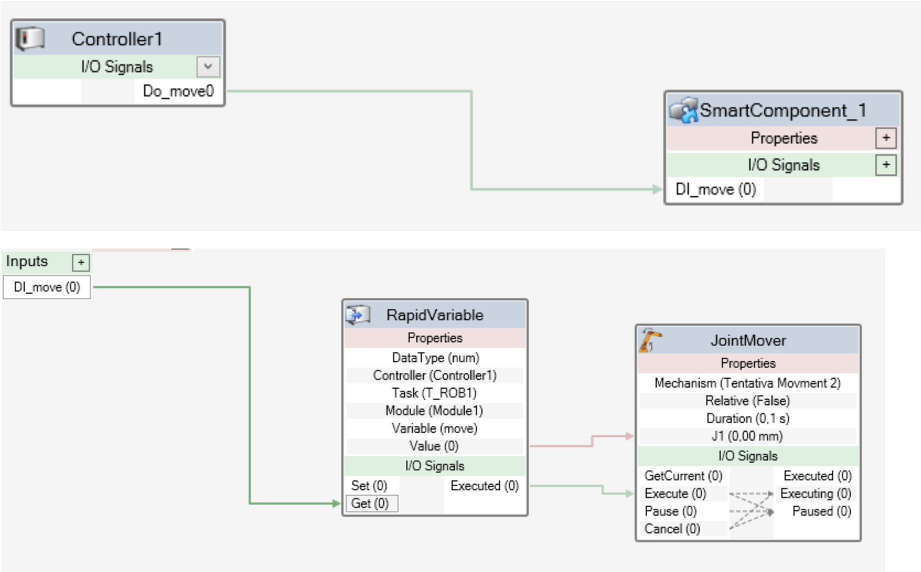


Figure 4.3. Robotic station.

The 3D model of the device, created by my college (Carvalho, 2020), was also imported into the *RobotStudio*, not as a normal geometry but directly as a tool with all the intrinsic configurations needed (purpose, centre of mass, DoF, etc) and the translational 25cm range of travel. But this stage by itself was not enough to accurately represent our device.

Therefore, it was used the *Smart Component* tool to associate infinite points in the translational range of the device to any given moment of the desired path. So was created a digital output in the controller to connect to a digital input on the *Smart Component* to control the I/O system of the device. It was next connected to the *RapidVariable* function to execute the *JoinMover* function (Figure 4.4). Then it was possible to program the position of the tool as part of the robot movement and not as an individual tool, creating a seven-DoF system.



DataType (num)
Controller (Controller1)
Task (T_ROB1)
Module (Module1)
Variable (move)
Value (0)

Mechanism (Tentativa Movment 2)
Relative (False)
Duration (0,1 s)
J1 (0,00 mm)

Figure 4.4. Station Logic.

This component was crucial as well for the communication protocols of the GUI, by translating the device's position into readable data and allowing to predefine some positions of the device to help the development of the tasks: for example, the spring mode talked earlier in the GUI chapter puts the device into its middle position to prepare it for the force application, but if there was a need for any position in the 25mm of travel of the device, it would be possible to program it.

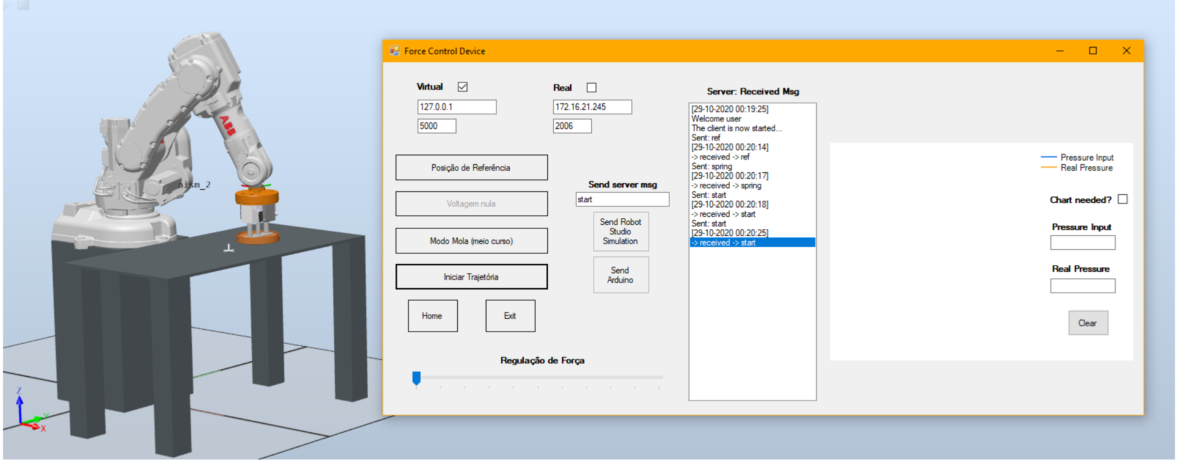
Additionally, were used functionalities of the *RAPID* module to program the system at our will like the manipulation of the path parameters and the activation of the I/O system described earlier.

