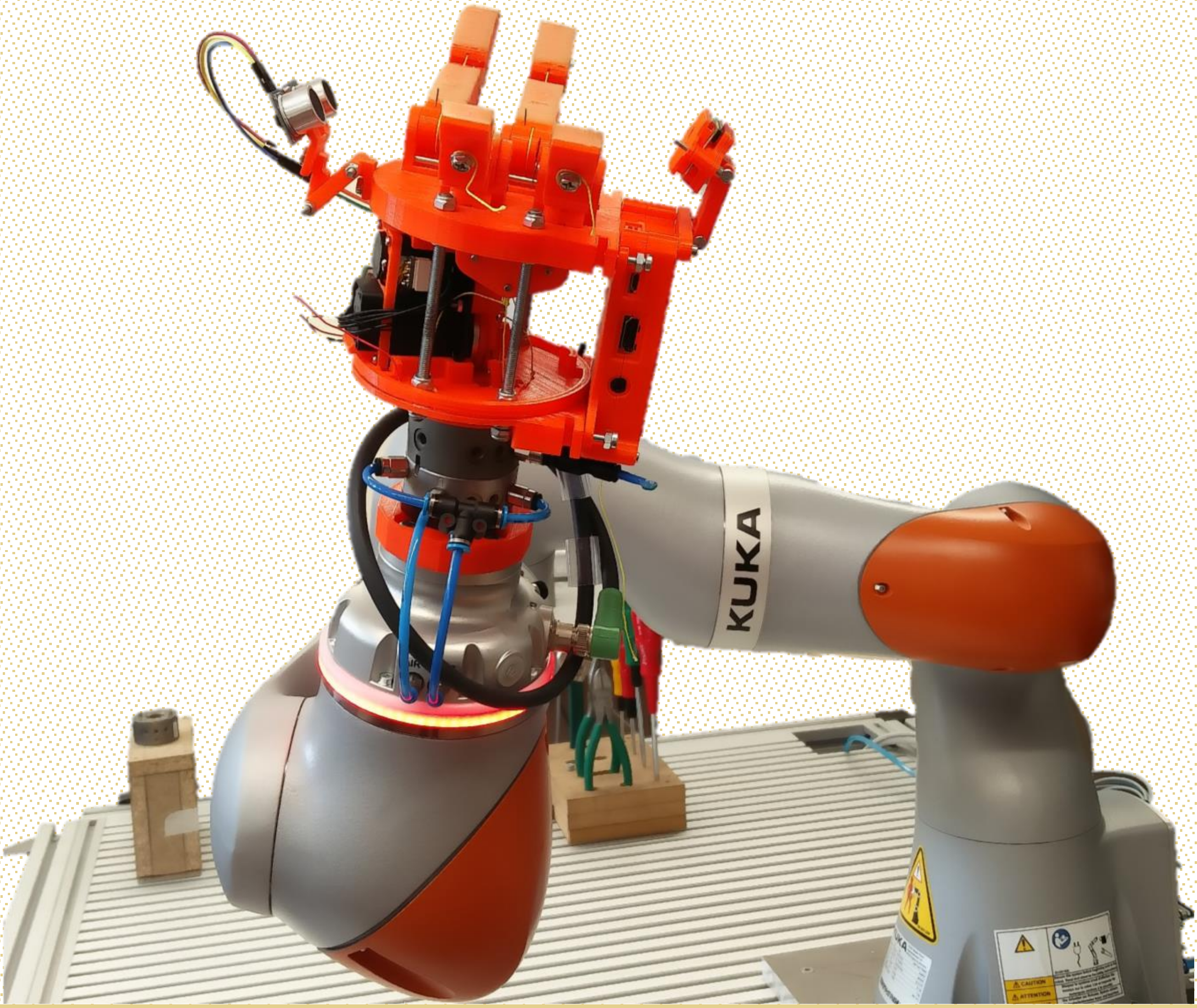

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Flexible Robot Grasping Tools Controlled by EMG Signals

Dissertação de Mestrado em Engenharia Mecânica
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Flexible Robot Grasping Tools Controlled by EMG Signals

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

Garra Robótica Flexível Controlada a partir de Sinais EMG

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“Whether you think you can, or you think you can’t, you’re right”

Henry Ford

Aos meus pais.

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Although this dissertation is not the end of my learning stage, it is, in principle, the end of my life as a student. Reaching here was only possible with the support of those around me, to whom I now show my acknowledgements.

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ABSTRACT

Nowadays, the robots assume a fundamental position in our society, and even a major one when talking about the industry sector. The most common robots are the robotic arms which can execute an enormous variety of tasks.

A correct manipulation of objects requires fine grasping capabilities so the evolving of the gripper should be parallel to the evolving of the robotic arm. The traditional approach resides in two completely different options, being the first one the use of conventional parallel grippers which demonstrate to be very sensible to position and/or orientation variations. The second one consists on a solution much more complex (anthropomorphic robotic hands), which guarantee an almost perfect operation, having as disadvantage a higher price and a greater difficulty of control.

Soft robotics emerges in the middle of these two options and will probably represent the future in almost all areas of robotics, particularly in robotic grippers. These manipulation tools, usually based on biological structures, assume good physical qualities and an enormous adaptive capacity.

This project consists on a production of a flexible robotic gripper produced by the hybrid deposition manufacturing (HDM) principle. The hard core, built on a 3D-printer assumes the structural responsibility while a polymeric compost gives to the hand the compliance and the grip required to assure perfect manipulation conditions. Despite the fact of using only one motor, the flexural joints act independently generating a good performance when grabbing different objects (shape, size and orientation). This happens due to the fact that we are operating an under-actuated hand where the only thing controlled is the opening/ closing mechanism.

In order to increase the quality of the gripper and to assure a more effective manipulation, it will be used a camera and an ultrasonic sensor (disposed on the hand laterals), which are controlled by a Raspberry Pi 3.

Currently, controlling robotic motion is resumed by long lists of code but when the robot environment is composed by people with no coding knowledge, it is essential to search for more intuitive ways of doing it.

The robotic gripper built on this project is controlled using an electromyography (EMG) device, converting the muscular movements into digital signals. Each gesture has a specific meaning, generating a specific response, which improves human-machine interaction (HMI). In this way, it becomes possible the control of robots by people without programming knowledge.

.

Keywords Robotic Grippers, Soft Robotics, Flexible Grippers, EMG, HMI.

RESUMO

Cada vez mais os robôs assumem uma posição fundamental na nossa sociedade, principalmente no sector industrial, dos quais destacam os braços robóticos, que possibilitam a execução de uma enorme variedade de tarefas.

A correta manipulação dos objetos requer uma pega de boa qualidade logo, a evolução da garra robótica deve acompanhar a evolução do braço robótico. A abordagem tradicional reside em duas opções completamente diferentes, sendo a primeira o uso de garras convencionais que demonstram ser muito sensíveis a variações de posição e/ou orientação. Quanto à segunda, configura uma solução bem mais complexa (mãos robóticas antropomórficas), que garante um funcionamento quase perfeito, mas que tem como desvantagens um preço muito elevado e uma maior dificuldade de controlo.

A designação de *soft robotics* surge como intermédio das opções anteriores e poderá representar o futuro em quase todas as áreas da robótica, particularmente nas garras robóticas. Estes instrumentos de manipulação, normalmente baseados em estruturas biológicas, assumem boas qualidades físicas e uma enorme capacidade adaptativa.

O objetivo deste projeto é produzir uma garra robótica pelo princípio da *Hybrid Deposition Manufacturing* (HDM). O núcleo rígido, produzido numa impressora 3D, assume a responsabilidade estrutural, enquanto um composto polimérico proporciona a conformidade e a aderência necessária à garra robótica. Estas características asseguram as condições perfeitas de manipulação. Apesar de utilizar apenas um motor, as juntas flexíveis dos dedos agem de forma independente, gerando um bom desempenho na pega de diferentes objetos (forma, tamanho e orientação). Isto é possível pois o número de graus de atuação é muito inferior ao número de graus de liberdade da mão, onde apenas são dados os comandos para abrir e fechar.

Para aumentar a qualidade da garra robótica e assegurar uma manipulação mais efetiva, foi utilizada uma câmera e um sensor ultrassónico (colocados nas laterais da mão), os quais são controlados a partir de um Raspberry Pi 3.

Atualmente, o controlo de movimentos robotizados é executado por longas linhas de código, mas quando o local onde o robô opera é composto por pessoas com baixos conhecimentos de programação, é essencial procurar maneiras mais intuitivas de o fazer.

