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COIMBRA

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DESENVOLVIMENTO DE UM SISTEMA DE CONTROLO ATIVO DE FORÇA PARA A INDÚSTRIA

PROJECTO MECÂNICO E CONSTRUÇÃO

VOLUME 1

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Development of an active force control system for industry – mechanical project and building

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Desenvolvimento de um sistema de controlo ativo de força para a indústria - projeto mecânico e construção

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Coimbra, October, 2020

“Success consists of going from failure to failure without loss of enthusiasm”

Winston Churchill

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Abstract

Over the years we have witnessed a robotization of the world of work as many manual jobs have been extinguished due to the introduction of robots. Increasingly the robot will be a fundamental part in the world of work as is warned by *Industry 4.0*. Despite this, there are other tasks that in spite of containing the characteristics that promote robotization, such as repetitive movements they continue to be performed by humans due to lack of robotic capacity.

Strength control is considered one of the most important challenges imposed on robotics, so a good command of the applied forces is essential for a successful task.

Many tasks, such as polishing, are still only partially robotized due to the complex geometry of most parts.

The motivation of this dissertation is intended to ally with the two previous premises. As such, it is proposed to develop an active force control system for polishing application. The objective is the creation of a force control device for use in industrial environments, however the experimental tests will be focused on polishing.

The tool consists on a pneumatic cylinder, electrically controlled using a pressure regulator. Regarding the electronic part, it is essentially made up of *Arduino* parts. Bearing in mind that all this mechanism is created as a base, the mechanical design of the connections is necessary to couple the various constituents, making it a single part. For this, the *Autodesk Inventor Professional 2020* software is used for Computer Aided Design (CAD) development. Later *Ultimaker Cura 4.5* software was used to print the various links created in three-dimensional (3D).

Although the prototype created has accomplished what was proposed, there may be possible improvements that can make the mechanism more ergonomic and more resistant.

Keywords [*Industry 4.0*], [Robotics], [Pneumatics], [Force Sensor], [Polishing], [3D Printing].

Resumo

Ao longo dos anos tem-se assistido a uma robotização do mundo de trabalho, uma vez que muitos trabalhos outrora realizados manualmente foram extintos, devido à introdução dos robots. Cada vez mais o robot será parte fundamental no mundo do trabalho, como é alertado pela *Indústria 4.0*. Ainda assim, existem outras tarefas que, apesar de conterem as características que promovem a robotização, como movimentos repetitivos, continuam a ser realizados por humanos, devido à falta de capacidade robótica.

O controlo de força é considerado um dos mais importantes desafios impostos à robótica e, por esta razão, para a realização de uma tarefa com sucesso é imprescindível um bom comando das forças aplicadas.

Muitas tarefas, como o polimento são, ainda, apenas parcialmente robotizadas devido à geometria complexa de grande parte das peças.

A motivação desta dissertação pretende aliar as duas premissas anteriores. Como tal, é proposto o desenvolvimento de um sistema ativo de controlo de força, com vista a aplicação ao processo de polimento. O objetivo é a criação de um dispositivo de controlo de força para utilização em meio industrial, contudo os testes experimentais serão focados no polimento.

A ferramenta é constituída por um cilindro pneumático, controlado eletricamente com recurso a um regulador de pressão. Relativamente à parte eletrónica, esta foi constituída essencialmente por peças *Arduino*.

Tendo em conta que todo este mecanismo é criado de base, é necessário o projeto mecânico das ligações para acoplar os diversos constituintes, tornando-a numa peça só. Para isto é utilizado o software *Autodesk Inventor Profissional 2020* para desenvolvimento de CAD. Posteriormente, utilizou-se o software *Ultimaker Cura 4.5* para proceder a impressão tri-dimensional (3D) dos vários suportes criados.

Embora o protótipo criado tenha realizado aquilo a que foi proposto, poderá haver possíveis melhorias que poderão tornar o mecanismo mais ergonómico e mais resistente.

Palavras-chave: [*Indústria 4.0*], [Robótica], [Pneumática], [Sensor de Força], [Polimento], [Impressão 3D].

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List of Symbols

2D - Two-dimensional

3D - Three-dimensional

Acronyms/Abbreviations

ABS - Acrylonitrile Butadiene Styrene

ACF - Active Contact Flange

CAD - Computer Aided Design

CPS - Cyber Physical Systems

DEM - Department of Mechanical Engineering

FDM - Fused Deposition Modeling

GND - Ground

GDP - Gross Domestic Product

IoT - Internet of Things

PC - Polycarbonates

PLA - Polyactic Acid

PVA - Polyvinyl Alcohol

USB - Universal Serial Bus

Wi-Fi - Wireless Fidelity

1. INTRODUCTION

Nowadays the word “industry” is present in every aspect of our daily life that we do not even question its meaning. Do we really know what industry is? What is an industry? Apparently it seems to be something simple to answer using the memory of something that we have present as a physical structure or a product that comes from it.

Figure 1.1. Industrial Environment. Source: https://www.prominent.pt/pt/Solu%C3%A7%C3%B5es-por-setores/Solu%C3%A7%C3%B5es-por-setores/Ind%C3%BAstria-qu%C3%ADmica/Ind%C3%BAstria-qu%C3%ADmica.html

According to the Oxford Dictionary, industry is defined as *“Economic activity concerned with the processing of raw materials and manufacture of goods in factories”* (US Dictionary LEXICO Powered by Oxford, 2020).

Industry was born in England during the First Industrial Revolution in the 17th century, spreading to Western Europe and the United States in little time. It marked the transition of the handmade production to the use of factories. It has resulted in a paradigm shift considerably reducing the production times practiced so far.

In the mid-19th century it took place the Second Industrial Revolution characterized by the big developments at a chemical and electrical level, as well as the valorisation of the oil, as an energy source. The increasing use of electricity has boosted mass production and people have become more urban.

The creation of the diode and sylicium transistor brought the possibility of designing all kinds of electronic components. This leads to the Third Industrial Revolution, also called the Digital Revolution, which was marked by the strong computerization and automatization of the systems. The production has become more efficient and predictable.

Unlike the previous revolutions, the Fourth Industrial Revolution resulted in a stated need. The word *industry 4.0* originated in a strategic project from the German Government, being for the first time mentioned in the Hannover Fair, in 2011 (Kagermann et al., 2011). After this, a work group headed by Siegfried Dais and Henning Kagermann presented a series of measures to follow by the German Government. They wanted to make the industrial process more optimised and consequently boost the profits of the organizations.

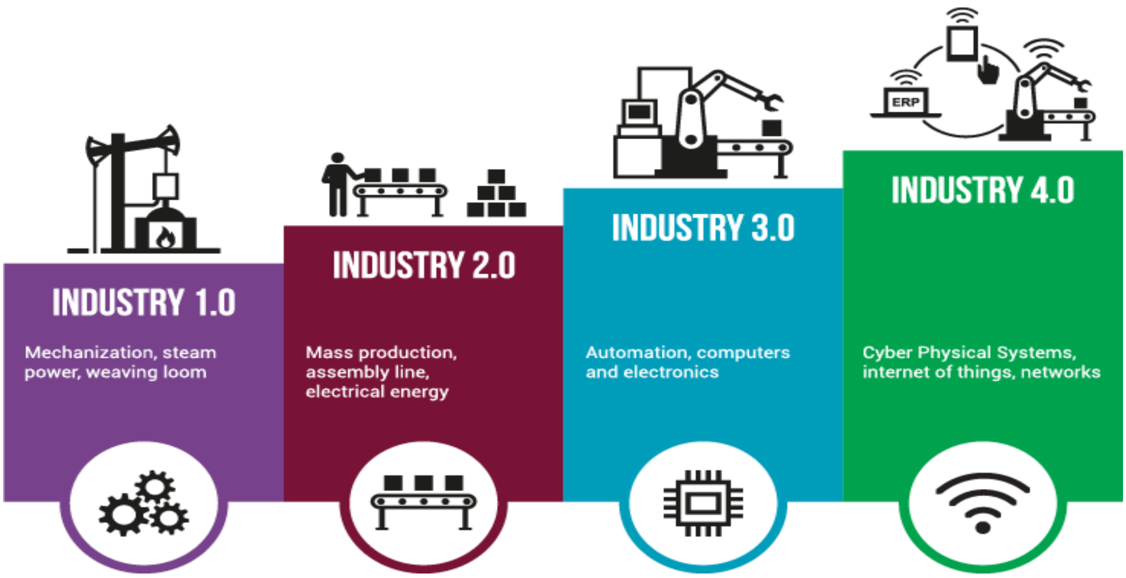

Figure 1.2. Industrial Evolution. Source: https://www.automationworld.com/factory/iiot/blog/13318945/industry-40what-does-it-mean-to-your-operations

Kagermann et al. (2011) consider that the extension of the concept of networking, process of digitisation using Internet of Things (IoT) and autonomous decision will change the paradigm so far imposed. Up to now verification of operations and the decision making by the human part will be passed to the machine. The final product will have the information to be given to the process of production, being the machine autonomous in its decision. They point out the potential of the Fourth Industrial Revolution not only in the industrial sector with the optimization of the process, but also in the service sector, that will suffer improvements. The creation of the “Internet of Services” will bring a constant connection of the service with the network with greater convenience, greater efficiency and easier troubleshooting and resolution. As an example, Tesla is in constant sourcing of updating the software with their products.

For Erboz (2017) the evolution of the traditional industry to an integrated, autonomous and optimised industry is dependent on nine pillars:

- Big Data and Analytics;
- Autonomous Robots;
- Simulation;
- System Integration: Horizontal and Vertical System Integration;
- The Industrial Internet of Things;
- Cyber security and Cyber Physical Systems (CPS);
- The Cloud;
- Additive Manufacturing;
- Augmented Reality.

Lasi et al. (2014) point out a tendency of equipment reduction. While computers and process machinery demanded a specific significant space, the current devices with an equal or better performance can be put on a short area giving the possibility of an advantage in the production field and in the logistics. The word “Intelligent Factory” will appear where the production will be totally equipped with sensors, actuators and autonomous systems using “smart technology” that will be controlled by an autonomous way.

The new technologies, like the 3D printing, are seen as key technologies and will facilitate the appearance of new products and technologies. They allow entrepreneurs to bring their ideas “to reality” without the time constraints resulting from the dependence of others in the prototype process. Small business creation is also facilitated because initial cost is lower (Anderson, 2012).

Schwab (2017), responsible for the “World Economic Forum”, classifies several technologies as promoters of the Fourth Industrial Revolution. Autonomous vehicles, 3D printing, advanced robotic and the study of new materials depend on the reinforcement of the digital capacity.

1.1. Motivation

As discussed earlier, robotic as well as automation, like 3D printing, will have an important role in the future of industry.

"Machines are substituting for more types of human labor than ever before. As they replicate themselves, they are also creating more capital. This means that the real winers of the future will not be the providers of cheap labor or the owners of ordinary capital, both of whom will be increasingly squeezed by automation. Fortune will instead favor a third group: those who can innovate and create new products, services, and business models (Brynjolfsson et al., 2014).

According to a report done by the PwC company, it was estimated that by 2030 artificial intelligence and robotics could contribute up to 14% to global Gross Domestic Product (GDP).

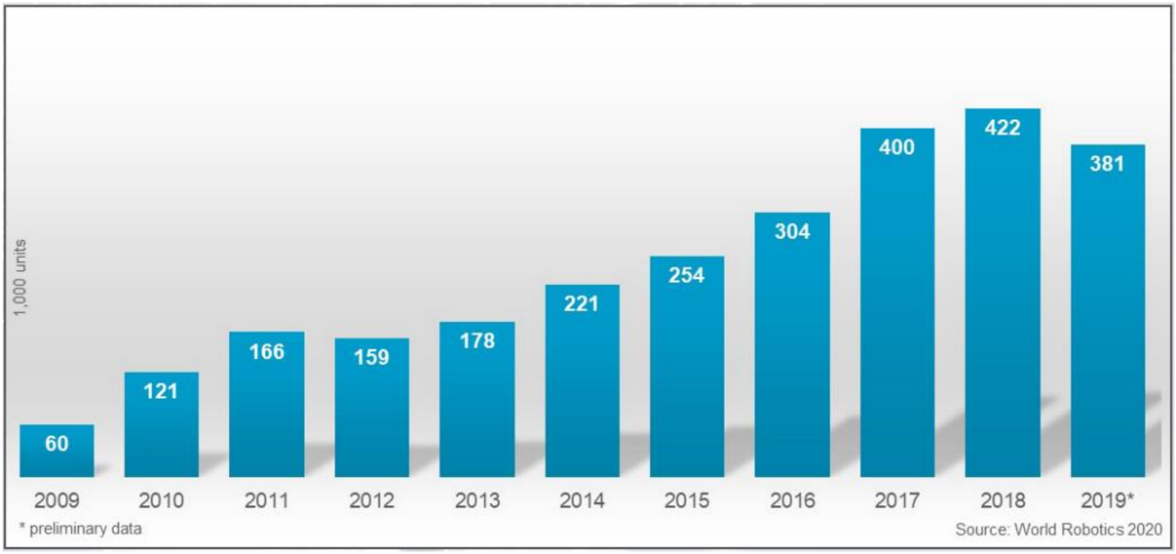

Figure 1.3. Annual installations of industrial robots in world. Source: https://ifr.org/img/office/World_Robotics_2020_Sales_Flyer.pdf

The previous figure, provided by the International Federation of Robotics, shows the evolution of the number of robots installed between 2009 and 2019. In the last year there has been a fall that is contrary to the growing trend of the previous six years. This can be explained by the commercial conflict between China and the United States. About 28% of the robots installed are intended for the automotive industry, with 24% electrical, with the metal and machine industry concentrating 12%.

Figure 1.4 shows the number of industrial robots in the years 2017 to 2019 distributed throughout the various sectors of activity. This confirms the importance of the automotive and electronic sector in the implementation of robotics.

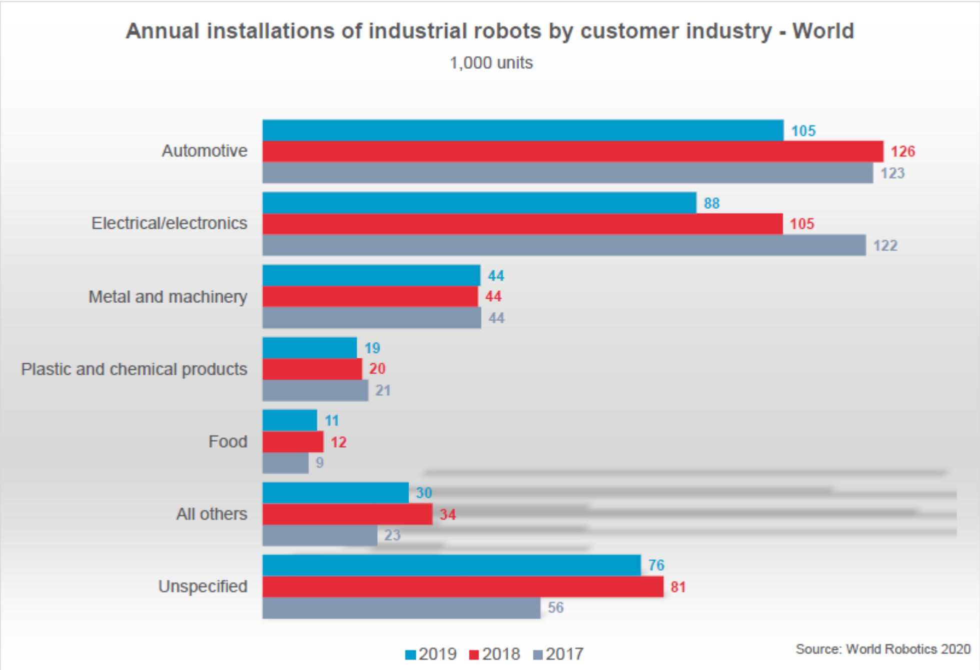

Figure 1.4. Annual installations of industrial robots by customer industry.
Source: https://ifr.org/img/worldrobotics/Executive_Summary_WR_2020_Industrial_Robots_1.pdf

This dissertation focusses on the development of an active force control system. It is intended to create a system that coupled to a robotic arm can perform several functions that many of them are currently performed by humans.

Siciliano et al. (2009) consider the force control as one of the fundamental requirements for the success of a task when performed by robotics means. High forces values are undesirable as they can call into question both the manipulator and the manipulated object. Typical examples include polishing, deburring, machining or assembly.

Fan et al. (2019) states that there are several methods studied and proposed by several researchers in order to control the contact force in robotic polishing.

The robot used in this dissertation was *ABB IR 140* illustrated in Figure 1.5. It is a compact and multifunctional 6 axis robot with a range of 810 mm. It moves a payload of 6 kg and it has a collision detection function which ensures that the robot is reliable and safe. It is suitable for a variety of applications and can be mounted in various positions and containing all various mechanical arms protected by *IP67*. According to the builder, this robot has as main applications:

- Arc welding;
- Assembley;
- Cleaning/Spraying;
- Machine tending;
- Material handling;
- Packing;
- Deburring.