Concerning the connection to the GUI, it was accomplished via TCP/IP by the creation of sockets in the *RAPID* module, with the capability of opening and closing them, connecting to a specific IP and port through wi-fi, listen the data coming from that port, save it and respond to it. By using the commands described in Figure 4.4, it was possible to communicate remotely with the GUI in both ways with total compatibility, receiving the messages sent by the click of the buttons described earlier, and executing the corresponding movement protocol.

Deepening on the simulation test structure (Figure 4.5), and to verify the system's behaviour under load, it was envisioned for the robot to move in a linear motion across the table and to sustain external physical disturbances without it being noticed.

So, it was only needed to create a few targets in a straight line, to connecting them by a path and to adjust the orientation of those targets to make sure the robot was capable of reaching them.

The user would then introduce the right IP address and port to connect remotely to the software via TCP/IP. Then the user could control the intended operation by pressing the corresponding button of the GUI which would call the respective movement protocol (Figure 4.5).



Virtual ☑
127.0.0.1
5000

Real ☐
172.16.21.245
2006

Send server msg: start

Chart needed? ☐

```
[29-10-2020 00:19:25]
Welcome user
The client is now started...
Sent: ref
[29-10-2020 00:20:14]
-> received -> ref
Sent: spring
[29-10-2020 00:20:17]
-> received -> spring
Sent: start
[29-10-2020 00:20:18]
-> received -> start
Sent: start
[29-10-2020 00:20:25]
-> received -> start
```

Figure 4.5. First simulation.

The second simulation (Figure 4.6) promised to demonstrate the device's polishing aptitude, where the constant force application should be guaranteed on a curved surface.

The early steps were shared with the first simulation, from the workspace preparation, to the construction of a complete robotic cell. The difference was the existence of a CAD workpiece with a curved surface where the test was going to be performed, and it was then placed according to the remaining components to define a virtual workspace.

The *Smart Component* feature was also available and it was possible to control the device motion in sync with the robot's movement. Once more, were introduced several targets on the surface of the workpiece, all with perpendicular orientations in each point, and was generated a path through those targets.

However, since this simulation did not have the GUI connection component, it was thought with a demonstration purpose and exclusively as a visual experiment to show a potential use to the device in an industrial environment.

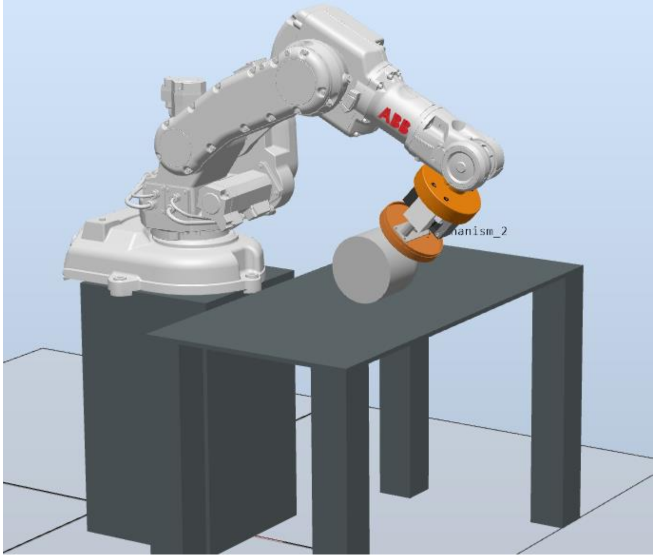


Figure 4.6. Second simulation.