A garra robótica resultante deste projeto é controlada através de um dispositivo de eletromiografia (EMG), convertendo os movimentos musculares em sinais digitais. Cada gesto tem um significado específico, gerando uma resposta específica, o que facilita o controlo do robô, melhorando a interação homem-máquina. Desta forma, torna-se possível o controlo de robôs por pessoas sem conhecimentos de programação.

Palavras-chave: Garras robóticas, Robótica suave, Mãos robóticas flexíveis, EMG, HMI.

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ACRONYMS

3D- Three-Dimensional

ABS- Acrylonitrile-Butadiene Styrene

AM- Additive Manufacturing

CAD- Computer Aided Design

DOA- Degree of Actuation

DOF- Degree of Freedom

EC-Embedded Controller

EMG- Electromyography

FDM- Fused Deposition Modeling

GPIO- General Purpose Input/ Output

HDM- Hybrid Deposition Manufacturing

HMI- Human-machine interaction

imEMG- Intramuscular EMG sensor

IMU- Inertial Measurement Unit

MIS- Minimally Invasive Surgery

PAM- Pneumatic Artificial Muscles

PLA- PolyLactic Acid

RP- Rapid Prototyping

SDM- Shape Deposition Manufacturing

sEMG- Surface EMG sensor

SMPS- Switched-mode Power Supply

STL- Stereolithographic format

1. INTRODUCTION

The human being, known in the scientific community by the species of *Homo sapiens sapiens,* represents the actual state of a long evolutionary line. Since our ancestors (*Australopithecus*) lived on earth, 3 million years of mutations were needed to get to our actual state. The primary reason for this huge success was the increment of cognitive capacities allied with the evolution of the hand. This small part of our body allowed us to manipulate and produce efficiently a huge quantity of instruments so we could be in advantage when compared with other species of the animal kingdom. The primary fact for the excellent performance of the human hand is the capacity to adapt to a wide range of object shapes and our skin which shows to have a good grip (Figure 1).

The capacity to hold and manipulate objects so easily is so important and necessary that with the evolution of technology and the invention of the robotic arm, scientists began searching newer mechanic parts capable to mimic the performance of the human hand.

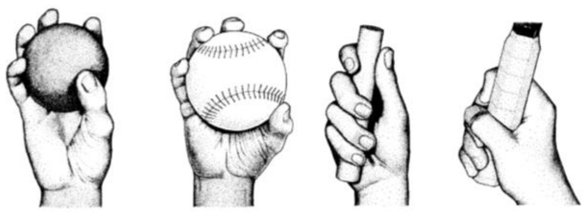


Figure 1- Human hand precision grip and power grip [1].

1.1. Problem and motivation

Nowadays, the quantity and variety of tools incorporated on all industry fields and even outside them is incredibly high. Specialized systems, assembled specifically to certain jobs have unique tools in order to maximize produtivity and reduce the variables to manage.

Changing the mindset to another reality, where quality is still important but the versatility of actions takes the major role, it’s still very difficult to find such tools capable of responding effectively. This will lead to higher prices while limitations will still constitute a problem. If the action requested from the robot is to grab something, this problem is even bigger, giving special interest to specifications like size, shape, surface material, and even fragility level.

Conventional grippers (Figure 2 (a)) consist on metal based elements with limited movement and few degrees of freedom (DOF). These grippers are the most widely used ones due to lower price, but are extremely restrictive in terms of usage.

Other types of robotic hands also available are, unlike conventional ones, very specialized devices with great technical abilities, managing to acquire and hold a wide range of objects easily (Figure 2 (b)). On the other hand, the great capacity of this type of components resorts to complex systems, which makes it difficult to program and control them. The high price and fragility associated to the large number of joints and actuators are another disadvantage of these robotic grippers.

Among the advantages and disadvantages of each of the options, the choice is hard. This project tends to solve this problem by proposing a production of a robotic gripper that combines the advantages of both, avoiding if possible, the disadvantages.

(a) (b)

Figure 2- Robotic grippers; (a) Conventional Grippers; (b) Complex robotic gripper Schunk SVH Hand [2].

1.2. Proposed approach

The approach to solving the previously mentioned problem consists in the production of a simple functioning robotic gripper, which lies between the two extremes declared above. In order to easily grasp a large number of different objects, it is necessary to change the way of operation, altering the large number of degrees of actuation (DOA) for a simpler structure, with a greater adaptive capacity and lower cost of production. Despite an obvious loss of precision, the compliance gain pays off, taking responsibility for the quality of the gripper. The material and equipment available are also a limiting factor to maintain a low cost. As such, the three-dimensional (3D) printer present in the laboratory will be the main production tool, using the designs obtained from computer-aided design (CAD) software, which allows a great versatility of production.

In addition to a good grip, other important requirements are compactness, low weight, collision resistance and simple operation, which must be counterbalanced in order for the hand to be functional. A camera was also added to the project, to provide the operator with the gripper's point of view. Furthermore, a proximity sensor is also added to quantify the distance between the gripper and the object.

Finally, controlling robots usually require extended and complex code what tends to increase the lack of qualified operators. This problem is even more emphasized in the present due to the rate in which the technology is evolving. The proposed solution is to use a gesture control system, which detects the muscles movement and converts it to a digital signal. With some computer manipulation, these gestures made by the operator can effectively control a robot.

1.3. Thesis Overview

This dissertation is composed of seven chapters, following the production chain from the idea and state of the art to the final results and conclusion, going through the entire process of manufacturing and assembly.

The first and second chapters represent respectively the introduction and the state of the art, describing the problem, the proposed approach and the developments made in the area, comparing the different options available and describing their operation.

The third chapter is responsible for describing the construction of the entire robotic hand, since obtaining each component to the final assembly. Fourth and fifth chapters describe the operation and installation of the actuator (which moves the hand) and the sensors used, namely the camera and the proximity sensor. In the sixth chapter, it is explained the procedure and equipment used for gesture control of the robotic hand.

Finally, the seventh and final chapter concludes this project presenting the results obtained and proposing some future improvements.

2. STATE OF THE ART

2.1. Robotic Grippers

In recent years, the quantity and diversity of robots working worldwide increased exponentially. This massive growth conquers several areas daily, forcing everything that is directly connected to robotics to evolve as well. The emergence of collaborative robotics, which consists on seeing the robot as an effective and harmless work tool, created to be an extension of the operator, maximizing productivity in terms of quality, also tends to increase the versatility required.

Extensive research in this area led to the creation of a large number and variety of robotic grippers, but the proportionality between the monetary value of the tools and their technological performance makes it difficult to have ideal solutions. This cost barrier prevents a large-scale implementation of really effective grippers (Figure 2 (b)), which are used only in specific cases when they are truly needed [2]–[4].

On the other hand, the conventional grippers were the first options to be created and continues to be widely used in industry and even outside it as a consequence of lower prices. Another reason that contributes to the predominance of conventional grippers is that their simpler systems allow easier control (Figure 2 (a)).

In turn, these simplifications bring attached limited movements, restricting the grasping possibilities to a lower number of objects. The low DOF makes the movement of articulated parts very rigid which leads to almost null compliance, and generally, the range of movement is very small so, the tool that grabs a pencil, cannot grab a bottle of water.

2.1.1. Soft Robotics

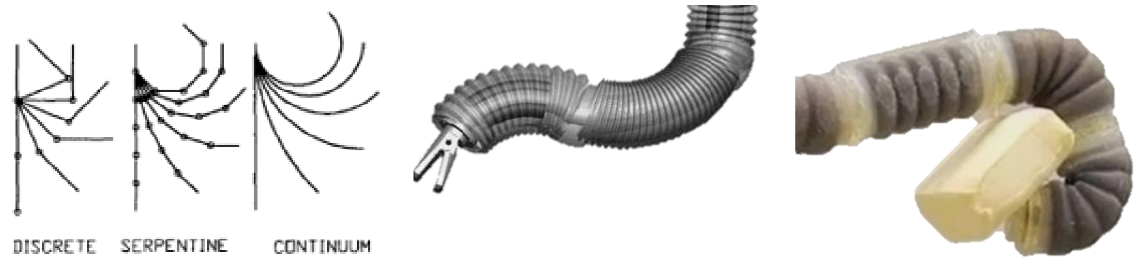
The various attempts to improve the robotic grippers quality, thus widening the range of possible objects to be successfully manipulated, forced engineering to look at the animal world as a source of inspiration, attempting to replicate living structures in laboratory instruments. The great difference between these two worlds begins in the way they both work. While conventional robots consist of rigid systems, built mostly from metallic materials, the animal world, which results of a long and complex evolution, has soft bodies.