Figure 1.5. Industrial Robot *ABB IR 140.* Source: https://new.abb.com/products/robotics/industrial-robots/irb-140.

The choice of this robot is justified by being one of the robotic arms available in the Robotics Laboratory of the Department of Mechanical Engineering (DEM) of the University of Coimbra. Nevertheless, the intention is to elaborate a universal system that could be used in any model of any brand.

To Kalt et al. (2016) despite the robotization of many of the industrial processes, they consider that there are still manual operations such as polishing where automation has only been partially imposed. The complexity and complex geometry of most parts has complicated this statement. There are few industries where robotic polishing is implanted as a routine production process, as it happens in the aeronautical industry. Mechanical finishing is critical for surface quality and final part geometry, and it can represent about 1/3 of the total production time. Manual polishing requires skilled labour and a lot of experience. It is considered that to develop an automated system it is necessary to understand the human skills in the process.

One of the tasks they had in the genesis of the elaboration of this mechanism was polishing. It is considered that the force applied during the polishing process plays an important role in performing a good finish. For this reason, tests to the system will be carried out using a polishing tool.

1.2. Objectives

The purpose of this study is to explain the process of developing an automatic and programmable active force control system for the industrial context.

The main objectives will be:

- Selection of the various constituent elements of the system hardware;
- Selection of electrical control elements and pneumatic connections.
- Create mechanical interface with the selected robot using Computer Aided Design (CAD) software;
- Printing planning the of prototypes mechanical parts.

To ensure that the full extent of the work is understood, the reader should consult the dissertation written by Fernandes (2020), where software and interface development is addressed. Finally, the simulation and application of the mechanism is explained by Gomes (2020).

1.3. Assumptions

Starting from scratch to create a system, there are various of possibilities for its creation. It is conceivable to say that it is possible to make a process in more than one way.

In order to simplify the creation process, it was based on several assumptions:

- As it is a system to be implemented in the industrial environment, the force will be generated on the pneumatic form;
- It will be necessary to select a pneumatic actuator cylinder. Knowing that the forces to which it will be subject may involve lateral efforts, it is required that it has a reinforced rod;
- A pressure regulator will be responsible for the control of the applied force;
- An electrovalve will be responsible for the inlet and outlet of air in the actuator cylinder;
- The electronic control shall be carried out with the use of an *Arduino* board;
- Being the Robot *ABB IR 140* the selected one, the maximum working force will be 6kg (mechanism weight + force applied).

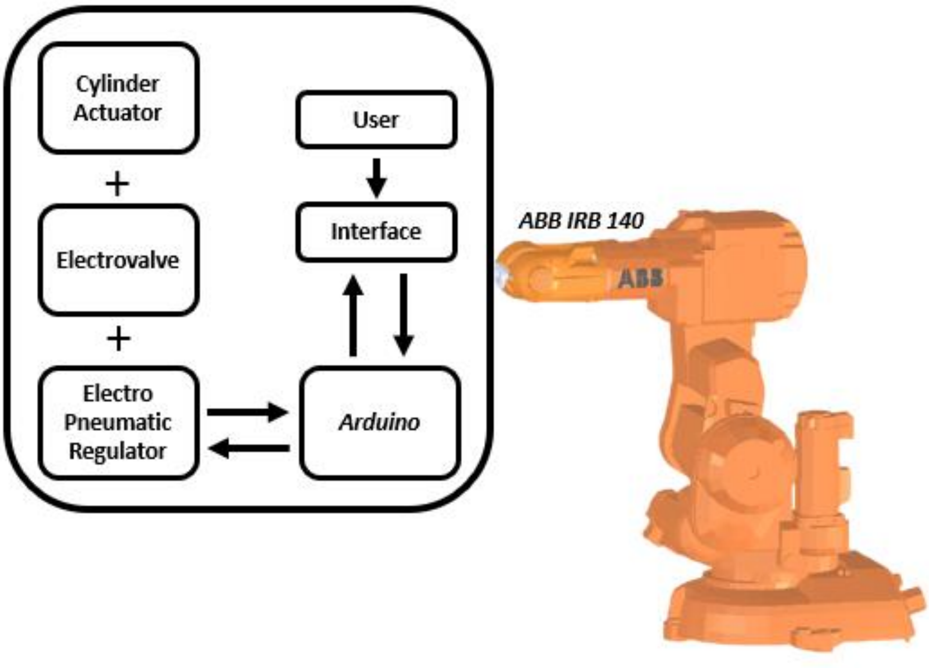

Figure 1.6. System Plan

1.4. Chapters organization

In the following text the structure of the dissertation and division of the chapters will be addressed. This dissertation is divided into nine chapters:

- Chapter 1: This chapter presents the motivation, objectives and also premises of this work;
- Chapter 2: It presents an analysis of the state of the art of the concepts used in this work as well as the studies conducted by other authors;
- Chapter 3: This chapter addresses the tools used in this work and their characteristics;
- Chapter 4: Pneumatic and electronic communication between the various components is explained in this chapter;
- Chapter 5: In this chapter the used software's are presented;
- Chapter 6: Mechanical Project and all parts drawn using CAD software is demonstrated;
- Chapter 7: The prototype printing process is shown;
- Chapter 8: The experimental tests and result are demonstrated;
- Chapter 9: Conclusion and future work.

2. STATE OF THE ART

As mentioned earlier, in this chapter will be address a theoretical basis of the concepts and technologies used in this dissertation. It seeks to have an overview of what already exists in the market and possible improvements that can be implemented.

2.1. Robotics

Siciliano et al. (2009) define robotics as the study of the machines which can replace the human being in the execution of tasks, and these can be physical activities as well as decision making. Over the years, the human being has tried to find substitutes capable of replicating their behaviours and carrying out their activities. This wish has in the beginning economic, social, philosophic and scientific motivations.

The use of robots by the industrial environment has been suffering an increasing evolution as there are many industrial fractions totally automated, mainly in the automotive and electronic area. Due to some tasks being done in aggressive environments, it can lead to its automation, as is the case of weld, painting, sanding or polish (Silva, 1999).

According to an article published by Forbes magazine (Forbes, 2018), there were on average almost sixty-six industrial robots installed for ten thousand workers worldwide in 2015. In 2016 the South Korean industry relied on six hundred and thirty-one robots for ten thousand workers, resulting mainly from the installation of machinery in the electronic and manufacturing area. In countries with heavy automation industries, like Germany and Japan, it is estimated that there are almost three hundred robots for ten thousand workers.

The robot is a system which consists on a control unity, sensors and actuators (Figure 2.1) These last ones have the skill to practise an action being a robot locomotion or manipulation of the robotic arm. For example, electric motors, hydraulic cylinders, tyres, and so on. In the case of the sensors, they have the skill of perception both as an internal state of the mechanical system and as an external state of the environment where it lies. For example, force sensors, temperature, pressure and so on. The control system as its classification shows it is responsible for the decision, it is the "brain" of the machine. It is the responsible for doing the connection between the sensors and the actuators in a clever way. It receives the data from the several sensors (inputs) and according to the information received, the actuators will be commanded (outputs).

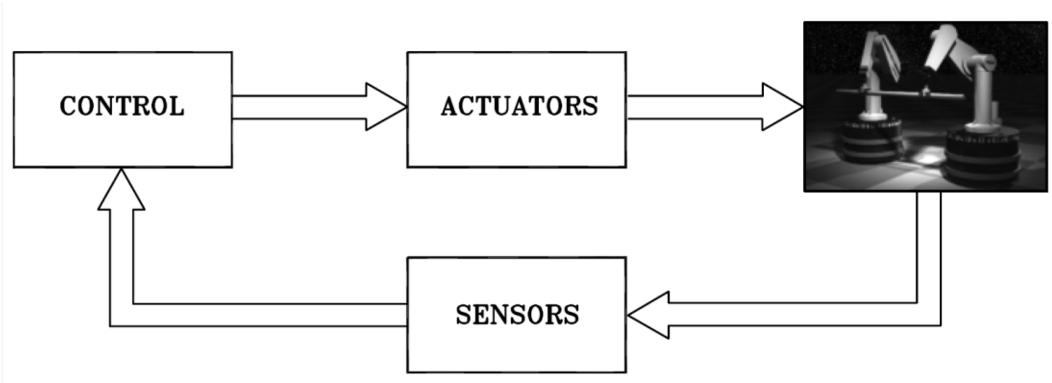

Figure 2.1. Components of a robotic system. Source: (Siciliano et al., 2009)

2.1.1. Robot types

Robots can be classified according to their mechanical structure or base typology. In the case of fixed-based robots, they are called manipulator robots and if their base is mobile, they are considered mobile robots.

In the case of mobile robots, their main feature is the possibility of movement in a particular environment. Due to their mobile base, these types of mechanisms are used in applications where an extensive autonomous movement is required. Within this type of mechanism, it is possible to distinguish two strands: mobile robots using wheels and legs. The most common are the robots which use a wheel system that provide movement in relation to the ground as shown in Figure 2.2.

Figure 2.2. *Mobile Robot MiR 200*. Source: https://cobots.ie/product/mobile-robots/mir200/

Manipulator robots are constituted by a sequence of rigid bodies (link) connected by joints. Links can change their position, there are several possible combinations according to the required applications. These elements are associated in series. Figure 2.3. exemplifies the *ABB IRB 140* robot, a manipulator robot, which will be used in the developing system as previously mentioned.

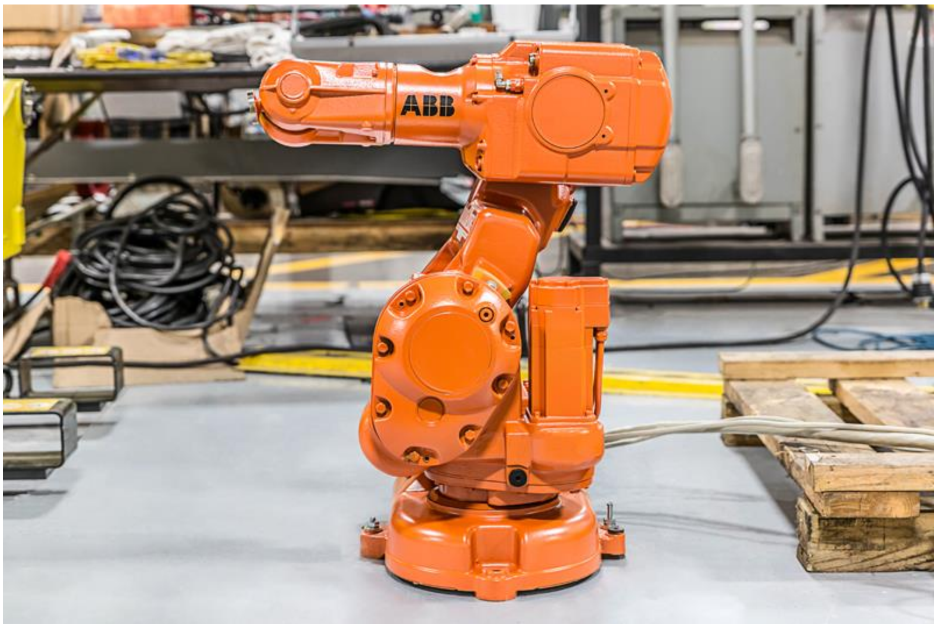

Figure 2.3. Robot Manipulador *ABB IRB 140*. Source: https://www.robots.com/robots/abb-irb-140

2.2. Pneumatics

The word pneumatics comes from the Greek word “pneuma” which means breath of life, blow, wind. Pneumatics is the branch of physics that studies the properties of gases, at rest or in motion (Dicionário Priberam da Língua Portuguesa, 2020).

Compressed air has long been used as an energy source, the first documented use reports to the year 280 BC. Over time compressed air has been widely applied as an energy source for pneumatic tool triggering.

Pneumatics plays a key role in industrial automation. The use of compressed air as an energy source has become appealing due to its characteristics: abundant in our atmosphere, easy transport and storage, safe, clean and allows high working speeds with low maintenance. The speed of pneumatic movements allows us to increase the pace of work and productivity, as well as to reduce fatigue accidents resulting from repetitive operations.

Saidur et al. (2010) mention that compressed air accounts for 10% of industrial electricity consumption in the European Union, with 9.4% used in China. Compressed air is considered one of the most expensive energy sources on the planet because only 19% of its power is usable. As such, it should only be used when there are safety improvements or significant gains in productivity.

Usually the pneumatic system implemented in an industry is composed by a compressor, the distribution line and ends in its application. Air is captured in the atmosphere, then is compressed under the action of a compressor and stored in a tank. It can also go through a dryer to remove excess water. It is then sent to the line that will distribute the outputs through space and it is in these outputs that the several mechanisms for the desired applications are applied. The following figure illustrates the previous described system.

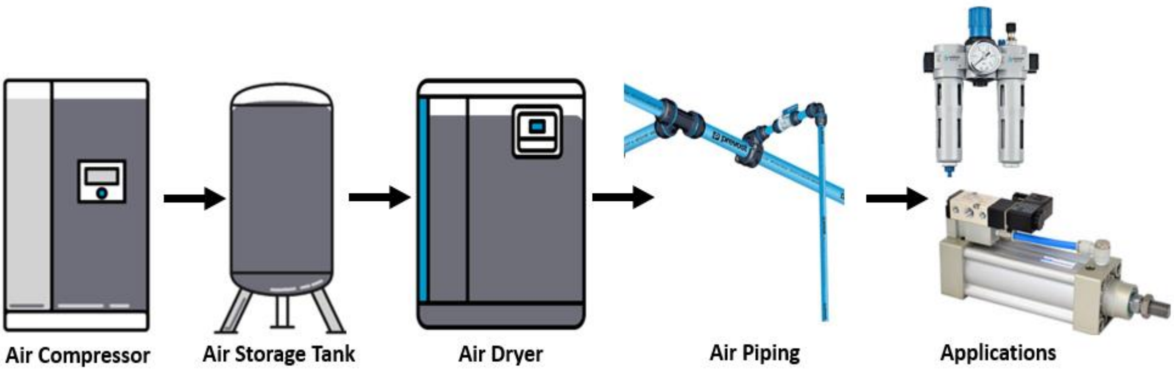

Figure 2.4. Air compressed system applied in the industry. Adapted from: https://www.atlascopco.com/en-tw/compressors/wiki/compressed-air-articles/what-is-condensate-in-air

2.2.1. Pneumatic Cylinder

As previously discussed, one of the main parts in the developing tool is the pneumatic cylinder. The cylinder will be powered with compressed air and it will be responsible for the force applied. In summary, the compressed air is responsible for the back and forward movement of the cylinder rod. Its most important characteristics are the diameter and the cylinder stroke. Greater diameter implies greater applied strength, but in the case of the course it refers to the distance between the maximum progress and the maximum retreat is done. The applied force by a cylinder is easily calculated by multiplying the compressed air pressure by the piston area exposed to it.

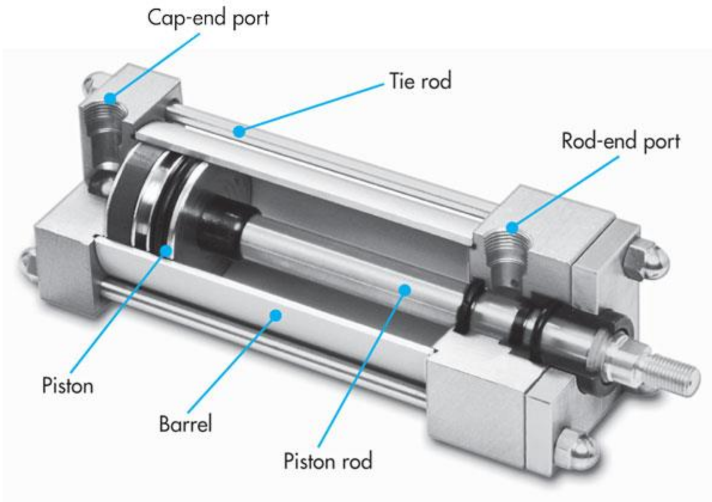

Figure 2.5. Pneumatic Cylinder specifications. Source: https://www.hydraulicspneumatics.com/technologies/cylinders-actuators/article/21885037/checklist-for-matching-air-cylinders-to-load-requirements

2.2.2. Pneumatic Electrovalve

Another pneumatic component required in the development of the tool under study is the electro valve or solenoid.

The electro valve is a valve that through an electronic control has the function of controlling the fluid flow that passes through itself. The solenoid valve can be used to close, dose, distribute or mix the fluid flow depending on the number of positions and ways. The control is carried out by an electric signal, depending on its value and changes in the transition of the flow will be visible. When the coil receives the electrical signal, a magnetic field is created that makes the plunger move and after the signal is over, the valve returns to its initial state.

The following figure shows an electronically controlled five-way and two positions valve.