4.3. Test

Besides the topics already reported, another objective of this thesis was to design and plan an experimental test capable of showing the benefits and potential of the system. All background content concerning the simulations and software was covered, so the preparation of that experimental test could begin. It was the inspiration used for the first simulation early referred, and the approach was to move the robot and the device across a table in a straight line while sustaining an external disturbance to prove it was capable of counteracting it and maintaining a constant force application.

The parts were all printed, the workspace arranged, the assembly of the system was doable and the software was ready to start the physical tests. The idea was to use the data from the first simulation and import it directly to the robot controller. Everything was ready to run it and supposedly there was only the need to calibrate the workspace to make sure the tolerances were correct.

Unfortunately, the assembly of the device failed due to the covid 19 outbreak and logistic problems, which caused continuous delays in the delivery of parts to the electrical circuit. So, this section wants to sum up the projected experimental test early phases, to show the virtues of the system.

Picking up the work carried out by my college (Carvalho, 2020), all 3D printed parts were assembled with the right bolts and nuts, according to their correct specifications.

The first time the device was connected into the robot showed the need for a stronger mounting link and a closer look to this problem was ensured by (Carvalho, 2020), so the parts were improved to correct those flaws.

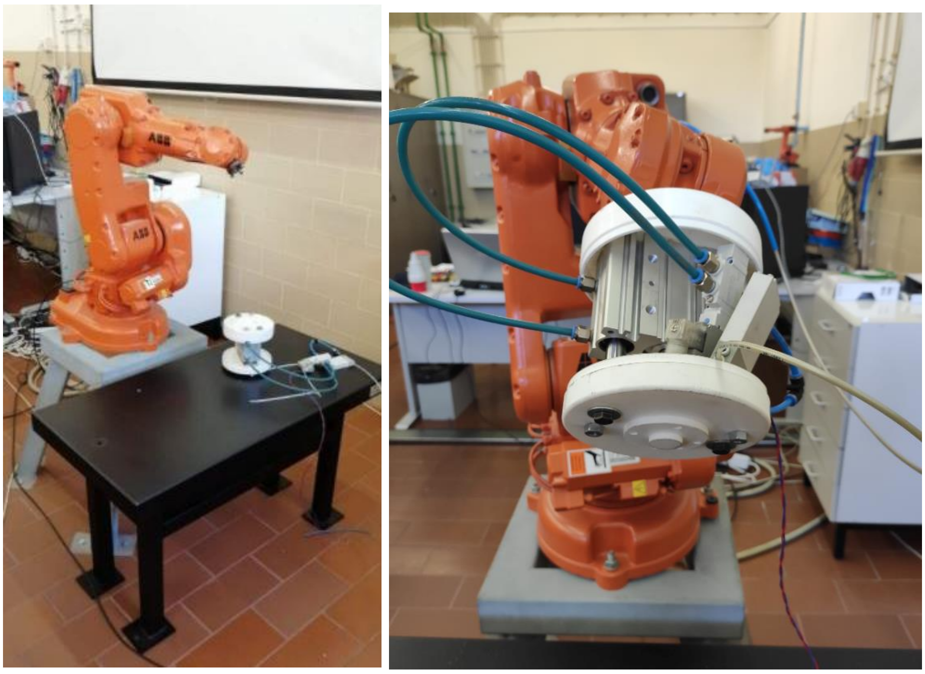


Figure 4.7. First assembly in the robot with 3D printed parts and all components described above.

Then, it was required to make sure the pneumatic system was correctly arranged with an air supply to feed the system and lines connecting the eletrovalve, pressure regulator, and cylinder to able the right passage of air pressure at the right time and the correct suitability of the correspondent contact force (Figure 4.8)

Figure 4.8. Pneumatic system.