The obvious difficulty of combining both worlds through the use of conventional mechanics induces the creation of new technological systems that are better adapted to the living being. This is where soft robotics comes in. This area of robotics does not guarantee equal precision or speed of execution, but it compensates with compliance and versatility. Wang et al. (2015) reports that there will be no total replacement of conventional robotics by soft robotics, but in some areas, such as soft manipulation [5].

The inspiration in the animal world for the obtaining of soft robotics can originate structures similar to the real, as is the case of robotic fish developed by Marchese [6], or the pneumatic artificial muscles (PAMs), which when inflated, reduce the axial length between the ends [7]. It also allows the creation of structures designed to work in conjunction with living systems, such as the rehabilitation gloves. These equipment, should articulate together with the hand, as if they were only one, which is impossible through conventional robotics [8]–[10].

Robots inspired by the octopus's tentacles, the elephant's trunk, or even the body of snakes, are also an important object of study. The first two differ from the third by the absence of rigid elements. The body of the snake, although totally malleable, is composed of a large number of joints. In the case of robots this division separates the mechanisms in "continuum" (infinite number of DOF) and "serpentine" (high number of DOF). The remaining systems, present in most robotic arms, are considered discrete (Figure 3 (a)) [11].

This type of robots, composed by long soft arms, can be used with the most diverse purposes, as is the case of medicine. The high internal sensitivity of our organism cannot be affected by the conventional tools, so were created soft robots capable of penetrating inside the human body through minimally invasive surgery (MIS) (Figure 3 (b)) [12], [13]. By imitating the tentacles of the octopus [14]–[16], or the elephant's trunk [17]–[19], these robots can use their own structure as if it were a gripper (Figure 3 (c)). The infinite (or almost) number of DOF causes it to be able to gain any shape, while soft structure makes the robot resistant to unexpected collisions. In turn, the larger the DOF of a mechanical structure, the greater the difficulty of controlling it effectively. Continuous robotics structures are still difficult due to the total malleability of the system. In order to overcome this problem, it is possible to try a similar approach by imitating, for example, the physical structure of a snake (serpentine mechanism) [20].



(a) (b) (c)

Figure 3- Soft Robotics; (a) Robot Motion [11]; (b) STIFF-FLOP arm [13]; (c) Prototype of jammable manipulator [19].

Finally, the locomotion of conventional mechanical structures, such as cars, works with wheels, which, when rotated on a certain axis, allow the vehicle to move. In the natural world there are no wheels, but a huge variety of forms of locomotion. Although it is easy to build a robot with legs, its control is complex. Once again, a possible solution can be found by turning to soft robotics [21]–[23].

2.1.2. Flexible Gripers

The application of soft robotics concepts in the production of flexible grippers allows to entry into a new world of options. By leaving behind excessive use of metal (which makes components heavy and decreases the number of DOF), and by resorting to new materials and manufacturing processes, it is possible to find robotic hands of all shapes, design to certain needs.

Despite the obvious association of robotic grippers with the human hand, some of the models do not demonstrate any similarities. One example is the model developed by Brown et al. (2010) wherein a nonporous elastic bag is used, in which a granular material is deposited. By varying the internal stiffness of the granulate after wrapping a certain object, it is possible to have the hand (Figure 4), functioning as a controlled robotic gripper by reversible jamming transition [24]. Based on the same principles of operation, the passive universal gripper developed by Amend et al. (2012) shows to be effective in acquiring and manipulating objects [25].

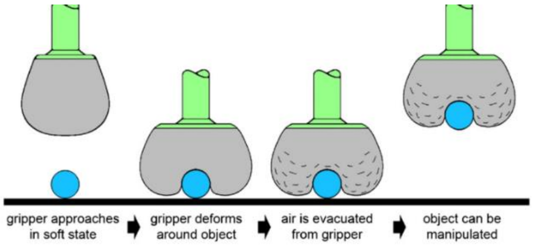


Figure 4- Scheme of operation of the universal robotic gripper [24].

Hau et. al. (2016) developed a robotic gripper made of silicon rubber (dragon skin 30, smooth-on Inc, USA), whose 4 fingers were actuated through a pneumatic system. The inflation of the fingers closes the hand (Figure 5 (a)), while the evacuation of air causes them to fold outside (Figure 5 (b)). As the fingers do not have any rigid components, to control the opening and closing of the robotic hand, an inelastic nylon tendon was used to block the movement of the fingers. The further from the base of the hand this tendon is placed, smaller is the opening of the hand [26]. These pneumatic actuated grippers have a very simple operation which, by varying the section of the fingers, it is possible to direct the flexion that occurs during the insufflation. Other examples of application of pneumatic grippers are reported in [27]–[30]. The same type of construction can, in turn, be adapted to other forms of actuation as, for example, tendon-driven robots [31]. This type of action proves to be effective, so that the next examples will be based on this principle.

Another robotic gripper with interesting features is the Festo FinGripper created by Wilson (2011), which, inspired by the tail fin of a fish, created finger-like structures that, when pressed against the object, wrap it gently, taking its shape [32]. The high quality of these "fingers" associated with a better basis, originated the Festo MultiChoiceGripper, which can vary the position of your fingers in order to optimize the grip (Figure 5 (c)) [33].

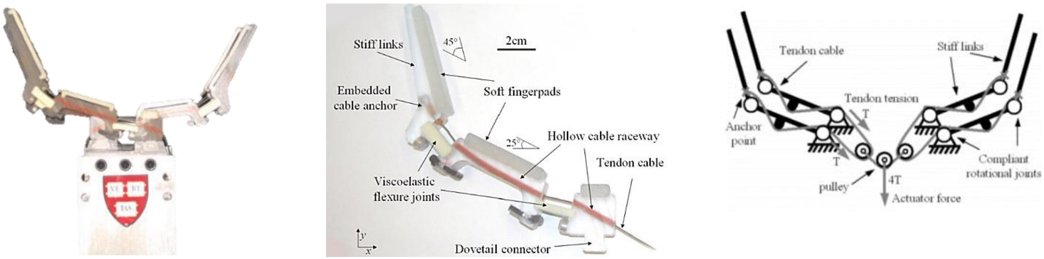
(a) (b) (c)

Figure 5- Hao robotic gripper; (a) Deflated state; (b) Inflated state [26]; Festo MultiChoiceGripper [33].

In search of superior motion accuracy, it is necessary to decrease the DOF of the system, making it more rigid. Furthermore, the choice of totally hard fingers causes problems such as impact forces and lack of strain dissipation. A possible solution to these problems, is the use of soft materials (plastic, rubber, sponge, fine power, paste and gel) that surround the surface of the fingers, providing an effect such as human skin [34].

The evolution of conventional robotic claws, with simple and restricted parallel movement, to two fingers flexible grippers, allows a huge increment of compliance. Some examples are the Robotiq (two-finger) [35] and the Velo Gripper [36], both with two biarticulated fingers (proximal and distal joints), which demonstrate good compliance with the objects. By increasing the number of fingers to three, it is possible to change the configuration of the fingers, to assume a triangular geometry (some of the models also allow the rotation of the fingers), which allows to obtain both a precision grasp and a power-grasp. This triangular arrangement of the fingers is so effective in acquiring irregular objects that it is used by various market hands such as the BarrettHand [37], 3-Finger Robotiq [38], RightHand Reflex [39] and Schunk SDH Hand [40].

Finally, the SDM Hand (Figure 6 (a)) is, as the name implies, a robotic gripper obtained through a shape deposition manufacturing (SDM) process [41]. This tendon (nylon-coated stainless-steel cable) driven hand has four underactuated fingers, consisting of rigid links connected to each other through compliant polyurethane joints in order to increase compliance with the object. The resistance of the joint to torsional and flexural deformation comes from its section area, being the deformations greater when the area is smaller (Figure 6 (b)). From the same process as the flexure joints are made, the finger pads are obtained with the purpose of increasing the friction and the surface area of contact between the fingers surface and the object to be grasped [42]. This robotic hand uses only one motor in its operation, which, through a system of pulleys, allows the fingers to function independently of one another (Figure 6 (c)) [43].



(a) (b) (c)

Figure 6- Images of SDM Hand: (a) SDM Hand in rest configuration; (b) Detailed finger design; (c) System of pulleys [43].

The SDM Hand was the inspiration for a series of robotic grippers such as the i-HY (iRobot-Harvard-Yale Hand) model (Figure 7), which uses five motors to control three underactuated fingers and their bases (adduction and abduction movements in order to transform a power grasp into a precision one) [44]. It was also the basis of the Yale OpenHand Project, which because of its extreme importance in this project, will be analysed in greater detail below.