Figure 2.6. 5/2 way Solenoid Valve. Source: https://www.hqc-tools.com/shop/solenoid-valves/52-way-solenoid-valve/4v210-08npt/

For understanding the operation of the electrovalve illustrated before, a working plan is made available. The following figure shows the two operating positions. Position 2 corresponds to activation and the starting position is represented at position 1.

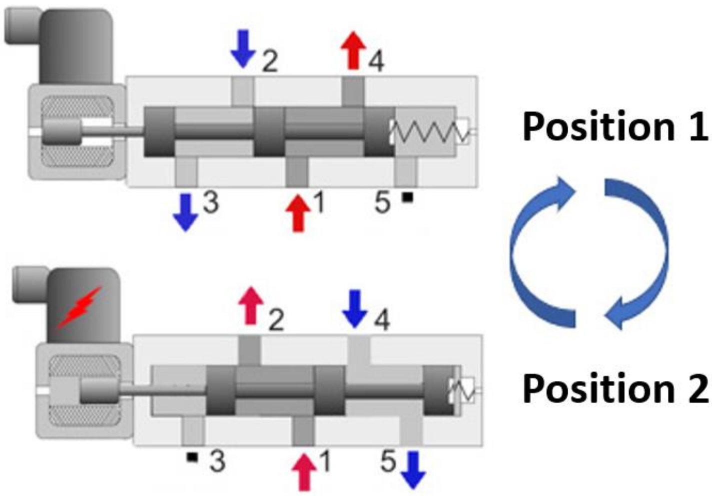

Figure 2.7. 5/2 way valve diagram. Adapted: https://www.mtibrasil.com.br/como-funciona-valvula-solenoide-52.php

2.2.3. Electro-Pneumatic Regulator

In the pneumatic device in development, it is necessary to have a precise control of the compressed air pressure as this is the only way to guarantee that the subsequently applied force is properly controlled. For this desired function, an electronic control pressure regulator will be selected that has the function of controlling the air inlet and outlet in order to have the proper pressure.

Despite the power signal, the regulator requires an input signal. This electrical sign will correspond to a pressure value. Briefly, the pressure value is controlled in proportion to a selected electrical sign, which can be given in current (A) or voltage (V).

Figure 2.8. High Pressure Electro- Pneumatic Regulator. Source: https://www.smc.eu/en-eu/products/itvh-high-pressure-electro-pneumatic-regulator-3-0-mpa~134585~cfg.

2.3. Software and Eletrical control

As previously mentioned, it is intended to control the electronic components using an *Arduino* board that will be responsible for the electronic management of the pneumatic components previously described. The choice fell on this boar due to the simple use, low cost and wide range of software and hardware.

The *Arduino* boards can read the input signals and transform them into an output signal, thus begin possible to create automatic systems. An example of a basic automatic system is a motion sensor that activates a lighting. In this case the motion sensor is responsible for sending the input signal to the *Arduino* board and then depending on this signal and what has been programmed, there will be an output signal (lighting on or not). This is illustrated in the following figure.

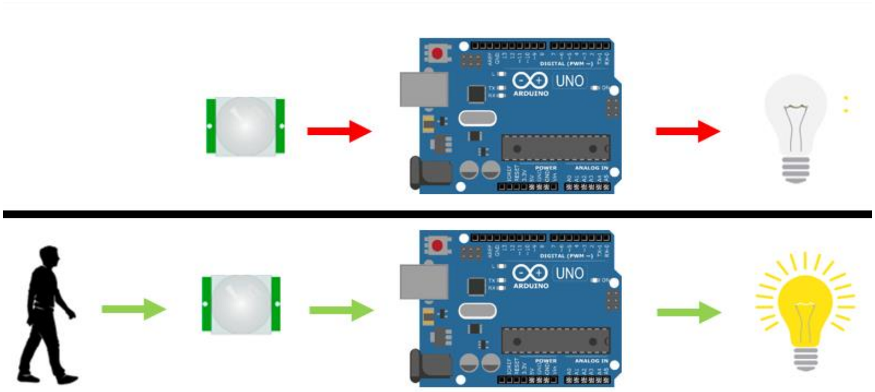

Figure 2.9. Example of using an *Arduino* board with a motion sensor that controls lightining.

Once again the reader is alerted to the reading of the dissertation of Fernandes (2020) where the aspects relating to electronics, control software and interface will be addressed in detail.

2.4. Force control

The force control in a robotic environment is something that presents great importance in order to not put at risk the elements present in a task. As expected, there are several mechanisms and techniques on the market capable of measuring and controlling the force applied by a robotic arm. Some of these mechanisms will be shown below.

2.4.1. Force sensor On Robot

The following figure demonstrates the *Onrobot* brand's force/binary sensor. This is a 6-axis sensor that according to the manufacturer provides accurate force and torque measurements along the 6 axes. It guarantees a precise control that determines for the execution of certain tasks such as assembly, polishing, grinding or deburring.

According to what *OnRobot* says, they are ideal especially for surface finishing tasks that require a constant speed and force during the whole finishing process. It is also said that they are designed to adapt to most of today's industrial robots.

This sensor, depending on the model, has a nominal capacity of 200N and up to 20Nm according to one of the axes. It requires a power supply in the [7-24V] range and above the nominal capacity the reading is not accurate.

Figure 2.10. Force sensor *OnRobot HEX*. Source: https://onrobot.com/pt-pt/produtos/sensor-de-forca-binario-hex-de-6-eixos

In this brief presentation the *OnRobots* brand sensor was used as an example, however there are other brands that sell sensors with similar functioning and characteristics.

2.4.2. Active Contact Flange

Active Contact Flange (ACF) is an equipment adaptable to a robotic arm with the ability to measure the force applied by it. It presents applications at all industrial levels with great emphasis in the automotive industry and also in aeronautics. Built for both the surface treatments of the most delicate materials and for sensitive handling of parts it allows working up to a maximum force of 800N. This tool is illustrated in the following picture.

Figure 2.11. *Ferrobotics Active Contact Flange* ACF121. Source: https://www.directindustry.com/prod/ferrobotics-compliant-robotic-technology-gmbh/product-88538-1045477.html

The use of compressed air in its operation is a point that differs from the previous type of force sensor shown. It is through the air pressure that the force subsequently applied is generated. ACFs adapt to surfaces with very complex morphologies and can measure the force to be applied on the material. They are capable of adapting to opposite forces, as when a surface movement occurs.

According to Carneiro & Almeida (2013) pneumatic actuators have advantages over electrical or hydraulic ones as they do not produce significant magnetic or thermal fields allied to an excellent power/weight ratio and low cost.

2.5. Polishing operations

Polishing consists in removing a thin layer of material by means of abrasive tools in order to obtain a uniform surface finish distributed over the entire surface of the part. Besides improving the surface quality, polishing can be very important in the final performance of the part.

For Bogue (2009) the robotic systems used in finishing have little functional similarity with other industrial applications that normally only perform one function. Finishing robots are responsible for several processes and use different tools. Each one of these tools may require different paths and process parameters such as applied force and speed. One of these robots can normally handle up to eight different finishing tools.

Kalt et al. (2016) exemplified with water turbines the importance of polishing in the final task of the part because the main factor affecting the efficiency of these turbines is the friction between the water and the blades. The friction depends on the quality of the surface finish, so improving the roughness of the blade surface the friction will be lower and consequently there will be greater efficiency. It is also important to remind that decreasing the friction will also increase the useful life of the part because it will be less subject to efforts.

In a study carried out to understand the skills present in the manual polishing process, Kalt et al. (2016) reached the conclusions: "Three polishing patterns were identified in manual polishing operations (constant pressure, linear translation, and surface profiling)". Tactile as well as visual and auditory feedback is also used to control the process. The following figure illustrates the device used to record human characteristics in polishing.

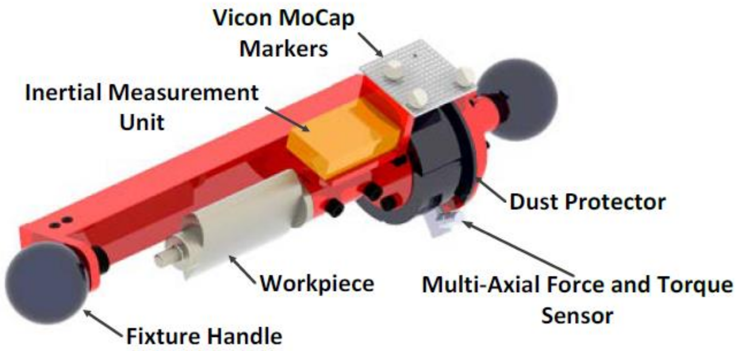

Figure 2.12. Device for capturing manual polishing parameters. Image taken from Kalt et al. (2016)

Mohsin et al. (2019) considers that polishing today requires a great deal of manual work, being time consuming, expensive and subject to errors. It is also responsible for creating risks to the respiratory health of workers and the solution to these problems will be robotic polishing.

2.6. 3D Printing

Seen as one of the technologies of the future, 3D printing or additive manufacturing as it is known consists on the process of creating a final object from a digital model created in CAD software or 3D scanning.

The creation of the printed object is performed by an additive process, depositing layers on layers and the parameters and characteristics of this layers may be adjusted.

Initially this technology focused only on polymers having also evolved to metallic and ceramic materials. Rapid prototyping is one of the great advantages of this process.

The application of 3D printing in the industrial context had a great effect making it possible to reduce the process times of prototypes from months to days or even hours. This acceleration allows for faster innovation and faster product launch (Rayna & Striukova, 2016).

Wang et al. (2017) exemplified the compatibility of this technique in aerospace applications. Because most components require complex geometries, the whole process is time consuming and costly to manufacture. Some parts are printed in 3D with metallic materials.

In this dissertation only the Fused Deposition Modeling (FDM) will be addressed because it is with this technique that the prototypes of the system under study are built.

essentially uses thermoplastics and elastomers. This process is based on heating the filament to a semi-liquid state, being later extruded layer by layer (Ngo et al., 2018). The quality of the final print depends on the print parameters (Figure 2.13).

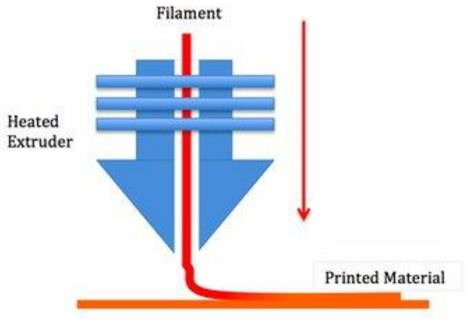

Figure 2.13 Exemplified 3D printing. Source: https://all3dp.com/2/fused-deposition-modeling-fdm-3d-printing-simply-explained//

The filament is heated and released by the extruder which will form overlapping layers until it reaches the projected shape (Figure 2.14).

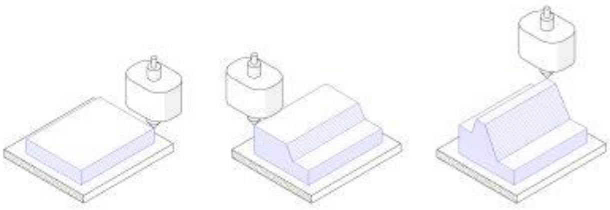

Figure 2.14 3D Additive Manufacturing. Source: https://www.3dhubs.com/guides/3d-printing/

The following figure demonstrates a scheme and constituents of a common FDM 3D printer used in household or laboratory environments.

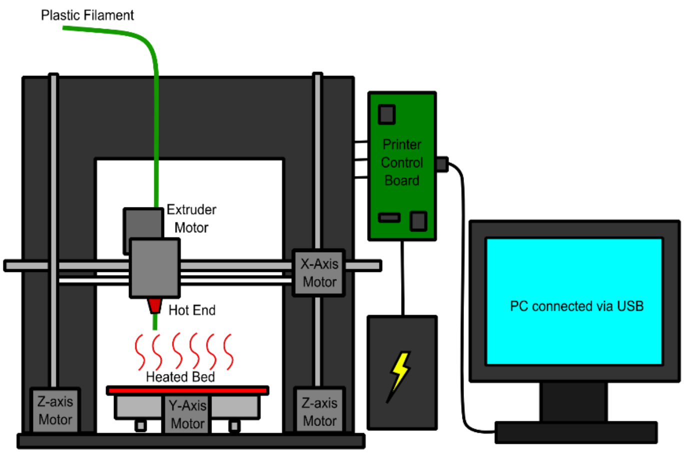

Figure 2.15 3D Printer Diagram. Source: http://suspensionarmor.lionsicilia.it/block-diagram-3d-printer.html

Wang et al. (2017) states that the polymeric materials commonly used in the form of filaments for extrusion are thermoplastics such as polycarbonates (PC), acrylonitrile butadiene styrene (ABS), Polyactic acid (PLA) and nylon. These have the main advantage of having a low melting point combined with a low cost, low strength and multi-material capability.

A thermoplastic is a polymer that at a certain temperature has a sufficient viscosity that allows it to be molded by maintaining the same shape after cool (Baeurle et al., 2006).

PLA is the main filament used in 3D printing because it has a lower printing temperature than opponents. It's a biogradable thermoplastic and its properties vary with the printing conditions (Wittbrodt & Pearce, 2015).

ABS has high fracture tenacity and impact resistance. It has low density.

In the case of the PC plastic this material has hight impact resistance, thus being used for applications that require high reliability. It presents better values of yielding stresses and fracture toughness than ABS and PLA

3. TOOLS

In this chapter are presented the components needed to this project and the criteria for choosing them is addressed.

For the reliability that the *SMC* brand presents it was chosen that all the pneumatic hardware be of that brand. Regarding the electronic control it was chosen as essentially components of *Arduino* brand.

3.1. *SMC MGPL40TF-25 AZ* Cylinder

Considering the importance of the actuator or pneumatic cylinder, the selection of parts began with it. Taking into account the nature of the efforts to which it would be subjected, something robust and compact was needed to support lateral load applications.

Within the entire *SMC* range, the choice was for the *MGPL40TF25AZ* model. This cylinder, besides the main stem, has two rods that serve as guides that safeguard the main stem when imposed to lateral forces, as can be seen in the subsequent figure.

Figure 3.1. *SMC* Cylinder. Source: https://cy.rsdelivers.com/product/smc/mgpm25tf-40z/smc-pneumatic-guided-cylinder-25mm-bore-40mm/7580718

It also has the following features:

- Main Rod Diameter: 40 mm;
- Piston Stroke 25 mm;
- Minimum/maximum pressure operating: 0.1/1 MPa;
- Piston Speed 50 to 500 mm/s;
- Cushioning Mechanical.

3.2. *SMC SY5120-5Dz-01F* Valve

After the choice of the pneumatic cylinder it was necessary to select a valve responsible for controlling the compressed air flow. As previously mentioned, the choice fell to a pneumatic valve for electronic control.

Wanting something that gives reliability to the system in design was selected a *SMC* brand solenoid valve of model *SY5120-5Dz-01F* illustrated in Figure 3.2.

It was intended a valve that had the responsibility to activate and deactivate the entry of compressed air in the cylinder being fed by 24V.

Its characteristics are:

- Type of actuation: 2 positions single;
- 5 ports;
- Solonoide Power Supply: 24V;
- Minimum/Maximum Operating Pressure: 0.15/0.7 MPa.

Figure 3.2. *SMC SY5120-5Dz-01F* Valve. Source: https://sa.rsdelivers.com/product/smc/sy5120-5dz-01f-q/smc-5-2-pneumatic-control-valve-solenoid-pilot-g/6862668

3.3. *SMC ITV0050-3BL* Regulator

In a system where the force applied by the cylinder is controlled, it is also necessary to control the pressure inside the cylinder. It is intended that the system be dynamic and in constant adaptation, always with the objective of a constant applied force.

Having said this, the need for an electronic pressure regulator that controls the air inlet and outlet has been verified. Taking into account the two pneumatic elements chosen and the required needs, the choice was for the *SMC* regulator *ITV 0050-3BL*.

The selected device has the following characteristics:

- Set pressure range: 0.001 to 0.9 MPa;

- Power Supply: 24V;
- Input signal: voltage type 0 to 10V;
- Electrical connection (4 connectors);
- Maximum Flow Rate: 6L/min;
- Maximum Input Pressure: 1 MPa.

Figure 3.3. *SMC ITV0000* Series Regulator. Source: https://mt.rsdelivers.com/product/smc/itv0050-0bs/compact-electronic-regulator-09-mpa/8732648

The connection cable of this regulator has four different connections: power supply, input and output signal and ground (GND).

3.4. Arduino MKR1000

Having selected a solenoid valve and an electronic pressure regulator it was necessary to create a programmable control system for these components. As previously mentioned, it was intended that the electronic components used were of *Arduino* brand.

The choice fell on the *Arduino MKR1000* board and its main feature is the Wireless Fidelity (Wi-Fi) connectivity.

The main features are:

- Board Power Supply: 5V;
- Circuit Operating Voltage: 3.3V.

Figure 3.4. *Arduino MKR 1000*. Source: https://store.arduino.cc/arduino-mkr1000-wifi

3.5. Arduino MKR Relay Proto Shield

In addition to the *MKR1000* board, the *MKR Relay Proto Shield* was also selected. This board provides two integrated relays and a small area to add other electronic components. The relays work as electromechanical switches.