Concerning the electrical circuit, the main issue was the different operation voltages of some components. For example, the eletrovalve was powered by a 24V source, but the *Arduino* board needed to run 3.3V and the pressure regulator range went from 0-10V. There was a discrepancy in these values, so in a first instance and to advance work it was created a primordial circuit (Figure 4.9).

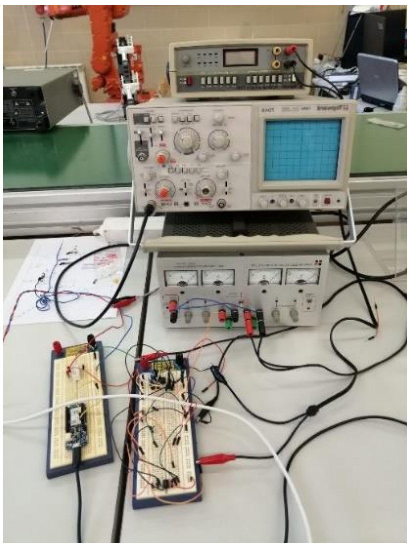


Figure 4.9. First iteration of the electrical circuit.

For complexity and space reasons, this 1st circuit was not viable so it was idealized a schematic diagram with all components needed to build a correct electrical circuit (Figure 4.10).

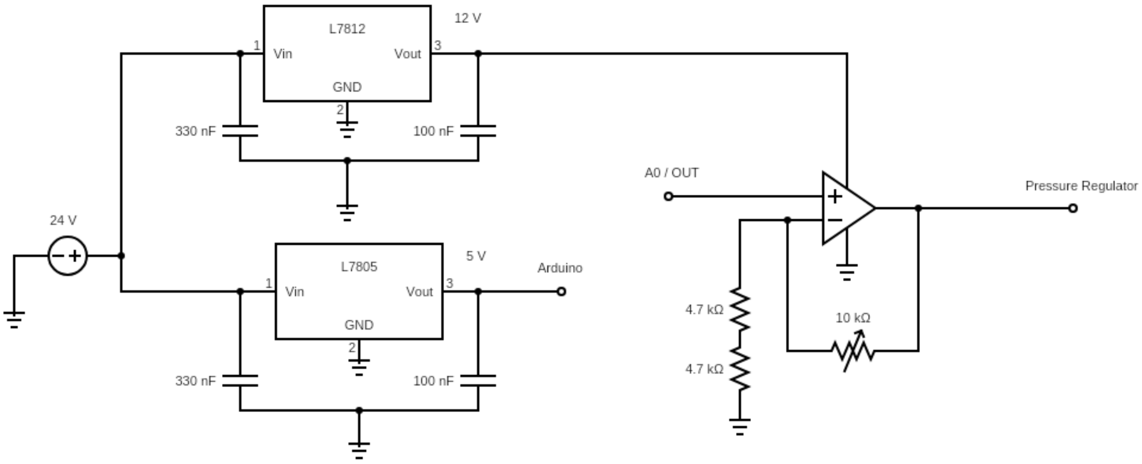


Figure 4.10. Diagram of the electrical circuit (Fernandes, 2020).

These questions are more developed in my college's thesis (Fernandes, 2020).

4.4. Results

This following section rounded up the whole chapter by analysing the results of the software, simulations, and general work development.

The simulations were performed successfully and exposed the potential of this device. On them, the robot and the device were capable of coursing through the path with the right positioning. In the first simulation, the tasks worked perfectly without glitches or bugs, showing its accuracy and proper calibration.

Since the *RobotStudio* software enables the direct implementation of the simulation code and logic into the robot controller, the real test had all the potential to succeed.

The GUI was very intuitive in its use and the commands worked correctly, showing it was ready to be introduced into a real system. Then, the bridge between the user and the simulation was a success because the GUI called the *RobotStudio* tasks accordingly to the right buttons, sending feedback data as well to be read by the user. The TCP/IP connection worked fine in both the real and virtual environments, as long as the IP address and port were properly entered, so the remote control of both realities was ensured.