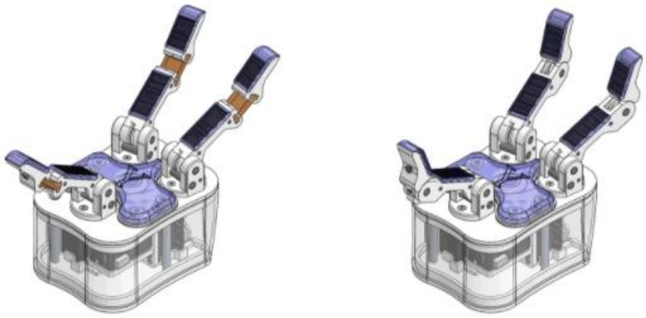
Figure 7- The i-HY robotic gripper [44].

2.2. Yale OpenHand Project

The Yale OpenHand Project aims at the construction of robotic grippers, built by rapid-prototyping (RP) techniques, that are extremely cheap when compared to the competition, while maintaining an efficient grasp and manipulation of different shape and size objects.

In this project, there are two options for the joints (pivot joints or flexure joints). Pivot joints are rigid and precise, but with worse grasping capabilities (derived from the lack of compliance) when compared with flexible joints, which, being driven by cables, permit great compliance and adaptability. These flexure joints are obtained through the principle of hybrid deposition manufacturing (HDM), which is also used in the production of the fingers pads, offering greater friction between the fingers and the object. This project has 4 models available, which vary among the number of fingers, number of actuators, position and operation of the same.

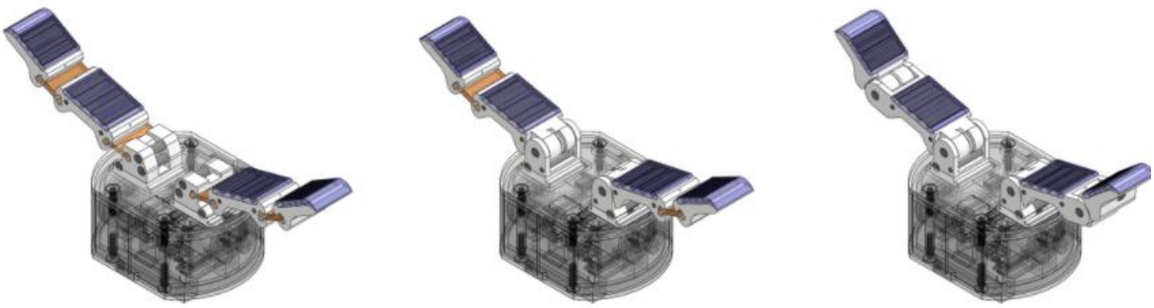
The Model O is one of models of the OpenHand Project and it uses three underactuated fingers that work independently from each other, guaranteeing good grasping capabilities. To increase performance, two of the fingers are still connected to a fourth motor, which allows to rotate the base of the fingers, making it vary between precision-grasping and power-grasping. This model has two finger options: Pivot- Flexure (Figure 8 (a)) and Pivot-Pivot (Figure 8 (b)). Comparing with Model T, this one is more expensive due to the bigger number of actuators [45].



(a) (b)

Figure 8- Model O fingers design options; (a) Pivot-Flexure; (b) Pivot-Pivot [45].

Another option is the Model T42 which consists in a simplification of the Model T design from 4 to 2 fingers. In turn, these fingers can work independently what is clearly an advantage, allowing a better grasping of certain objects. This two joint model has three different possible configurations (Flexure- Flexure, Pivot-Flexure, Pivot-Pivot), which are presented by the same order in Figure 9 [46].



(a) (b) (c)

Figure 9- Model T42 fingers design options; (a) Flexure-Flexure; (b) Pivot-Flexure; (c) Pivot-Pivot [46].

The Model M2 presents a construction slightly different from the other options. Despite using the same rapid-prototyping techniques, it has one tendon driven finger like the other models, which uses an actuator to move properly (in both directions as presented in Figure 10), and a passive compliant thumb, which can take many forms. Due to the Model M2 exclusive construction design, the way it works is different too. The modular thumb can have some compliance depending how it was designed, but it still fixed to the gripper so the grasping is generated by the movement of the dexterous finger, which can be Pivot-Flexure (Figure 11 (a)) or Pivot-Pivot (Figure 11 (b)) [47].

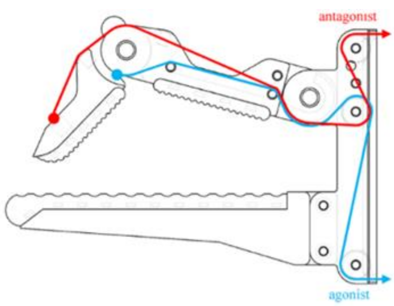
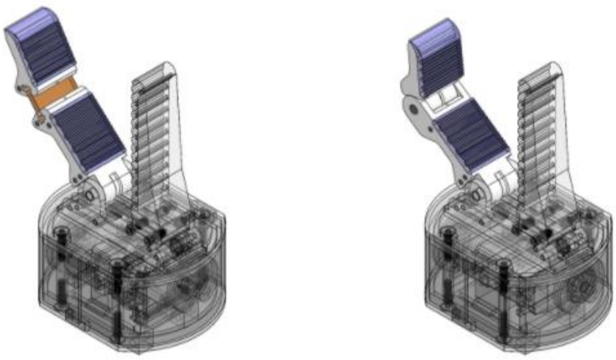


Figure 10- Model M2 tendon driven finger [48].



(a) (b)

Figure 11- Model M2 fingers design options; (a) Pivot-Flexure; (b) Pivot-Pivot [48]

Last but not least, Model T was the first model to be created in OpenHand Project and it was based on SDM Hand, referenced before. It is a tendon-driven robotic gripper, which uses only one motor to control four underactuated fingers. With a main structure divided between 3D printing and other components available in the market, this gripper presents a solid structure, able to be mounted on any robotic arm, and ensures a good object manipulation regardless of shape and size [49].

As shown in Figure 12, it is possible to choose one of the three options (Flexure-Flexure, Pivot-Flexure, Pivot- Pivot).

(a) (b) (c)

Figure 12- Model T fingers design options; (a) Flexure-Flexure; (b) Pivot-Flexure; (c) Pivot-Pivot [49].

The following table (Table 1) compares the physical characteristics of the previously mentioned models.

Table 1- Comparison of Yale Openhand Project models [45], [46], [48], [49].

Model	Model O [45]	Model T42 [46]	Model M2 [48]	Model T [49]
Actuator	4x Dynamixel RX-28/MX-28	2x Dynamixel RX-28/MX-28 or Power HD Servo	2x Dynamixel RX-28/MX-28 or Power HD Servo	Dynamixel MX-64
Base Height [mm]	90	55-80	55-80	95
Base Diameter [mm]	100-125	90-105	90-105	100
Weight [g]	750	400	375	490
Holding Force [N]	11-13	10	-	10-13

Raymond and Dollar (2017) tested three models (Model O, Model T42 and Model T) in two different joints configurations (pivot-joints and flexure joints), in order to evaluate the different performances of these robotic hands. The test consisted in evaluating both the acquisition of the object and its capacity to hold it during subsequent manipulation. The 4 objects chosen are shown in Table 2, as well as some relevant characteristics. For the test to be valid, all hands started in the same position and each of them had 5 attempts for each object [50].

Table 2- Objects used to the grasping test.[50]




Object	Coffee Cup	Mustard Bottle (Full)	Spatula	Cheez-It Box (Full)
Weight (g)	118	432	104	453
Size (mm)	89 × 89 × 83	38 × 76 × 178	38 × 102 × 356	64 × 161 × 229

Table 3- Results of open-loop grasp test [50].

Hand	Grasp Acquisition Test	Hold Test
T (Pivot)	20/20	17/20
T (Flexure)	19/20	11/20
T42 (Pivot)	19/20	12/20
T42 (Flexure)	18/20	08/20
O	20/20	14/20

The results of this study can be found in Table 3, where it is concluded that the best performance was achieved through a Model T with pivot-base.

This device achieved full effectiveness in the first component of the test, having grabbed the object successfully in all 20 attempts (5 to each object). In the hold test, in spite of continuing with the best performance, it had an effectiveness of 17 in 20, presenting more difficulty for the two objects with greater mass. The worst performances are associated with the excess flexibility provided by the flexure-bases, which causes the fingers to rotate and eventually lose grip.

A comparison with other hands available in the market, is presented in Table 4. Although it is based only on the physical characteristics of the different robotic grippers, it presents some interesting values from the number of fingers to the grip force.

Table 4- Comparison of robotic grippers [50], [51].