The main features of this board are:

- Operating voltage: 3.3 V (supplied from the *MKR 1000*);
- Two *OMROM G5V13DC* relay.

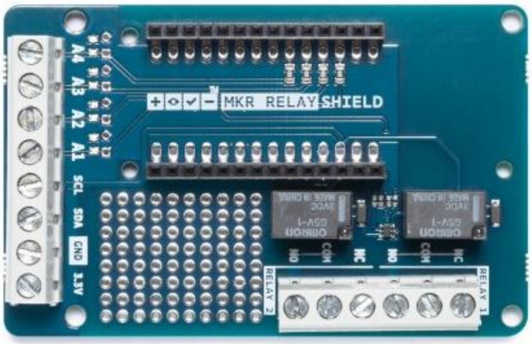

Figure 3.5. *Arduino MKR Relay Proto Shield*. Source: https://store.arduino.cc/arduino-mkr-relay-proto-shield.

3.6. Sparkfun I2C DAC Breakout MCP4725

The choice of boards for the electrical circuit ends with the selection of the following board, that works as a digital to analog signal converter.

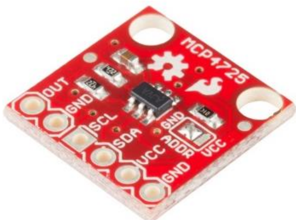

Figure 3.6. *SparkFun I2C DAC Breakout*. Source: https://www.sparkfun.com/products/12918

4. COMUNICATION

The following chapter serves as an explanation of the pneumatic and electronic communication between the various components used in this work. Schematics of the pneumatic and electrical circuits used will be represented.

4.1. Pneumatic Circuit

The existing pneumatic elements are cylinder, electrovalve and electro-pneumatic pressure regulator and these three components are interconnected.

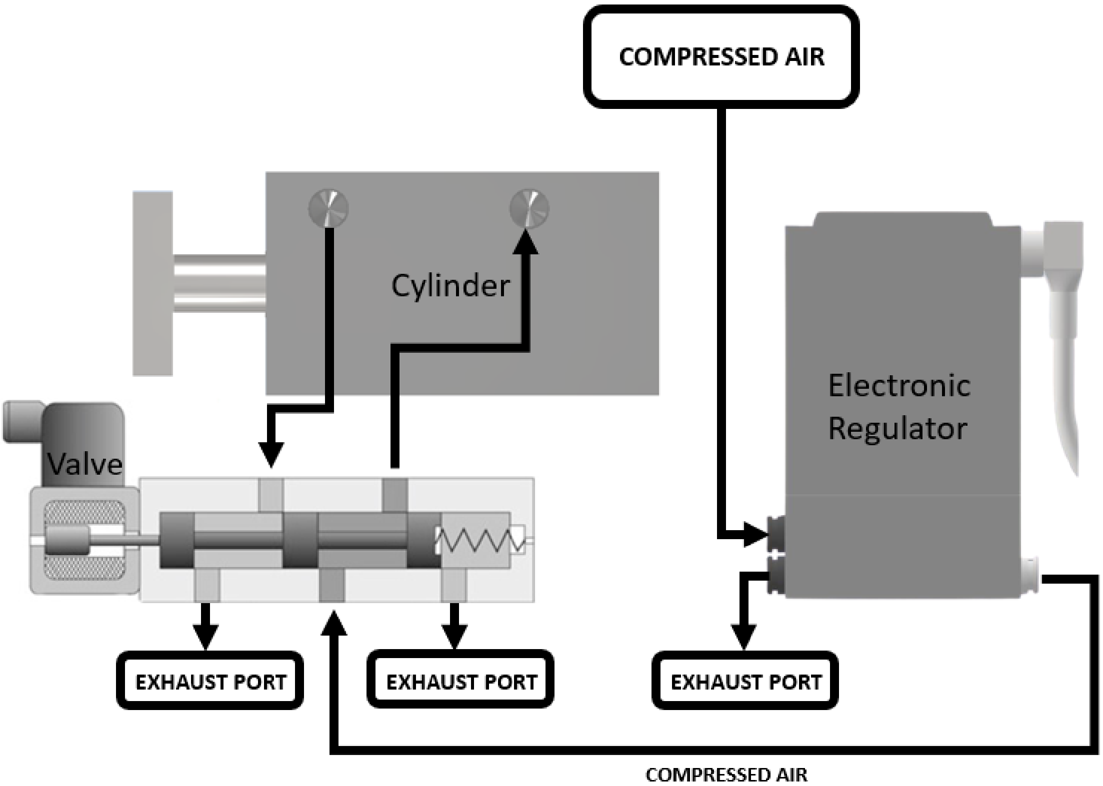

Figure 4.1. Pneumatic Circuit.

The pneumatic connections are schematized in the previous figure. The implantation of a pneumatic circuit requires a compressed air source as announced before. The compressed air intake is done through the electronic pressure regulator, being directed to the solenoid valve ending up entering the cylinder. In the figure are still represented the exhaust ports.

4.2. Eletronic Circuit

Regarding the electronic circuit, only a superficial approach will be made. The reader is once again advised to read the dissertation of Fernandes (2020) where this subject will be addressed in detail. This theme was only approached in this dissertation in view of important aspects in mechanical construction.

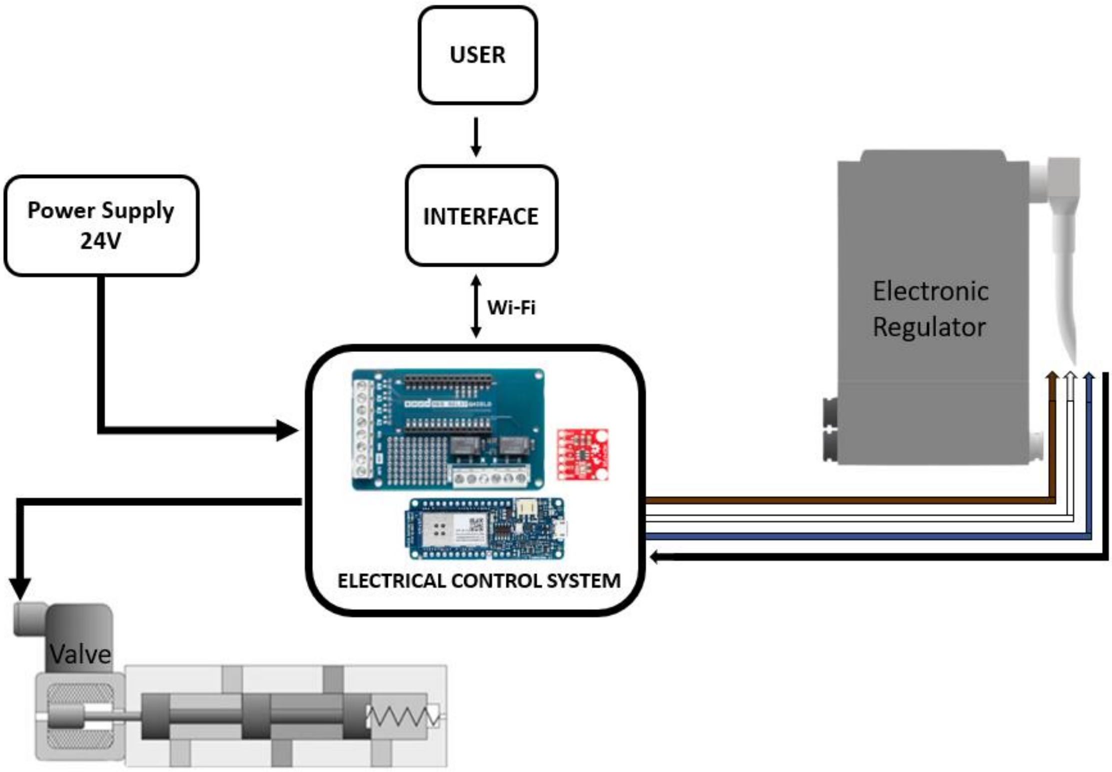

Figure 4.2. Electronic Circuit.

It is intended that all functionalities of the system are controlled through the interface. There will only be a 24 V power supply that will be connected to the Electronic Control System and from there the valve and the regulator will be supplied. Knowing that both operate at 24V and the *MKR1000* card at 3.3V, a voltage reduction system will have to be created.

The *Arduino MKR 1000* board allows Wi-Fi communication between the user and the electronic system.

The solenoid valve is controlled by a 24V signal having only two states on (=24V) and off to (=0V).

In the case of the electronic pressure regulator the scheme is more complex. The following table shows the correspondence between connectors and function performed.

Connector Colour	Function	Range
Brown	Power Supply	24V
White	Input Signal	0-10V
Blue	GND	-
Black	Output Signal	1-5V

Table 4.1. Eletronic Regular Connector's.

The pressure control is performed through a correspondence between a voltage value (V) and a pressure value. The user selects a desired force value that will be sent over the voltage form through the Signal Input. The drive returns a pressure value to the cylinder corresponding to the previous voltage.

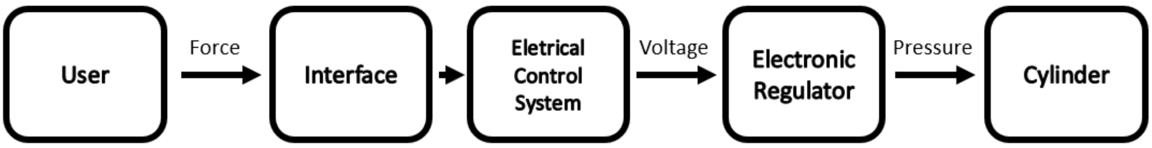

Figure 4.3. Input Signal's Diagram.

Regarding the Output Signal, its function is to return the real instantaneous force value resulting from the relation with the measured pressure.

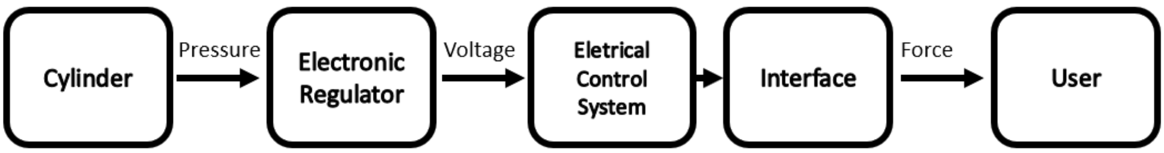

Figure 4.4. Output Signal's Diagram.

5. SOFTWARES

In this chapter the software used in this project will be discussed. It was necessary to create a series of links between the various hardware elements of the tool under development in order to couple everything.

First of all, the *Autodesk Inventor Professional 2020* CAD software was used. In it was possible to create all the necessary supports to fix the pneumatic and electronic components to the cylinder. Finally, the connections to the *ABB* robot and the future working tools were created.

Later, using the software *Ultimaker Cura 4.5*, the selection of the parameters and the printing simulation of the drawn part was carried out. This serves as a connection between the computer and the printer software.

5.1. Autodesk Inventor Professional 2020

Autodesk is an American multinational company responsible for the creation of a software for engineering, architecture and design activities. Its creation dates back to 1982.

The software used in this project, *Autodesk Inventor Professional* was developed in 1999, being its native version exclusive for *Windows*. It provides a number of tools for 3D mechanical design and simulation. It allows the creation and visualization of parts in 3D format, establishing the measurements and format intended by the user, as well as the assembly of several parts, forming mechanisms. Besides these features, the possibility of simulation is very important for mechanical design. Selecting a material for the drawn part, applying efforts in certain points of the part makes it possible to observe the capacity of the part when subjected to those forces and possible rupture. Compatibility with other CAD software is one of the advantages of its use compared to others.

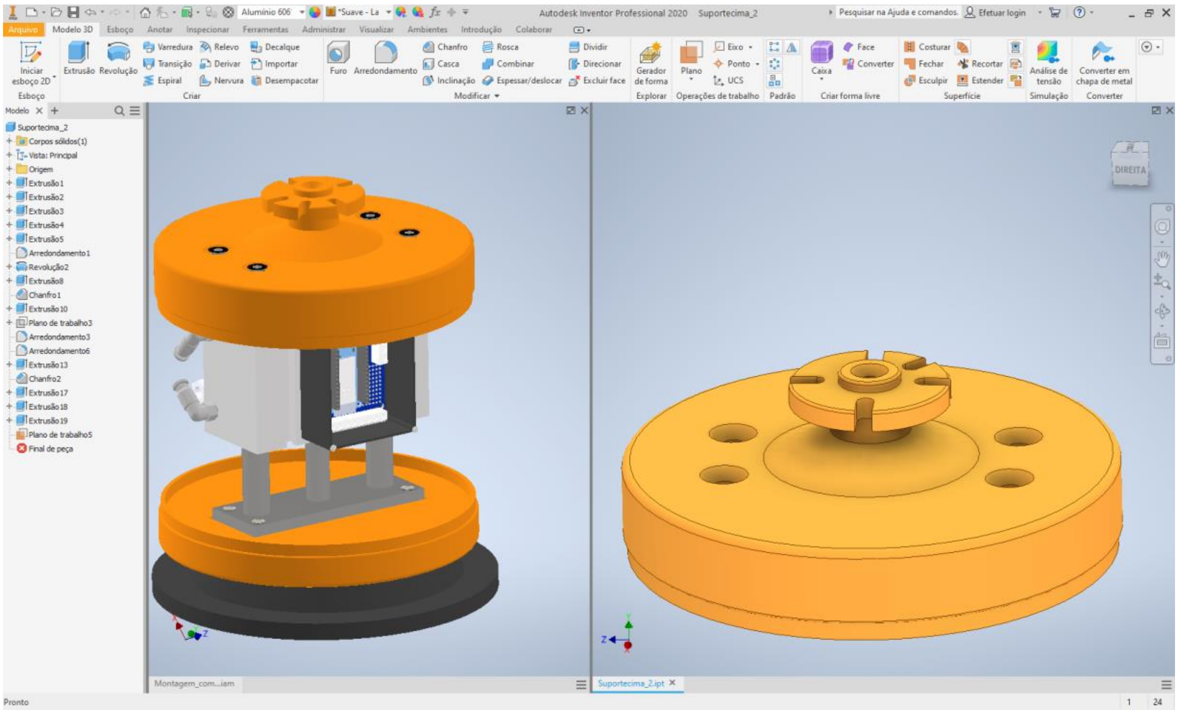

Figure 5.1. *Autodesk Inventor Profissional 2020* Desktop.

5.2. Ultimaker Cura 4.5

Cura is a software used in 3D printing of parts, allowing communication between the computer and the printer. It was created in mid-2014 and was later acquired by the printer brand *Ultimaker*, now called *Ultimaker Cura*. It is the software most used in this activity, being estimated to be used by about 2 million users weekly. This is benefited by the ease-of-use in different formats and can be used by both *Ultimaker* printers and other brands. It is also available in *Windows*, *Mac* and *Linux*.

It allows the user to select the printing specifications desired from infil density, printing temperature to the support structures of the printed part. There are a range of different configuration options, and the user must choose the one that best suits the project in question and the efforts to which it will be subject. The estimated time for printing, number of layers and paths made by the extruders are presented after the printing parameters have been selected.

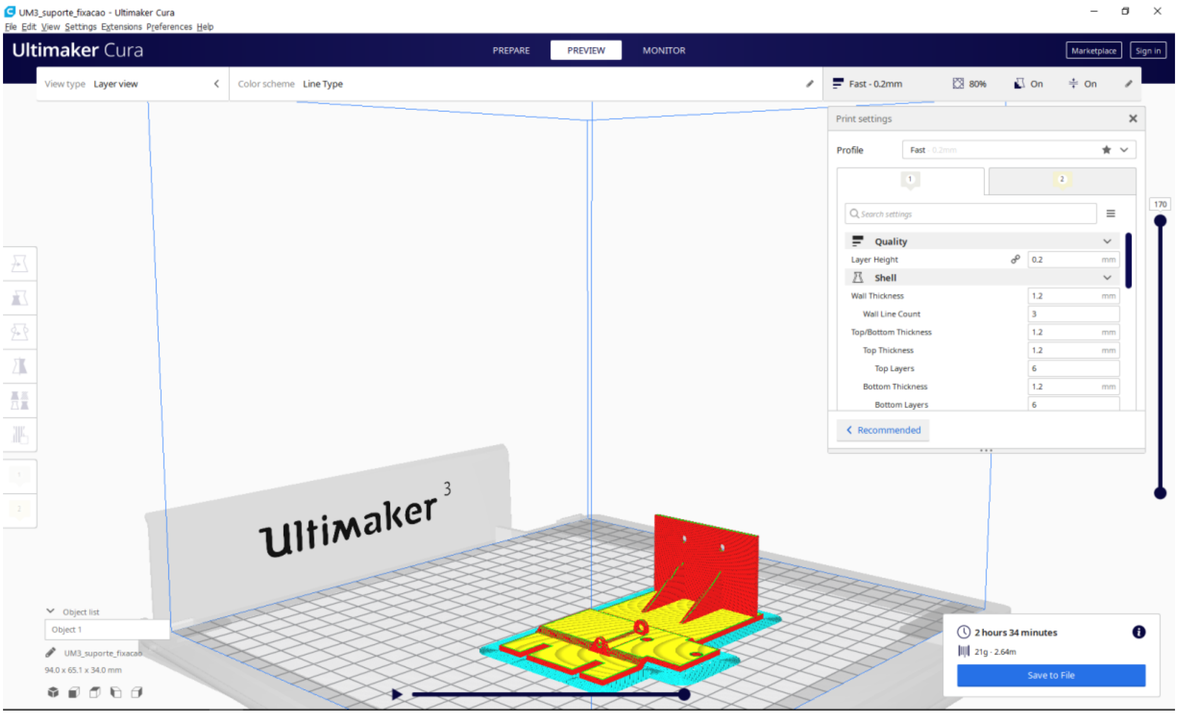

Figure 5.2. *Ultimaker Cura 4.5* Desktop.