Regarding the second simulation, the system was able to travel properly through the curved surface of the workpiece, showing the force application on those kinds of shapes was also possible. It served as a warning to carefully analyse the positioning of the workspace and the dimensional clearances between the robot and the active force control device because some poses and range of movements in the path could cause the collision of both.

Unfortunately, despite the whole experimental test was projected and prepared to be conducted with the data from the first simulation (directly entered in the robot controller) and controlled remotely by the real environment component of the GUI, it wasn’t possible to execute it. Nevertheless, all the parts fitted nicely, the pneumatic system worked well when tested with the *Arduino* software (it was capable of applying the intended force) and assembled with the end-effector, the workspace was well arranged, and it was a chance to study the best way of showing the capabilities of the system. Everything was suitably ready to work according to the intended objectives.

5. CONCLUSIONS

Since the beginning of this thesis, some objectives and milestones were established to be accomplished during the development of the active force control project.

Throughout this dissertation, those goals were answered to corroborate the accomplishment of the system's tasks, and as seen in the Chapter 4.4, the application side of the device was developed correctly.

The robot was capable of coursing through the path using the active force control device as a tool with the right positioning and using its final translational degree of freedom as a 7th DoF, programable on *RAPID* and with the possibility of being controlled remotely via the GUI and the user. The *RobotStudio* components used to manipulate the active force control system were significant to guarantee this harmony between the robot and the device.

The data exchange between the components proved to be crucial because the active force control would only be possible if the pressure reading and feedback were correct. Additionally, the communication protocols shown on Figure A.1 allowed a perfect sync between the software and hardware used.

Also, the accuracy of the simulations was important to reduce the time needed to calibrate the real-life test, and the possibility of remotely control the system via the GUI both for the simulation and the real system was a major added value.

To present the development of the system as a whole, the three dissertations were synthesized into an article soon to be published.

Obviously, there were still points to improve and the workings of the system could be refined, but this dissertation can be considered a success.

5.1. Future Works

Despite the success of this project, there were some aspects that we thought could be improved and further developed due to the lack of time, the overall situation of the covid 19, and the nature of the project itself.

For instance, and starting with the execution of the experimental test, it wasn't possible because the electrical circuit components weren't available, but its implementation would be crucial to prove the data from the first simulation, the GUI, the software, the components, and the connection between them were working correctly.

In order to automate and industrialize the system into another level, it should be developed a more intelligent and general path planning program to avoid it being too specific, since at this current state the system only works within the workspace and workpieces conditions earlier presented.

Regarding the GUI and the *RobotStudio* configurations, it would be attractive to add more functionalities to their tasks, like a real-time pressure reading and adjusting component connected directly to the *Arduino* to improve the communication protocols and optimizing the force application.

It would be interesting to develop and implement the polishing component into the system by adding rotational movement to the device, studying the vibrations and dust problems it could bring, and optimizing the polishing parameters (ideal force, path, overlapping model, roughness measurement), like the articles addressed in the state of the art.

To sum up the active force control system project, it shown that this kind of solutions are feasible and it left a good basis for future works within the *Industry 4.0* goals.

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APPENDIX A

Table A.1. *ABB IRB 140* specs.

Payload	6 Kg
Reach	810 mm
Max TCP Velocity	2.5 m/s
Position Repeatability	0.03 mm
Other features • Floor mounted/Inverted/Wall mounted at any angle; • Collision detection function.	

Table A.2. *MKR 1000 Arduino* specs.

Board Power Supply	5V
Circuit Operating Voltage	3.3 V
Digital I/O Pins	8

Table A.3. *ITV 0050-3BL* pressure regulator specs.

Pressure Range	0.9 MPa
Power Supply Voltage	24V DC +/- 10%
Input Signal	Voltage type 0 to 10V DC
Cable Connector	90º Angle with 2m
Other Features • Flat Bracket	

Table A.4. *SY5120-5DZ-01F* eletrovalve specs.

Type of Actuation	2 Position Single
Coil Type	Standard
Rated Voltage	24V DC
Electrical Entry	DIN Terminal D with Connector
Port Size	1/8
Thread Type	G
Other Features • With light/surge voltage suppressor • Non-locking push type	

Table A.5. *MGP L40 TF-25AZ* cylinder specs.