Hand	Number of Fingers	Number of Actuators	Base Height (mm)	Base Width (mm)	Weight (g)	Grip Force (N)
Barrett Hand [52]	3	4	75,5	130	1200	15
2G Velo [36]	2	1	80	45	-	10-20
Robotiq (two-finger) [35]	2	1	90	140	890	30-100
Robotiq (three-finger) [38]	3	2	126	126	2300	15-60
Schunk SDH Hand [40]	3	7	98	122	1950	-
i-HY [44]	3	5	80	105	1390	15
RightHand Reflex [39]	3	4	-	-	800	-
Festo MultiChoiceGripper [53]	3	4	215	148	660	-
Meka H2	4	5	63	96	800	-
OpenHand Model T42 [46]	2	2	55-80	90-105	400	9.60 ± 0.25
OpenHand Model O [45]	3	4	90	100-125	752	12.33 ± 0.71
OpenHand Model T [49]	4	1	95	100	490	11.54 ± 1.20

2.2.1. Underactuated Fingers

The concept of soft robotics described above is entirely related to the freedom of a certain structure, either by internal action or by external influence of the environment. A widely used concept in this area of robotics is the so-called "underactuation". The simplest way of explaining this concept is referring to a structure whose number of DOF is greater than the number of DOA. Although it seems to give the robot some weakness and inefficiency, when well used, this feature demonstrates impressive qualities.

The inclusion of underactuated fingers in the Yale OpenHand Project is one of the main reasons for its success, since it allows a great geometrical adaptability to the object, ensuring a good handle on objects of the most varied shapes and sizes. An example of how these fingers work is shown in Figure 13, where the grasping process takes place in two stages, beginning with the contact of the proximal finger links and ending when the distal finger links touch the object. These two phases are called respectively sweeping phase and caging phase [51].

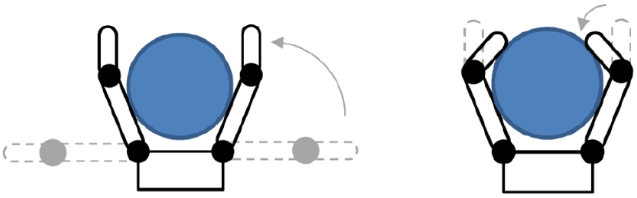


Figure 13- Underactuated fingers compliance capabilities [51].

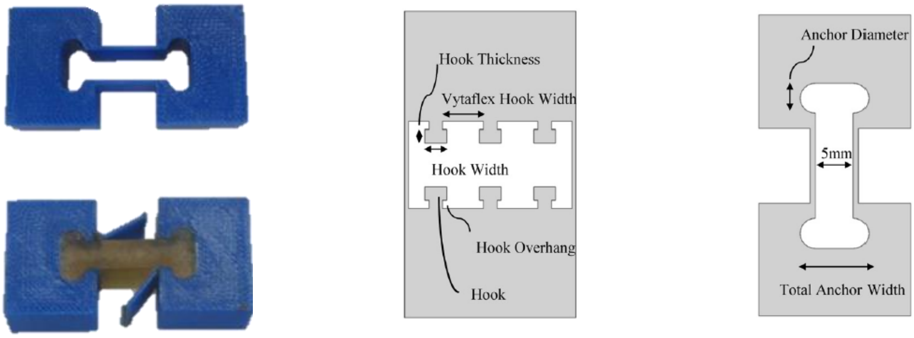
Although still possible to perform precision graps using underactuated hands [54], the disadvantages associated with loss of accuracy and excessive flexibility of the robotic hand, can turn the task unsuccessful. For this reason, the admission of underactuation by the robotic hands must be carefully considerated.

The Yale OpenHand Project is one of the examples where underactuation is used for better compliance between the fingers and the object. The fingers get this status because of their way of working that is based on the principles of tendon driven hands, but it is not all. Using an elastomer as finger joints, compliance is improved, both at the bending and torsion points. The variation of the flexure joint thickness allows controlling its resistance to deformation, optimizing its characteristics. The process used to produce these joints is called HDM which will be explained further.

2.2.1.1. HDM

The 3D printing technology is considered one of the possible fused deposition manufacturing (FDM) processes which allows rapid-prototyping (RP) of complex parts, representing an added value. Since this additive manufacturing (AM) technique is limited to certain materials such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and others, it is impossible to obtain certain structures. Raymond et al. (2015) proposed a solution to this problem through HDM, which consists of using the pre-printed structures (FDM parts) as a mould to the epoxy resin or to the two-part urethane, giving rise to a unique piece that joins the best characteristics of each component, without the need for any fastening elements. The cavities are formed by the borders with the piece and thin walls, responsible for the containment of the urethane mixture while it is in the liquid state. After the curing process is finished, the thin walls are removed as shown in Figure 14 (a). In addition to the use of thin walls, other techniques can be used for mould removal, but they are not as effective [55].

The absence of fasteners also facilitates the use of this system, but it is essential that the integrity of the monolithic component is ensured completely so two different strategies can be used, for example in the Yale OpenHand Project. The first one is to use a set of hook-shaped structures on the surface of the mould which borders the cavity, preventing the elastomer to separate from the printed body (Figure 14 (b)). The second strategy consists in using "dog bone" shaped cavities (Figure 14 (c)).



(a) (b) (c)

Figure 14- HDM process and structures used to increase adhesion between different materials; (a) Mold cavity and sacrificial walls; (b) Printed anchors for Vytaflex pads; (c) “Dog bone” shaped urethane anchors for flexure joints [55].

2.2.2. Model T

The previous results (Table 3) show that the Model T can surpass the remaining hands of the Yale OpenHand Project, both in grasp acquisition and in the hold test. It also has a satisfactory grip force considering its mass, and despite having 4 fingers, uses only one actuator, which gives greater economic viability.

2.2.2.1. Construction

As previously mentioned, Model T results from a combination 3D printed parts with off-the-shelf materials. It is a tendon-driven robotic hand, actuated by a single motor, installed inside the wrist. A more detailed explanation of this characteristics will be presented in the next sub-chapters.

2.2.2.1.1. 3D Printed Parts

Most of the gripper parts come from 3D printing, achieving a great speed of production, without neglecting quality (which is a direct consequence of the material and the printer used). This production technique also facilitates the geometric optimization of the components and easy replacement of them.

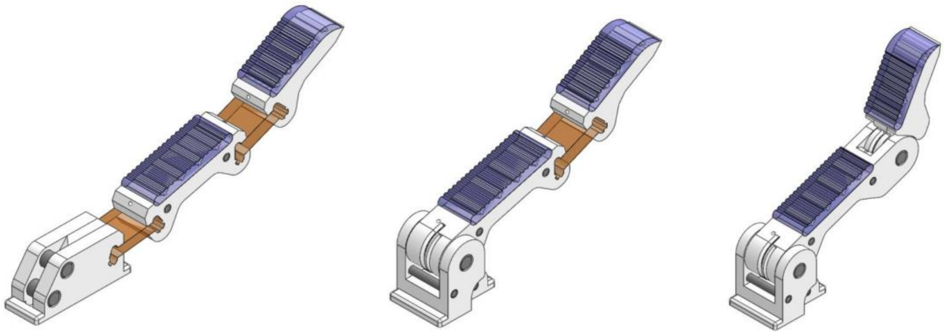
All Yale OpenHand Project prints were obtained from a Stratasys Fortus 250mc, which consists of a Fused Deposition Manufacturing (FDM) printer (Figure 15) [50].

Figure 15-Stratasys Fortus 250mc [56].

The robotic hand should ensure compactness, low weight and a structure strong enough to ensure that the work that is proposed to it is done without problems. The thickness of the walls varies between 0.7 mm and 3 mm thick whether they are sacrificial walls or structural walls respectively.

2.2.2.1.1.1.Fingers

In this project, produced mainly by FDM, in which the fingers represent a fundamental part, it is possible to choose one of the 3 formats available (Flexure-Flexure, Pivot-Flexure, Pivot-Pivot). Although flexure joints (Figure 16 (a)) confer great compliance (but subject to twist-out behaviour) and pivot joints (Figure 16 (c)) provide precision, the best option is a pivot-base model, with flexure distal joints (Figure 16 (b)) [50], [57].



(a) (b) (c)

Figure 16- Yale OpenHand Project fingers; (a) Flexure-Flexure; (b) Pivot-Flexure; (c) Pivot-Pivot [57].

The flexure joints are obtained through the previously explained HDM process, in which the printed fingers have their own spaces enclosed in thin walls of 0.7 mm thickness, which, after being filled with the necessary elastomers, are freed by removing the walls (Figure 17). These elastomers consist of a mixture of urethanes (PMC-780 for the flexure joints and Vytaflex 30 for the fingers pads) and require a cure time superior than 24 hours at a temperature of not less than 24 °C. If the flexure joints impart greater geometrical adaptability to the hand, it is up to the finger pads to reliable contact with the objects [50].