6. MECHANICAL PROJECT

This chapter will be an approach to the CAD work developed. The supports that will work as a link between the various elements forming a compact tool will be illustrated. The 3D of the components purchased were obtained from the web pages of the brands.

6.1. Top Link: Robot-Cylinder

The following support (Figure 6.1) will work as a connection between the pneumatic cylinder and the *ABB IRB 140* robot. The connection between the bracket and the cylinder will be made using the threaded hole (M8*1.25mm) in the cylinder (Figure 6.2) and hexagon flat head socket bolts were used for better coupling.

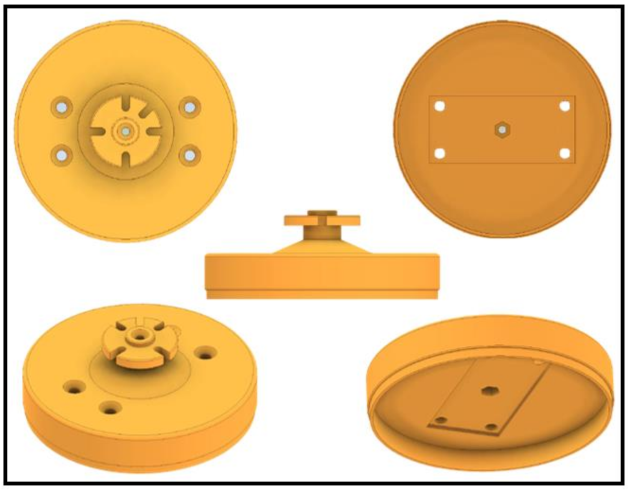

Figure 6.1. Top Link.

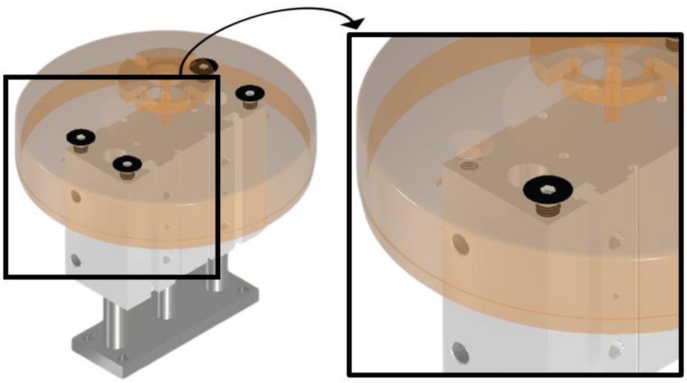

Figure 6.2. Bolted Connection.

The following figure illustrates the connection between the robot and the tool that is made through five M8x1.25 bolts (Figure 6.3).

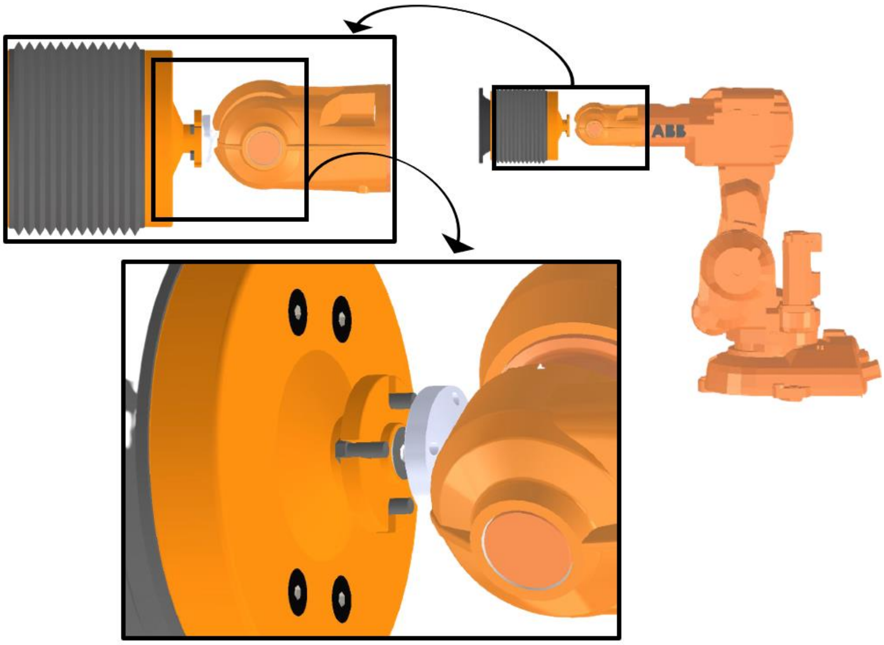

Figure 6.3. Connection to Robot *ABB IRB 140.*

Considering the connection to the robot as an area subject to great efforts, a bolt was introduced to serve as reinforcement (Figure 6.4). That part of the structure, when subjected to compression, will react better to the efforts resulting from the weight of the tool and the efforts resulting from the application at work. The previous reinforcement was done using a flat head M6x1mm bolt for a perfect connection.

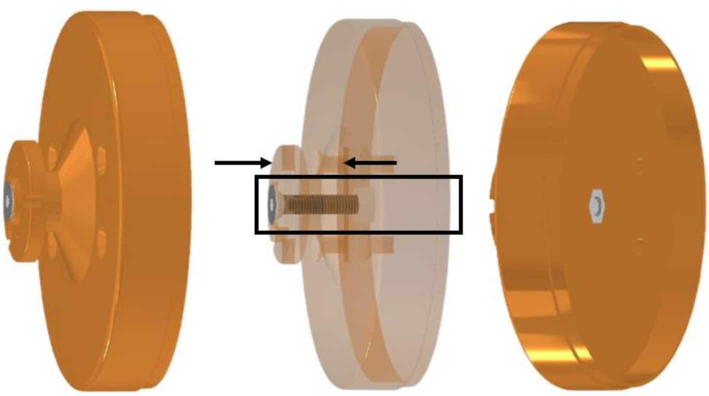

Figure 6.4. Reinforcement Bolt.

6.2. Bottom Link

The following structure will work as a cylinder connection and support for future work tools (Figure 6.5).

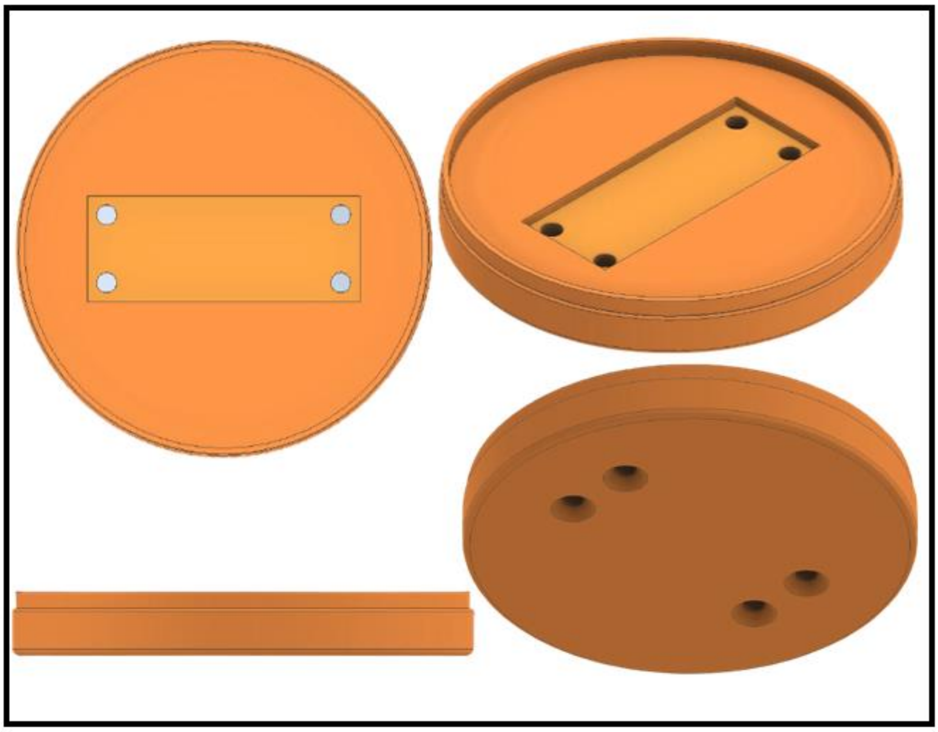

Figure 6.5. Bottom Link.

Once again the existing drilling in the cylinder will be used. This will be done by using four hexagonal flat head bolts (M8x1.25mm). This situation is demonstrated in the following figure.

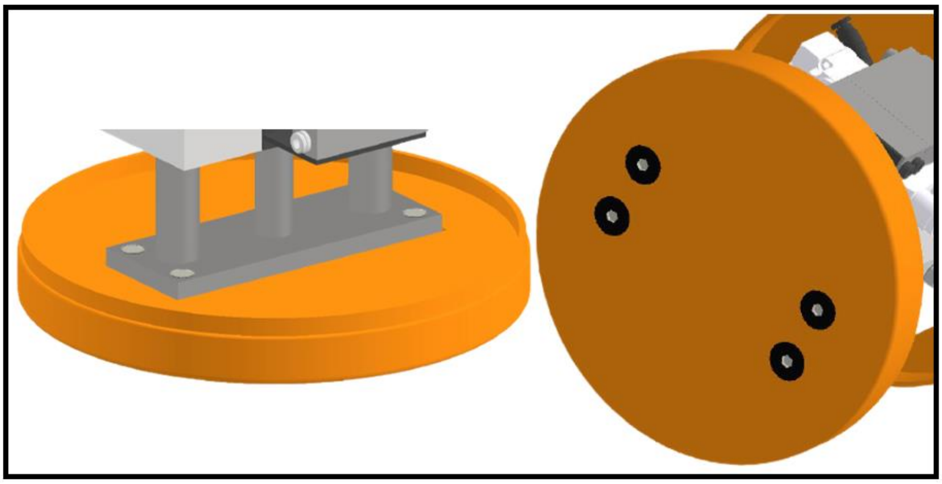

Figure 6.6. Bottom Link.

6.3. Link Valve- Regulator

The pneumatic control elements are fixed using the existing drilling in them and this fixing holes are signalized in the subsequent figure.

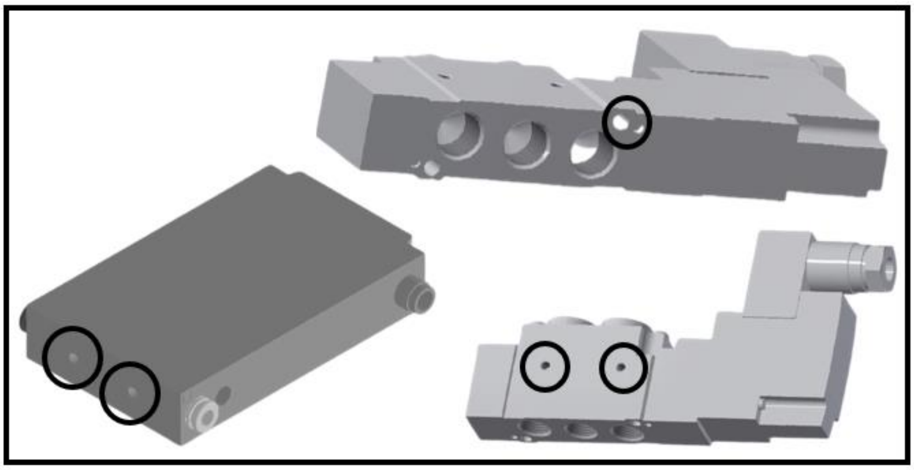

Figure 6.7. Regulator and Valve fixing holes.

The following bracket will be used, which will allow the solenoid valve and electric regulator to be attached to the cylinder body.

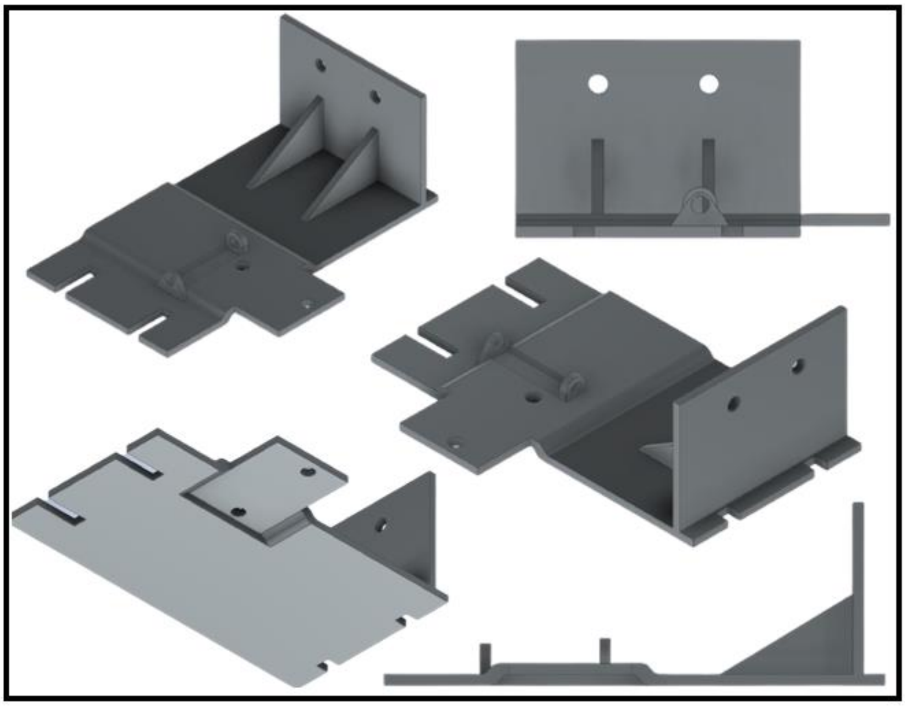

Figure 6.8. Link Valve Regulator representation.

The next figure illustrates the final support assembly with solenoid valve and electronic pressure regulator (Figure 6.9).

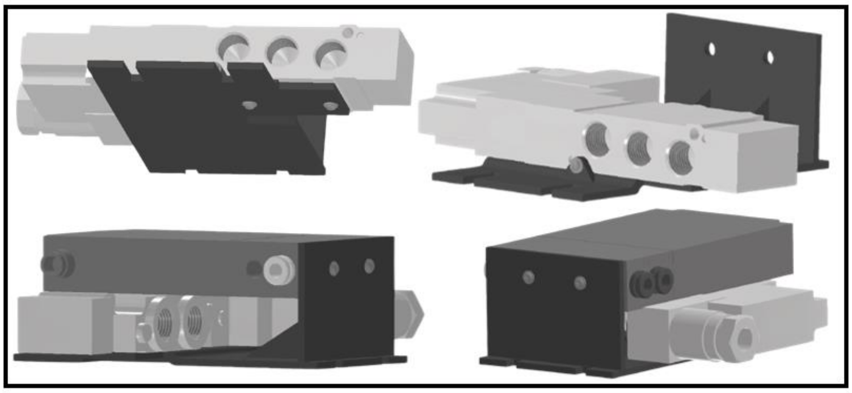

Figure 6.9. Link Assembly with regulator and valve.

The connection between the designed bracket and the cylinder is made using four *SMC D-M9B MGP-AZ* fasteners. These have the same profile as the holes in the cylinder body and available drilling.

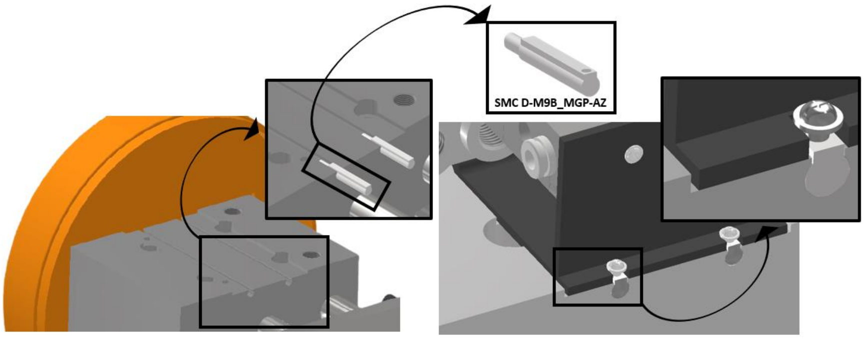

Figure 6.10. Link fixing to Cylinder body.