Cylinder Type	Double Action
D_{piston}	40 mm
D_{rod}	14 mm
Cylinder Stroke	25 mm

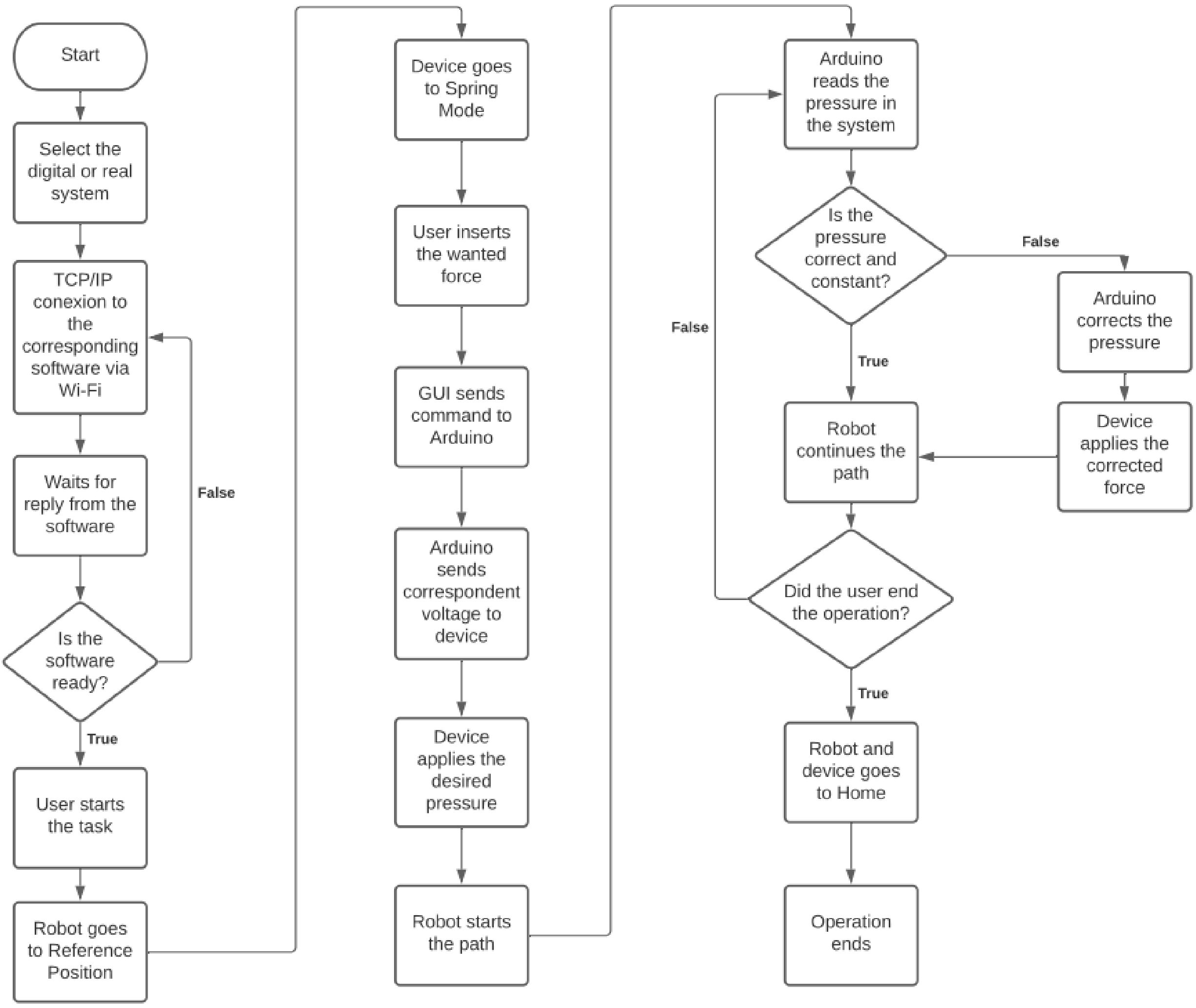

Figure A.1. Communication protocols.