Figure 17- Processo de fabrico dos dedos HDM [51].

2.2.2.1.2. Other Parts

The remaining components required for hand-mounting come from standard series of "off the shelf" mechanical elements such as screws, springs and spacers.

Being this a tendon driven robotic hand, all the drive made in it depends on the use of a cable, which, despite having a maximum thickness (the cable used need pass freely through the finger holes), must guarantee the necessary tensile strength so the filament chosen was the 100-lb Spectra fishing line. The continuous movement of this cable during the normal operation causes a corrosion problem, eventually cutting the parts manufactured in the 3D printer. The solution to this problem leads to another component also used, which is nothing less than 3.18 mm metallic pins, placed strategically along the fingers and at the base of the hand, serving as a base for the passage of the cable [51].

The system responsible for closing the hand uses the rotation of the motor to pull the cable, but, this being a single-acting system, to open the hand (counter movement), it is necessary to use another type of components. While in the case of flexure joints, the joints themselves do this work, in the case of pivot joints, two suggestions are presented, which are torsion and extension springs placed on the outside of the fingers.

At the structural level, the top and bottom plates are fixed through bolts and female standoffs, which allows to put all the mechanism inside the wrist, protected from the outside world, and ensuring a good and solid construction.

With the exception of the motor (to which the following subchapter is dedicated), the remaining extra components of the hand are not relevant enough to be described.

2.2.2.1.3. Actuator

The hands of the Yale OpenHand Project belong to a group of grippers which is called tendon driven robotics, so the motor rotation is responsible for pulling the wire, closing the fingers.

The Dynamixel actuators were chosen to be implemented in this project, being the MX-64AR, used in Model T. With good compacity and high torque, this engine allows the hand to remain light and guarantees good grasping capabilities.

The actuator dimensions are 40.2 × 61.1 × 41 [mm], weights 126 g, and presents a torque of 7.3 Nm [50], [51].

2.2.2.2. Working Capabilities

The basic purpose of the Yale OpenHand Project models is the constitution of robotic grippers that demonstrate good grasping capabilities. The various models previously mentioned, although working on the same principles, differ from each other by the type of grasping they have.

The Model T has 4 fingers (2 on each side) that close perpendicular to the plane that separates them. This type of operation is considered to be power-grasp which is effective in handling various objects with different shapes and sizes, and is optimized by the presence of flexure joints and finger pads previously described (Figure 18). Another interesting feature of this model is the fact that it uses a floating pulley transmission mechanism, positioned in the course of the tendon, between the motor and the fingers, which allows them to function independently of each other. This mechanism thus allows the fingers to move freely in the central direction, only finalizing their movement when they encounter an obstacle, or when one of the joints reaches its limit [50].

Figure 18- Model T compliance capabilities to different objects [50].

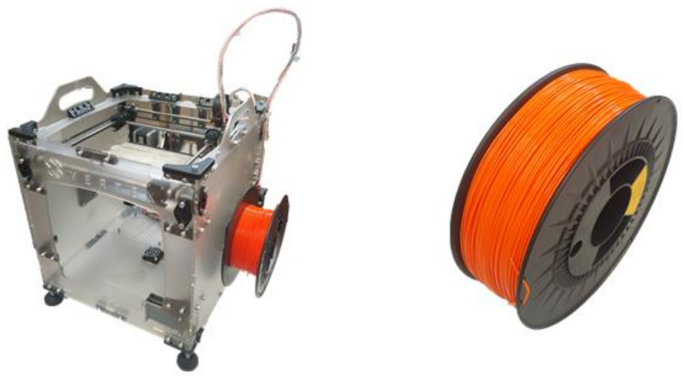
3. ROBOTIC GRIPPER

3.1. 3D Printed Parts

The construction of this robotic gripper, based on Model T from Yale OpenHand Project begins with a PLA filament that will be used by the 3D printer to transform it in the correct shape. This subchapter intends to describe the full path taken from the filament until we get the final 3D parts.

3.1.1. 3D Printer

In the original project, it was used Stratasys Fortus 250 mc [18] to print all parts, which, in this project, has been replaced by Vertex K8400 from Velleman Company, presented in Figure 19 (a). As a filament used, ABS will be replaced by PLA (both thermoplastics), which presents some differences such as the fact that the latter is organic, does not require a warm bed and allows greater precision in the prints [58], [59]. This printer has a build volume of 180 x 200 x 190 and transforms a 1.75mm PLA filament (Figure 19 (b)) into a 0.35mm output filament. The print speed is between 30 mm/s and 120 mm/s and the travel speed between 30 mm/s and 300 mm/s. Despite the maximum nozzle operating temperature is 270 ºC, it was recommended to use 210 ºC with the PLA filament [60].



(a) (b)

Figure 19- 3D Printing; (a) Vertex K8400 3D printer; (b) 1.75 mm PLA filament.

The design of the robotic gripper parts requires some CAD software so it was used *SolidWorks* and *Autodesk Inventor* to obtain the drawings which were saved in stereolithographic (STL) format. It was also necessary the *Vertex 3D Printer Repetier-Host* to transform the designs in printing models, converting the drawing into layers.

3D printing consists of a PR process that creates pieces layer by layer and is susceptible to the occurrence of some problems such as wrapping or layer misalignment. In order to reduce the likelihood of these errors occurring, some procedures were taken such as correct printer handling, good calibration of moving parts and periodic cleaning and lubrication [61]. To ensure good fixation by the printed parts, the printing surface was also been covered with painter's tape and white glue.

3.1.2. Construction Parameters

Creating parts using a 3D printer require some attention to the construction parameters utilized. In this project, *CuraEngine* was used through the software *Vertex 3D Printer Repetier-Host* to obtain the "cutting", and the type of support "touching bed" and adhesion type "brim" was chosen. The remaining parameters are shown in the Table 5.

Table 5- Printing parameters utilized on Vertex K8400.

Quality [mm]		0.1
Speed [mm/s]	Print	45
	Outer Perimeter	43
	Infill	55
Infill Density [%]	Structural Parts	30
	Non-Structural Parts	20

3.1.3. 3D Printed Parts

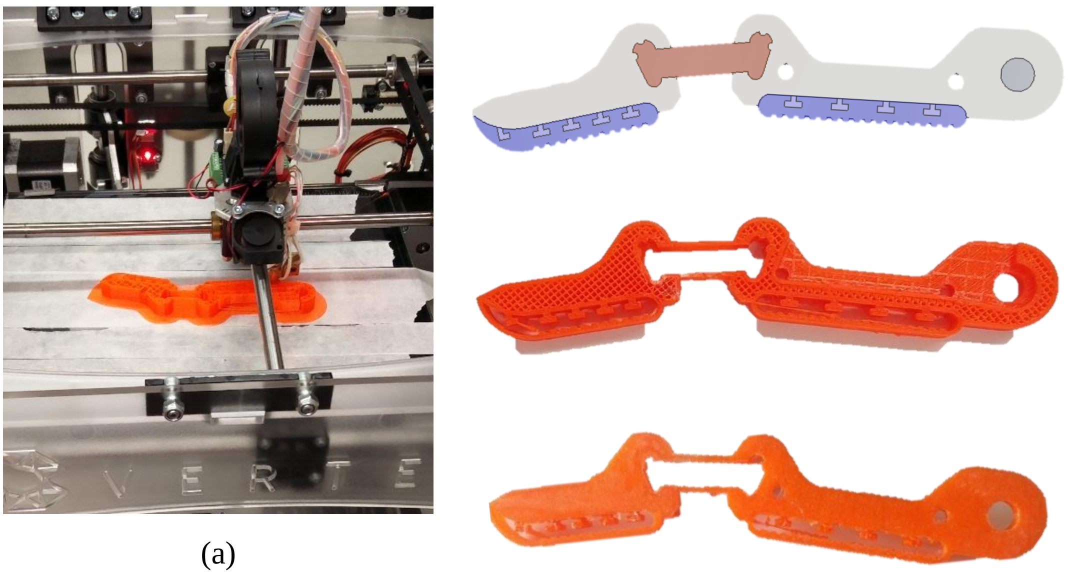
The 3D printed parts of this project consist in all pieces from the gripper produced on the 3D printer (Figure 20 (a)). Some modifications to the primary model had to be done because it was all in imperial measurements and not all components were available. As the connection between printed parts and other parts should be properly done it was all converted to metric measurements.

The implementation of the ultrasonic sensor, camera, Raspberry Pi and supplementary components also requested CAD modifications, being the primary goal to have the more functional and compact robotic gripper.