Round head bolts with washers are fixed to *SMC* fasteners to check the required fastening. The following figure shows the tightening scheme used.

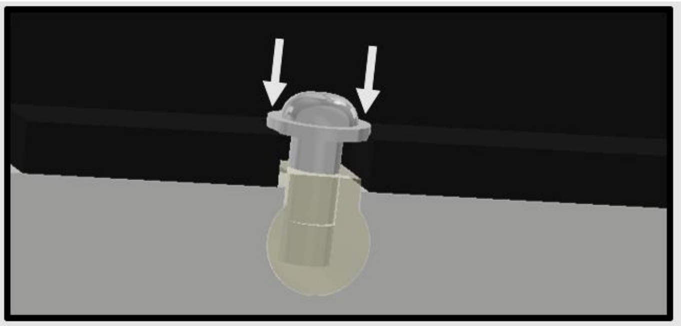

Figure 6.11. Bolt connection representation.

6.4. Eletronic Enclosure

In order to protect all the components of the electronic control system, a box with removable cover will be used.

After analysing the measurements of the various components, it was ascertained that the *Arduino MKR Relay Proto Shield* board would be the largest. As such these measurements will be used as a reference.

The following figure illustrates the box that will be used and that contain an opening for the wiring passage.

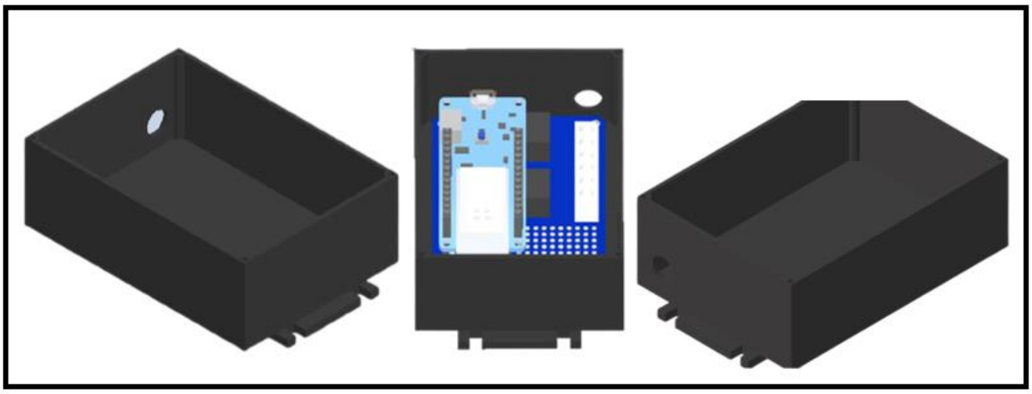

Figure 6.12. Eletronic Enclosure with *Arduino* board.

The method of attachment will be the same as the one used for the support of the pneumatic components. The fasteners supplied by *SMC* will be used and the result after mounting on the cylinder body will be as shown in Figure 6.13.

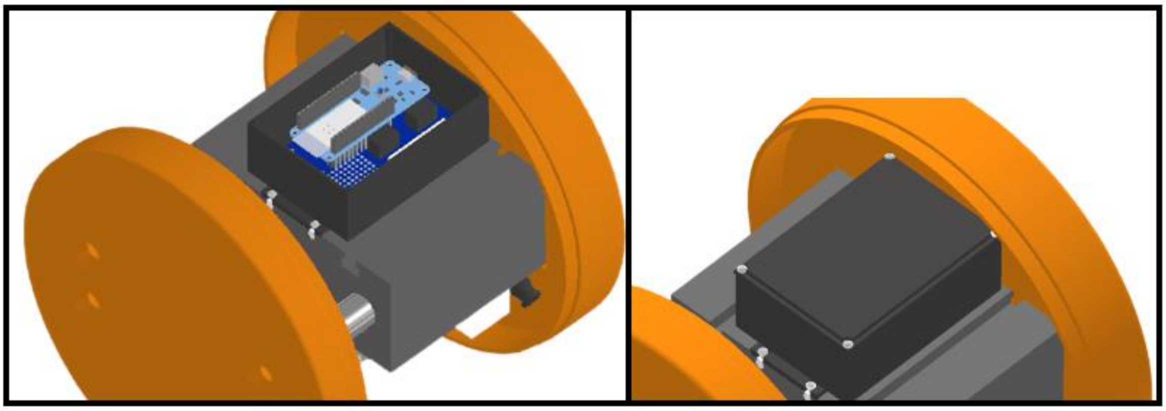

Figure 6.13. Eletrical enclosures assembly on Cylinder body.

6.5. Polish Backing Pad

As was originally stated, one of the purposes of the active force control device was the polishing tasks. It was intended that the tests to be carried out should have this aspect. This being said, a support for elements used in polishing such as sandpapers or polishing bonnets was created (Figure 6.14).

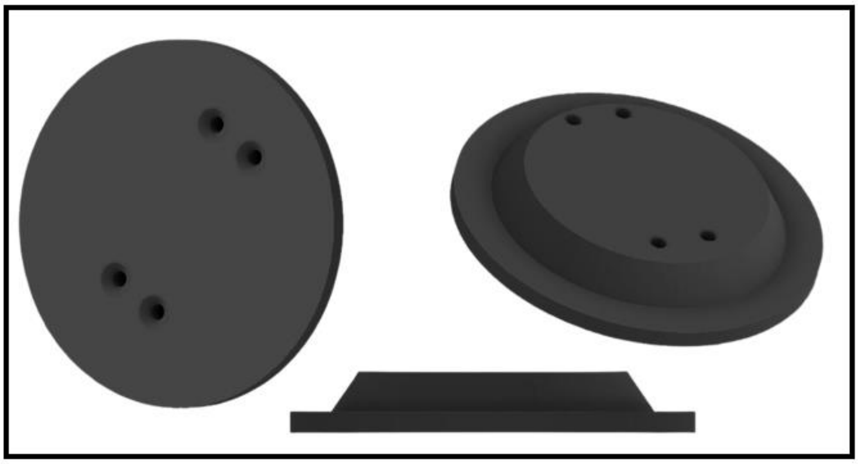

Figure 6.14. Polish Backing Pad.

After a brief market research a conclusion was reached that a 200 mm diameter support would be a good choice. Polishing elements for this support will be easily found.

This support will be tightened together with the bottom support of the cylinder taking advantage of the threaded holes in the pneumatic cylinder. Then it is advised to replace the bolts used for tightening the bottom bracket with longer ones as shown in the following figure.

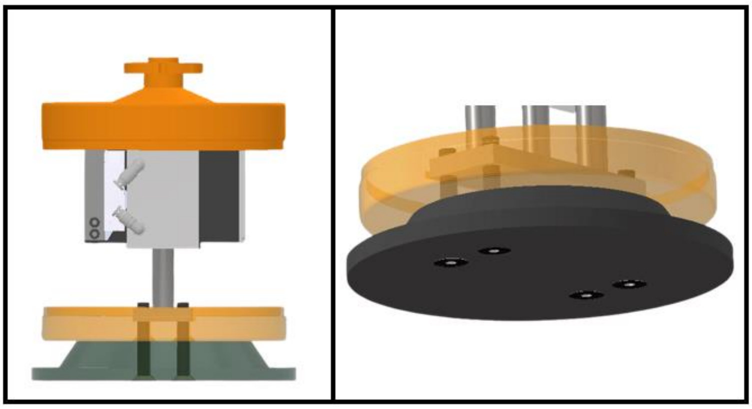

Figure 6.15. Backing Pad Assembly.

6.6. Final Assembley

It remains to be shown the result of what will be the tool developed with all the assembled elements. In this final version there are the rubber bellows placed with the protection function of all electronic and pneumatic components and it will be fixed using two boot clamps.

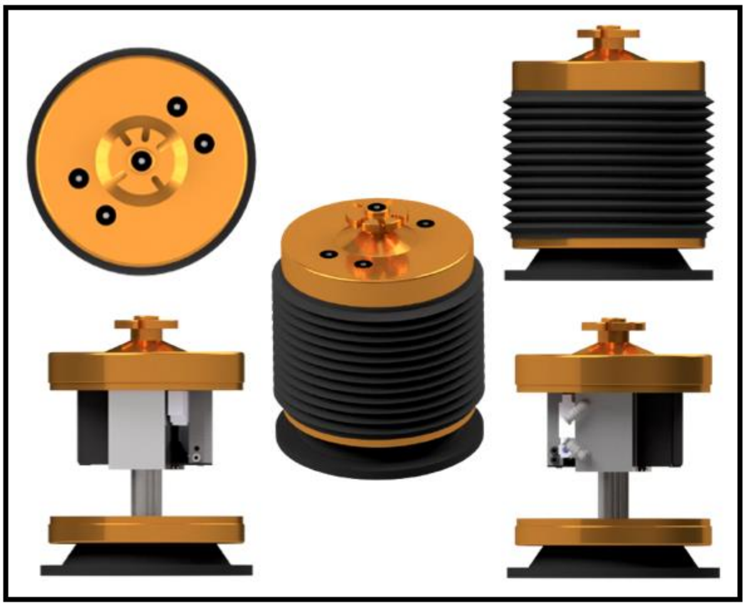

Figure 6.16. Final Assembley.

The assembly of the *ABB IRB 140* robot is shown below (Figure 6.17):

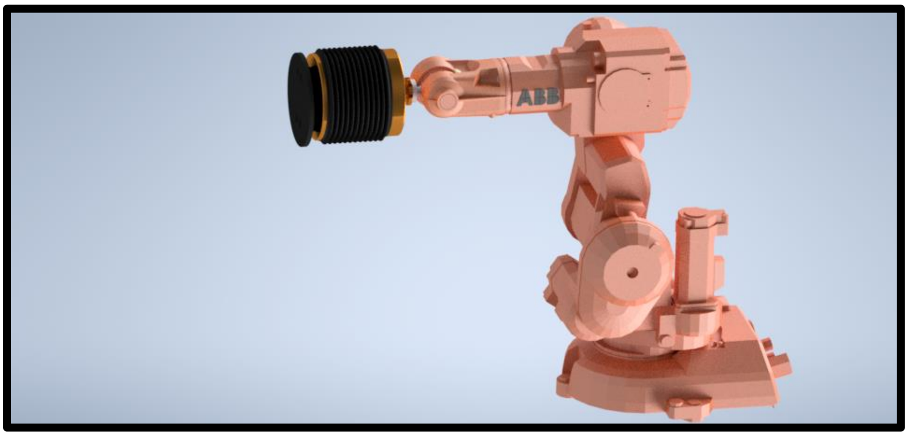

Figure 6.17. Assembly of the *ABB IRB 140* robot.

The two-dimensional (2D) materials of all drawn parts as well as final tool assembly plans are available in the Appendix.

7. PROTOTYPE

This chapter will discuss aspects related to the printing of prototypes. The materials selected and processes used will be listed.

7.1. 3D Printer

The 3D printer *Ultimaker 3* was used in the prototyping process. The choice fell on this one because it is present in the Robotics Laboratory of DEM which facilitates its use. It presents great printing capacity and precision.

Besides the advantage of having its own software (*Ultimaker Cura*) it contains dual extrusion which allows to use two different materials in the same print. The AA core uses materials such as PLA, ABS, etc. The BB core uses dissolvable support material such as Polyvinyl alcohol (PVA).

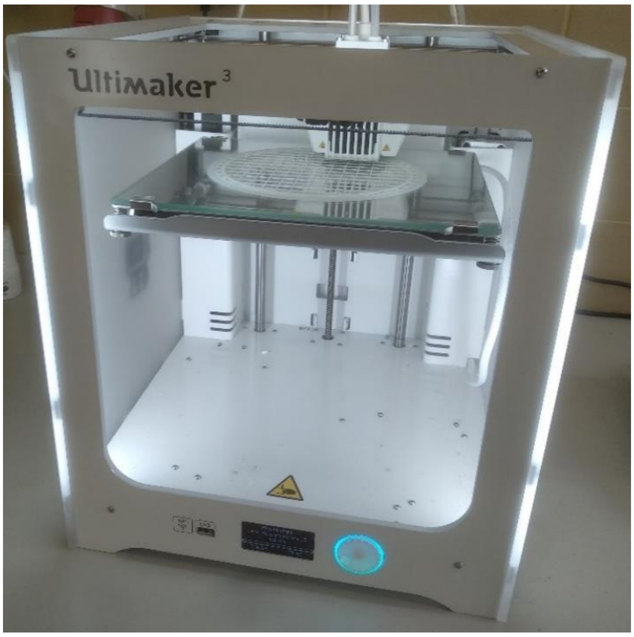

Figure 7.1. *Ultimaker 3* printing a Top Link.

7.2. Software and Materials

The materials used in the production were PLA and PVA. The latter works as support and needs to be dissolved in water after printing.

The software used as mentioned above was *Ultimaker Cura 4.5* and through it the desired printing parameters were selected.

The following table shows the materials used and the parameters selected for each part drawn.

Part Name	Core AA	Core BB	Infil Density	Layer Height[mm]
Top Link	PLA	PVA	20%	0.2
Bottom Link	PLA	PVA	20%	0.2
Link Valve+ Regulator	PLA	PVA	100%	0.2
Electronic Enclosure	PLA	PVA	100%	0.2
Backing Pad	PLA	PVA	20%	0.2

Table 7.1. Parts 3D Printing Characteristics.

Considering that the pneumatic components support and the electronics box are small section pieces, a 100% infil density was chosen to give a higher resistance. The remaining parts were printed using only a 20% infil.

Due to a fault in the printer extruder, at first only the top link and bottom link were printed. It was only with these that the experimental tests were carried out.

The following figure shows two different stages of the Top Link piece. In the first figure (Figure 7.2A) it shows if the part still with the PVA supports present. The second illustration (Figure 7.2B) represents the dissolution of the PVA support in water.

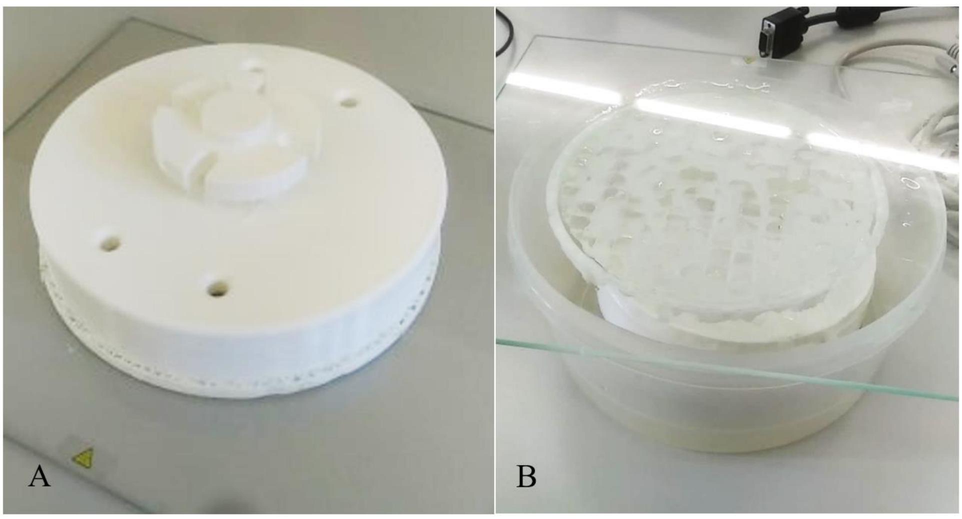

Figure 7.2. A) Top Link 3D printed with PVA support; B) Dissolution of the PVA support.

8. EXPERIMENTAL TESTING AND RESULTS

Due to the Covid-19 pandemic and successive delays in order deliveries it was not possible to have all the desired materials available. Being selected all the pneumatic components and printed the first parts then proceeded to the assembly of the circuit. This was fed by the compressed air network of the Robotics Laboratory of DEM.

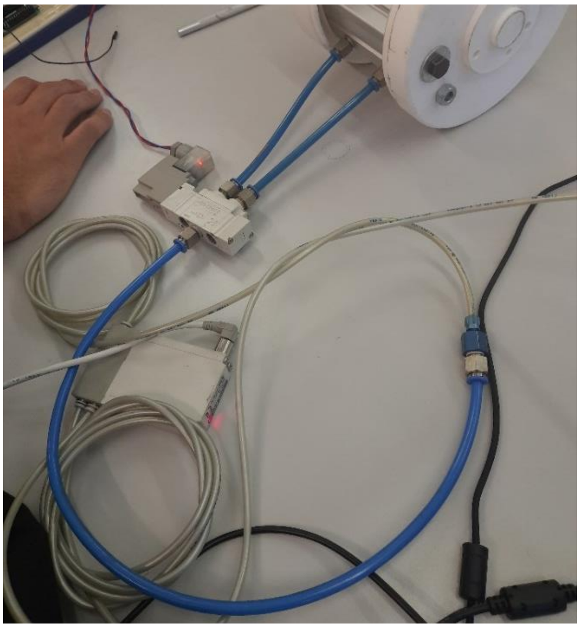

Figure 8.1. Pneumatic Circuit Assembly.

Still without part of the electronic circuit the first tests of connection of the solenoid valve and regulation of air inlet pressure to the actuator have been performed. When applying a force to the pneumatic cylinder is perceptible that the work is being done by the electronic regulator.

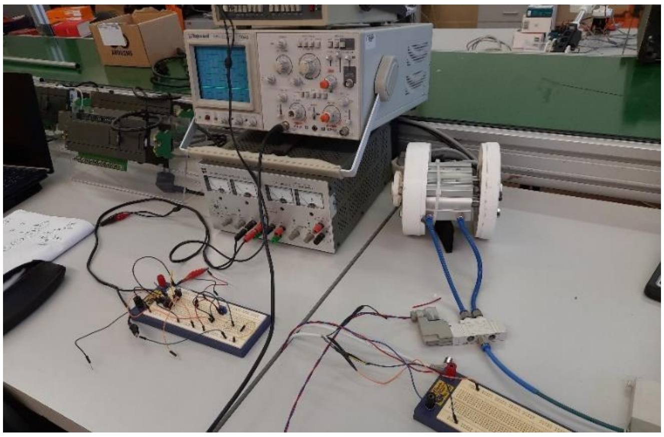

Figure 8.2. Electronic Regulator and Solenoid Tests.

The tool's attachment to the *ABB IRB 140* Robot was tested and it demonstrated the need for improvement of the first Top Link version. The material and printing characteristics are insufficient for the weight of the tool alone and it was necessary to intervene in the design and the selected material arriving at the current version.

Figure 8.3. Assembly of the *ABB IRB 140* robot.

9. CONCLUSIONS

The conclusions and the work forecast of possible project improvements will be presented below.

9.1. Conclusions

Due to the lack of experimental tests, the conclusions to be drawn are unfortunately not many as intended. It is believed that with more testing of the tool it would be possible to achieve a more complete work and with greater capacity to approach the market.

It is believed that the material used for printing some parts is not sufficient for the tasks to which this system is proposed, and it is assumed that with the progress of the tests these parts would start to give way. This conclusion is based on the little that has been tested.

Regarding the pneumatic circuit due to the lack of accessories it takes up a lot of space and it is believed that it would jeopardize the updating of the protective bellows. It was necessary to better accommodate the compressed air circuit.

It is considered that a very ergonomic tool has been achieved and with some adjustments to the pneumatic circuit and change of materials this could be implemented in an industrial universe.

9.2. Future Work

The aspects to improve in the future are:

- After completing a final prototype, change the top link and bottom link by a metal alloy like alumina. This has great mechanical strength and moderate weight at an affordable cost;
- The pneumatic circuit should be made as ergonomic as possible, using accessories such as tee or L fitting connections. This should be as compact as possible to take up as little space as possible;
- A power supply, and air compressed input should be attached to the top link to facilitate connections to power networks. There should also be a Universal Serial Bus (USB) port for software update without the need for disassembly.

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APPENDIX

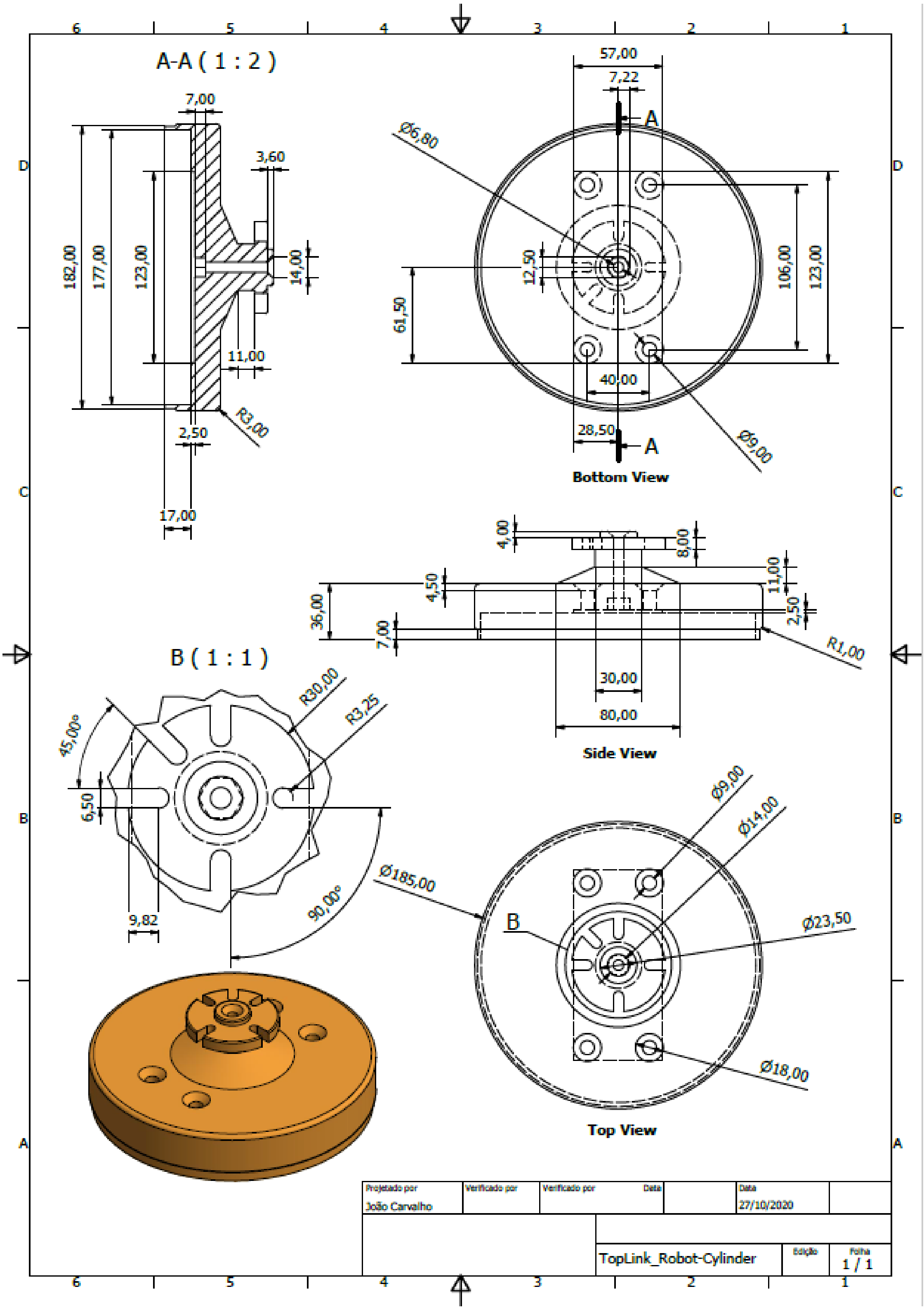

Figure 0.1. Top Link 2D Drawing.

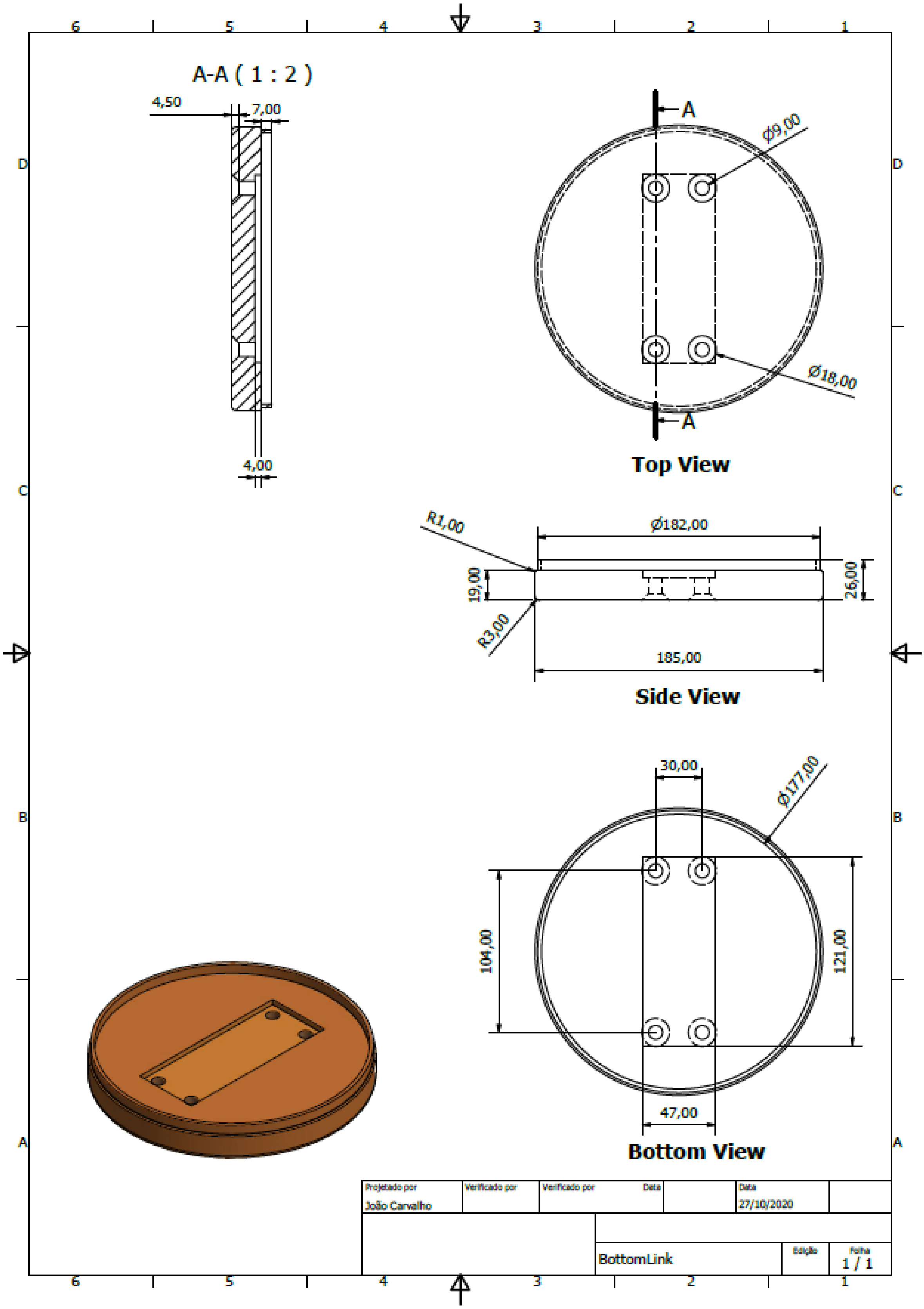

Figure 0.2. Bottom Link 2D Drawing.

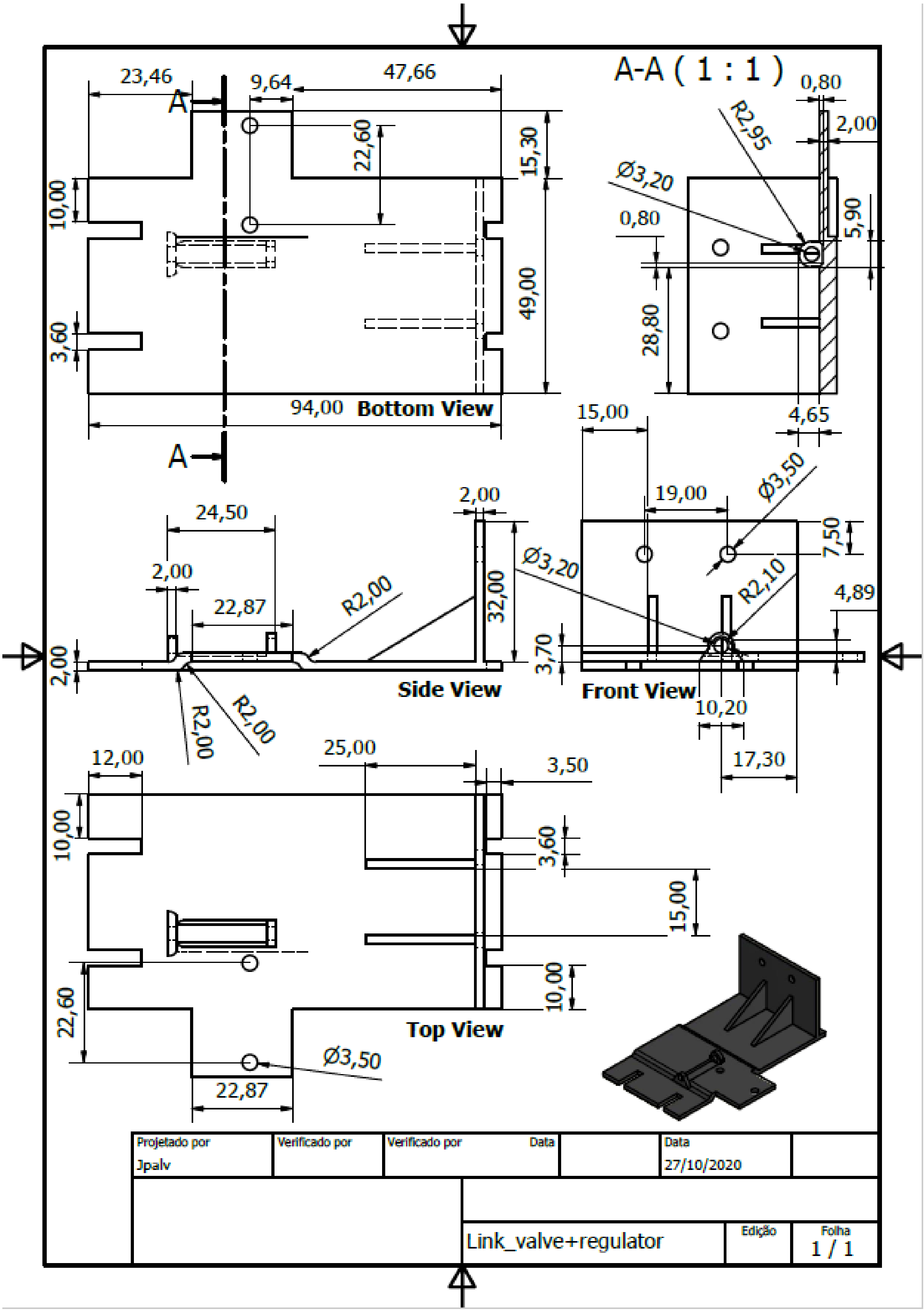

Figure 0.3. Link Valve-Regulator 2D Drawing.

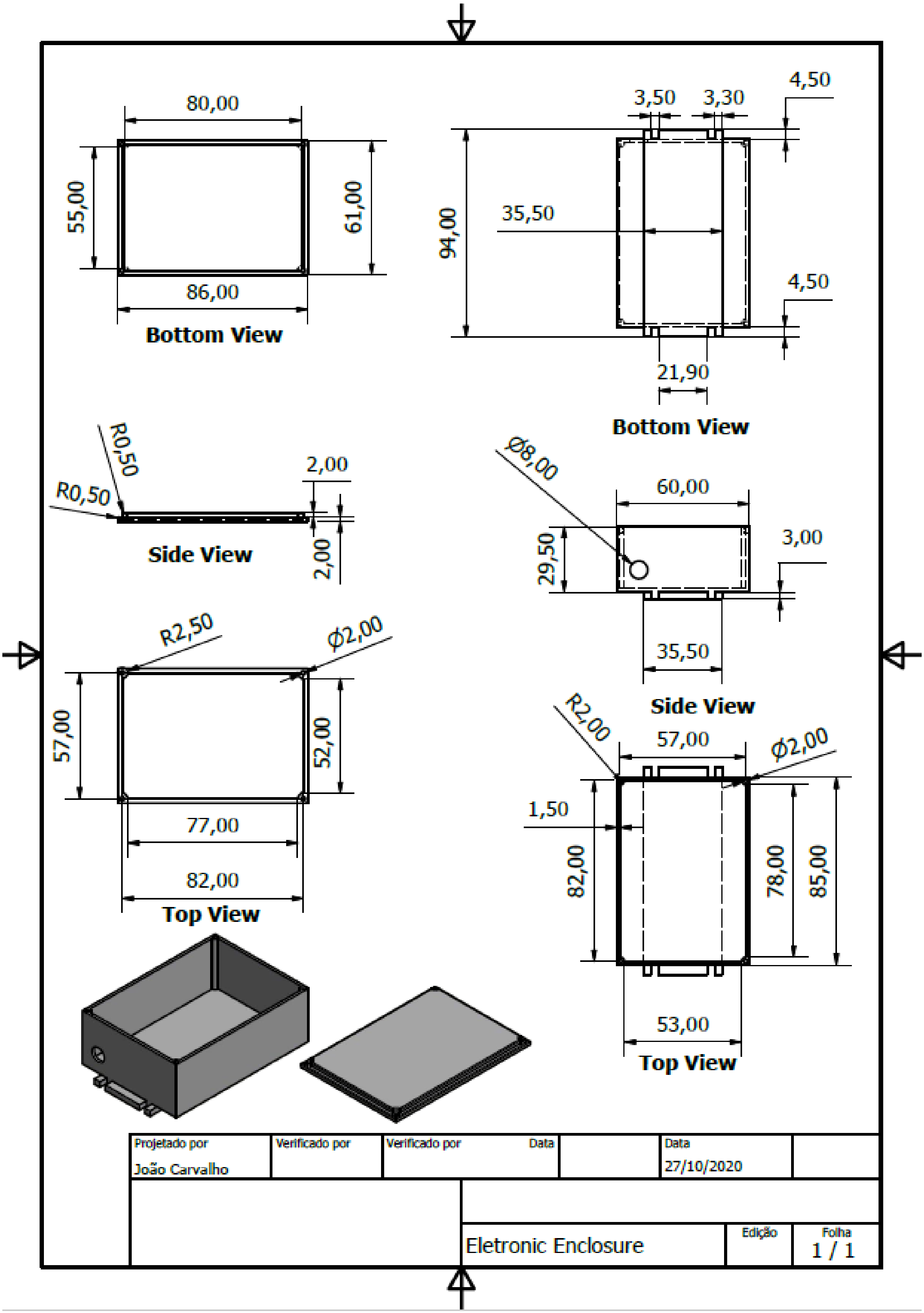

Figure 0.4. Electronic Enclosure 2D Drawing.