The printing time and the material required for the manufacturing of each part are directly proportional to its volume and its internal density. The layout of the parts on the printing platform has been adjusted to optimize printing using the extruder fan, the direction of the shafts and the ability to print multiple parts at the same time. All components of the hand have structural needs so the internal density chosen was 30% and the disposition of the parts caused the axes of the holes to be perpendicular to the printing surface, using support structures when this is not possible.

The process itself begins with the CAD drawing of the component (Figure 20 (b)), which, after being recorded in STL, passes through the *Vertex 3D Printer Repetier-Host* software. This program creates a G-code responsible for giving the printer the necessary information for the fabrication of the part, such as trajectory, internal density, among others (Figure 20 (c)). At the end of the process the final piece is obtained (Figure 20 (d)). In some cases, it is advisable to use support structures to ensure the integrity of the part. Although the use of these structures is automatic, they must be removed manually.

A list with the 3D printed parts is accessible in Appendix A, presenting some information about each component.



(a) (b) (c) (d)

Figure 20- 3D printed parts; (a) Printing process of a finger; (b) Finger CAD design; (c) Finger intern structure (while printing); (d) Final finger structure.

3.2. HDM

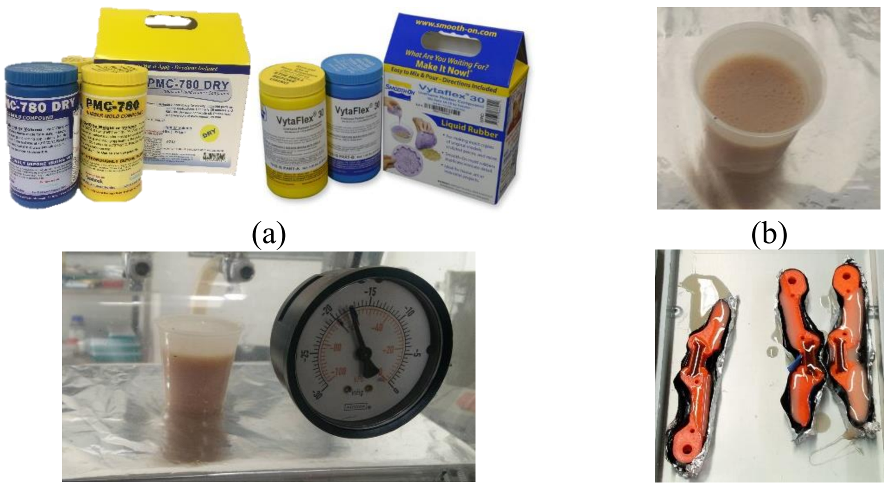
The most relevant pieces originated from 3D printing are the fingers. These components are responsible for the grasping itself and the good performance of the hand depends on the effectiveness of their actuation. The rigid structure of the fingers from the print does not allow proper compliance so HDM was used, "releasing" the fingers distal joint. The use of HDM was also extended to the finger pads in order to improve the friction between the gripper and the objects to grab.

Since the process were the same, they were approached together, starting with the placement of the fingers (Figure 21 (a)) on a movable metal base and covering the sides and the bottom with tape and aluminium foil to avoid elastomer leakage (Figure 21 (b)). Thereafter, both components are mixed in a beaker for about three minutes in a ratio of 1:1 in Vytaflex and 2:1 in PMC-780 (Figure 22 (a,b)), and placed in a vacuum chamber for two minutes in order to reduce the amount of air bubbles (Figure 22 (c)). The mixture should be carefully deposited in the fingers (Vytaflex 30 for the fingers pads (Figure 21 (c)) and PMC-780 for the flexure joints (Figure 21 (d))) to avoid blistering (which leads to fatigue rupture). The fingers should then remain for at least 48 hours at rest, with a room temperature of not less than 18ºC (the recommendation is 24ºC) and in an area where it is not subject to vibrations or drafts (Figure 22 (d)). After the cure of the urethane is completed, the thin walls are removed (Figure 21 (e)) promoting the release of the flexure joints and finger pads, being possible the superficial improvement of them through the use of the scalpel and a sandpaper. After all these processes, the finger is done (Figure 21 (f)).

The entire process requires safety equipment due to the release of toxic vapours and the room must be aired.

(a) (b) (c) (d) (e) (f)

Figure 21- HDM Process; (a) 3D printed finger structure; (b) Finger covering to prevent urethane leakage; (c) Deposition of Vytaflex 30 for finger pads; (d) Deposition of PMC-780 for flexure joints; (e) Thin walls removal; (f) Final finger.



(a) (b) (c) (d)

Figure 22- Urethanes production process; (a) PMC-780 and Vytaflex 30; (b) Mixture of urethanes; (c) Vacuum chamber; (d) Urethanes process of cure.

3.3. Other Parts

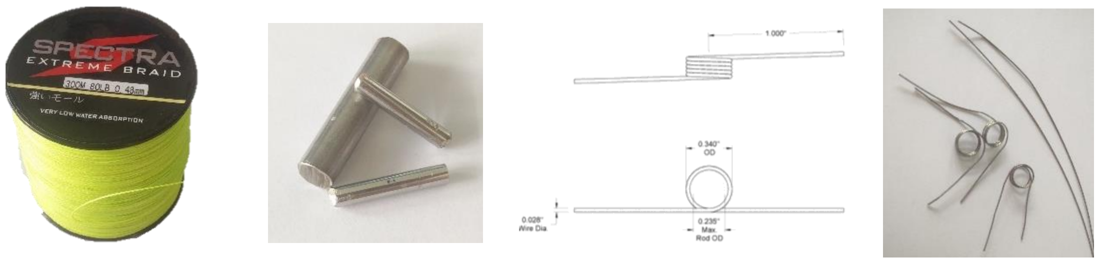
In addition to the pieces produced by the 3D printer, the robotic gripper is constituted by a set of components with unique characteristics that make them irreplaceable. Although mostly "off-the-shelf" components, due to dimensional and geometrical issues, it was not possible to simply acquire all of them, some of them having to be manufactured exclusively for their final function.

This subchapter seeks to cover some of these components that are most relevant, describing how they were obtained and their function.

Like any other tendon-driven robot, the developed hand uses a filament to move its fingers. Based on the similarity with the filament used by the other projects, the Pro Spectra fishing line (Figure 23 (a)) was chosen, with a diameter of 0.48 mm and a load capacity of 36 kg. It is also extremely resistant to moisture and abrasion which gives it a high life time, and is malleable enough for knots to be made.

The repeated movements of this filament cause the abrasion of the PLA so that the contact between these two elements should be avoided (especially in the presence of relative movements between them). The solution found is the use of metallic pins, placed strategically along the fingers, which serve as guides to the filament, maintaining the integrity of the PLA. These pins come from a 3-mm diameter stainless steel rod, then cut and heat-sealed to the fingers. Similar but differently sized pins were also used for the finger base joints and as a base to the ends of the torsion springs (Figure 23 (b)).

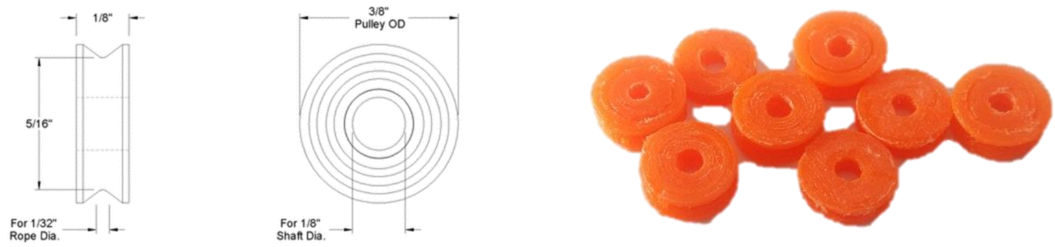
With only one motor, this hand driven by cables only allows one-way operation (close the fingers) so the opening of the hand must be automatic. In the distal joint this problem is easily solved because it has a predefined position, from the manufacture, to which it returns whenever the external forces on the finger disappear. In the case of the base, being a revolute joint, the return to the original position is achieved through the use of elastic elements, such as a torsion spring. In order for the spring to work effectively, it is necessary to match its torsion axis to the axis of the finger joint, which limits the dimensions of the spring to the dimensions present in (Figure 23 (c)). The wire diameter should be approximately 0.7112 mm (0.028 "), the number of coils is 5 and the deflection angle is 180 °. The coil outside diameter is 8,636 mm (0.340 ") and the maximum shaft diameter is 5,969 mm (0.235"). Torsion springs with these characteristics were not found so they were handmade from guitar string with 0.64 mm in diameter. This wire was wound around a stainless-steel rod creating a torsion spring with 5 coils and an outside diameter of 9 mm (Figure 23 (d)).