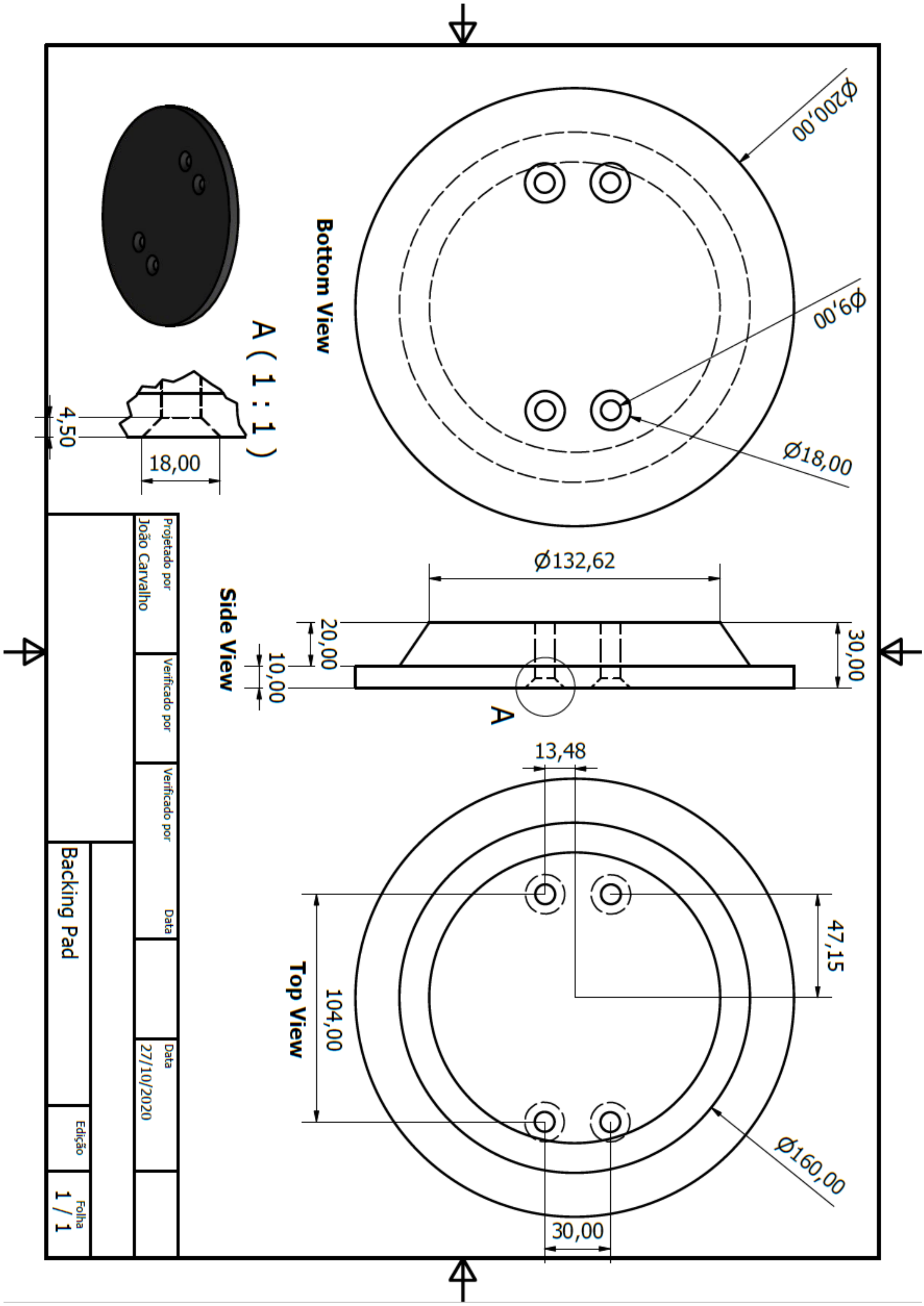

Figure 0.5. Backing Pad 2D Drawing.

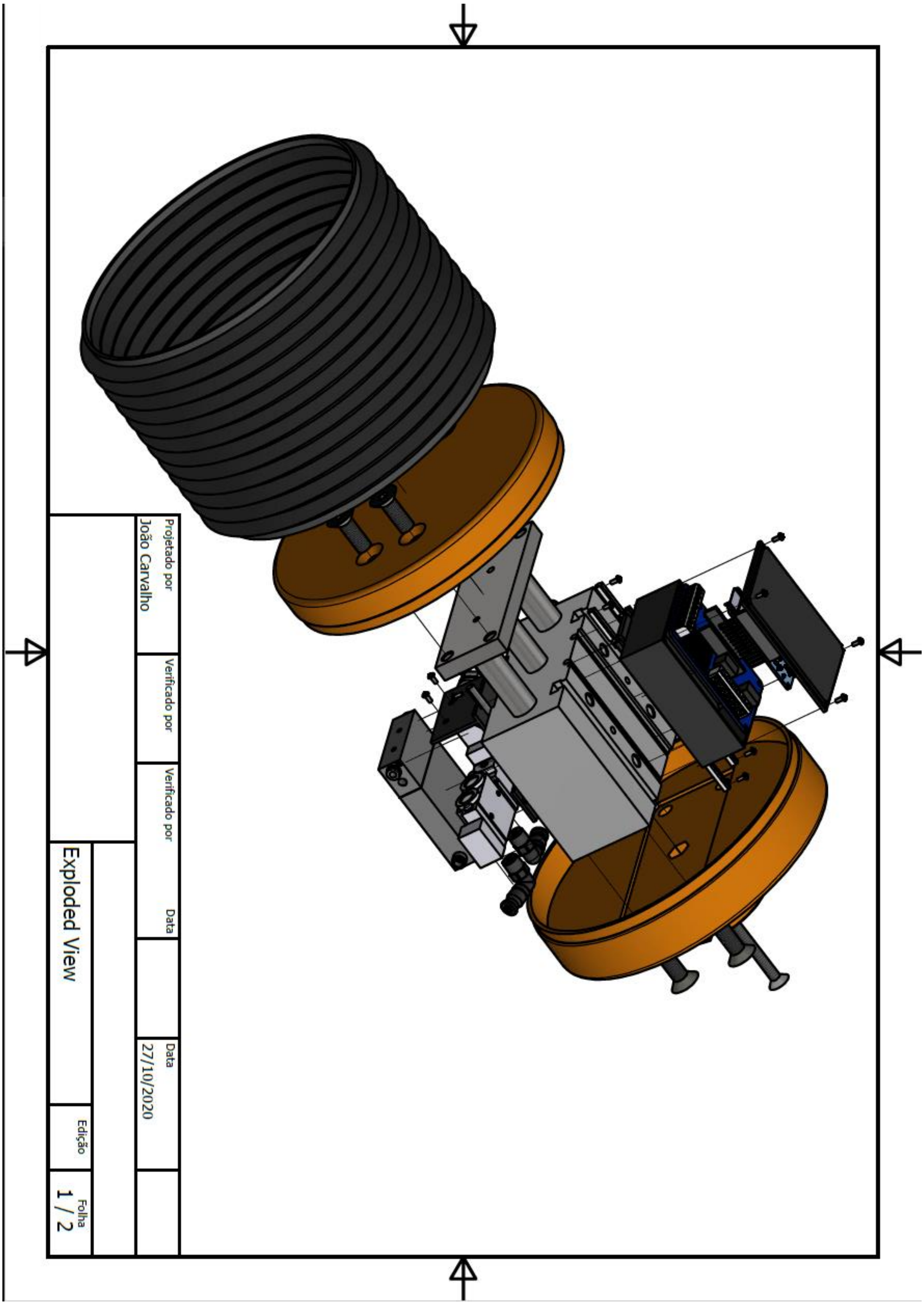

Figure 0.6. Explode View 2D Drawing.

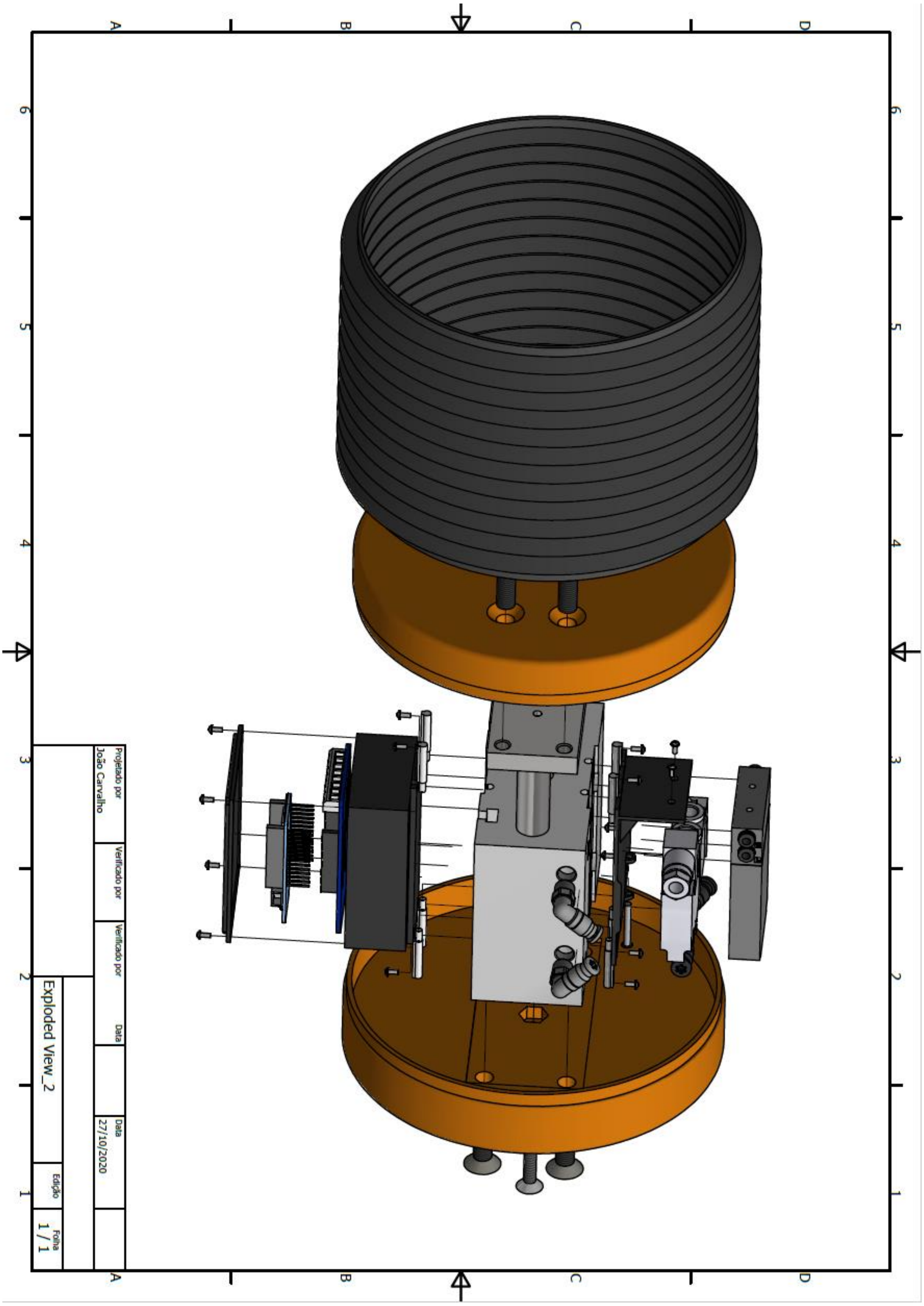

Figure 0.7. Explode View 2D Drawing.

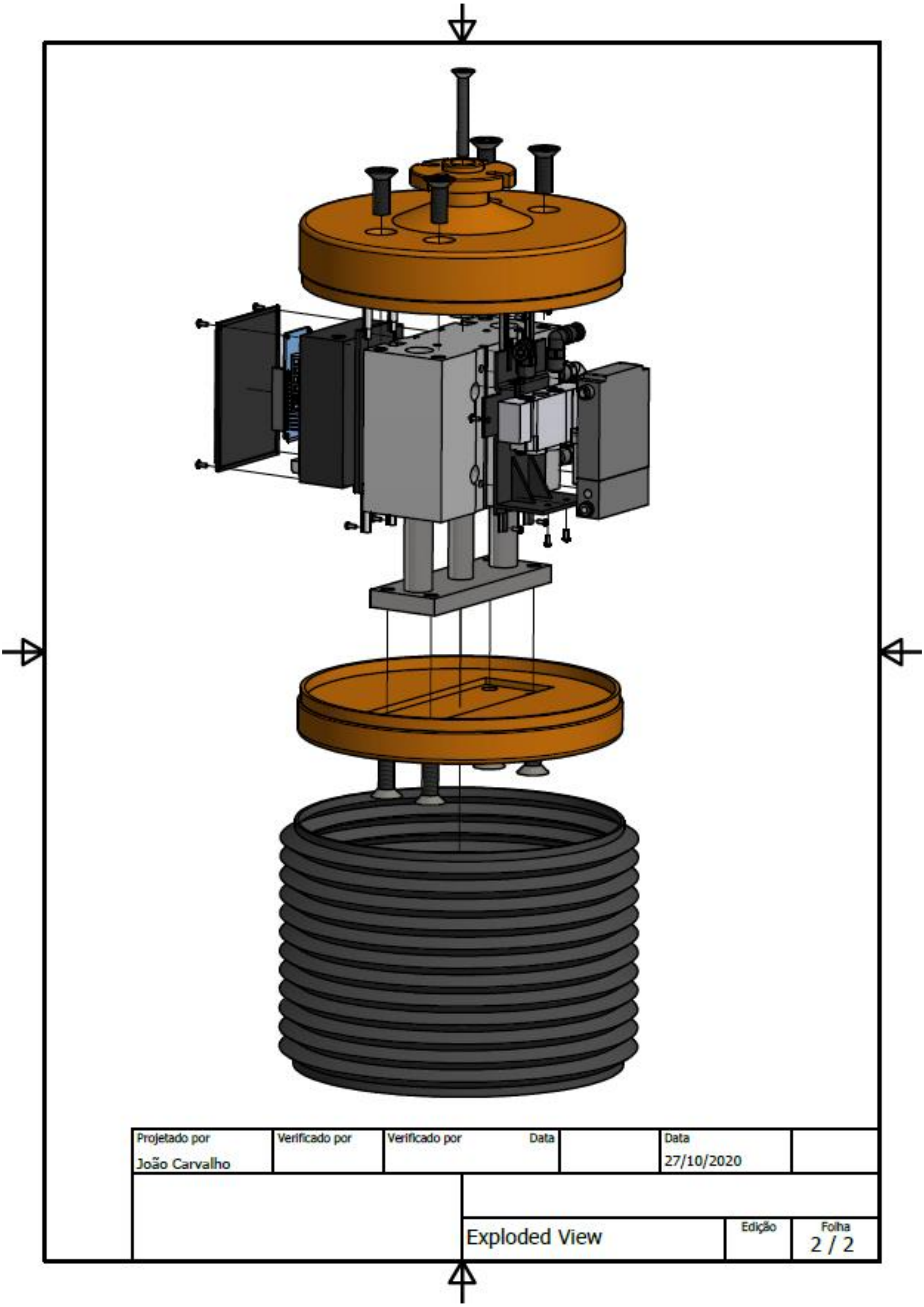

Figure 0.8. Explode View 2D Drawing.