(a) (b) (c) (d)

Figure 23- Key components for hand construction; (a) Power Spectra fishing line; (b) Stainless steel pins; (c) Torsion spring dimensions [62]; (d) Handmade torsion springs.

To drive the wire between the motor and the fingers, pulleys are used, which, when rotated freely on a pin 3 mm in diameter on its axis, allow a harmonious movement of the fingers (Figure 24 (a)). These pulleys cannot be influenced by the friction with the space surrounding them, being preferably of nylon. In turn, and due to the lack of availability of this component in the required dimensions, these were obtained PLA, through 3D printing. After many attempts, the most favourable dimensions for the pulley are an outer diameter of 9 mm, a width of 2.2 mm and an internal diameter of 3.3 mm (Figure 24 (b)).



(a) (b)

Figure 24- Pulley; (a) Pulley dimensions [63]; (b) 3D printed pulley.

As for the remaining structural components, they were all converted to the metric system. The most relevant are the bars used to ensure the stability of the entire structure, fixing with pretension the upper base of the hand to the lower base. For this purpose, a 6-mm diameter stainless steel threaded rod (M6) was cut into 4 parts of 95 mm and fixed to the structure by 16 self-locking nuts.

Appendix B present a list of the components used in the gripper that does not come from 3D printing.

3.4. Assembly of the Hand

After obtaining and/or manufacturing all the necessary components for the construction of the hand, it is required to prepare the fingers, making the holes and cuts needed for the passage of the tendon and placement of the springs. This process was aided by the indications given in the [57]. With the fingers fixed to a bench vise, the cable passage was secured by drilling with a 1 mm diameter drill bit (Figure 25 (a)). For the springs, keeping the finger on the bench vise, a 1.5 mm hole was made with a drill bit and the cut with a normal iron saw (Figure 25 (b)). This process was replicated equally to all the fingers of the hand.

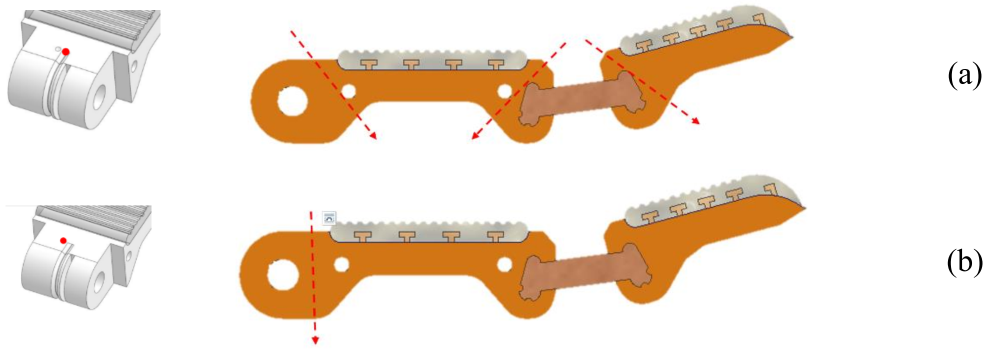


Figure 25- Fingers preparation; (a) Preparation to the tendon; (b) Preparation to the torsion springs.

The metal pins and the tendon terminating screw were then inserted in the fingers with the aid of heat (Figure 26). This step requires some care because high temperature deforms the PLA, which causes the part to be lost. Finally, the torsion springs are placed in the respective compartments and the fingers are fully prepared to be mounted in the hand.

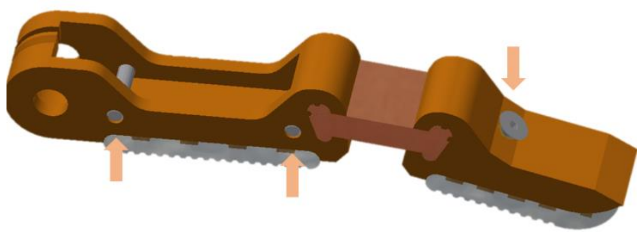


Figure 26- Insertion of the metal pins and tendon terminating screw.

After the fingers, the various groups of components that make up the transmission of pulleys between the motor and the fingers are assembled. These conjugations have the pulleys that are followed by the tendon, which, upon assembly, should rotate freely on the metal shaft. The insertion of these pins in the remaining parts must be tight to prevent them from disassembling Figure 27.

(a) (b) (c)

Figure 27- Components of transmission.

The motor is also incorporated inside the wrist of the robotic hand, to which are coupled a set of components responsible not only for serving as the interface between the motor and the tendon, but also for guiding it correctly to the following components (Figure 28). All of these parts were obtained from the 3D printer and are assembled through the use of screws.

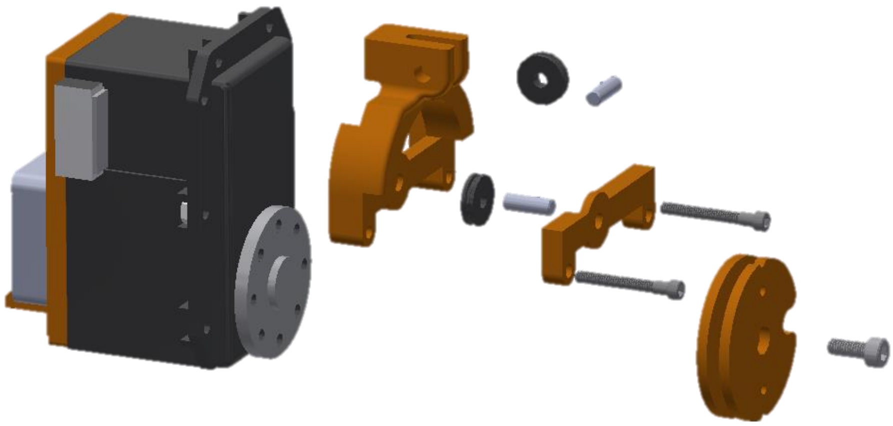


Figure 28- Assembly of the motor additional parts.

The fingers were attached to the base of the hand, which, through the threaded rods, was connected to the lower plate. It is among these plates that all the components were placed including the motor, from which the tendon part towards the fingers, passing through all the components, as shown in Figure 29.

The lower hand plate has been modified to make it easier to mount it on the robotic arm (Appendix E). Considering that the latter uses a pneumatic tool change system, a similar component was also added to the gripper so it could fit correctly.

Figure 29- Robotic gripper assembled.

3.5. Working Capabilities

This robotic gripper is considered a low-cost equipment, not having the electronic complexity of some of the competition. To compensate for the financial constraints, this device relies on several features, which together allow a good grasp.

One of the key points is the effectiveness of the fingers which comes from the contact surface and the distal joint. The contact surface is composed of a layer of urethane, which allows good friction and even some compliance with the objects. The flexure joint allows both parts of the finger to articulate freely, having an infinite number of DOF (Figure 30). As the flexure joint is entirely related to its dimensions and geometry, the width is much greater than the thickness, making flexing preferential in the direction of the object, without, therefore, restricting it in any other (Figure 31).

The fact that the flexure joint has a greater modulus of elasticity than the torsion spring causes the fingertip to close after the base contacts the object, which is also positive for the quality of the grasp.

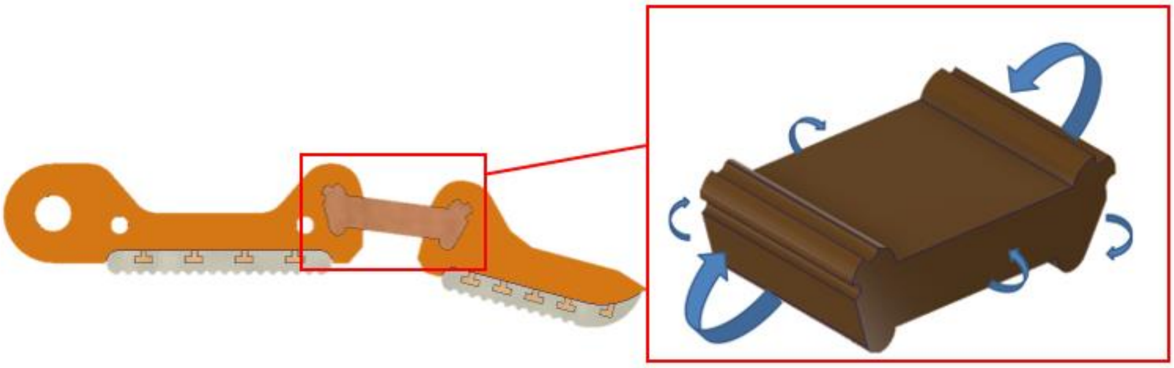


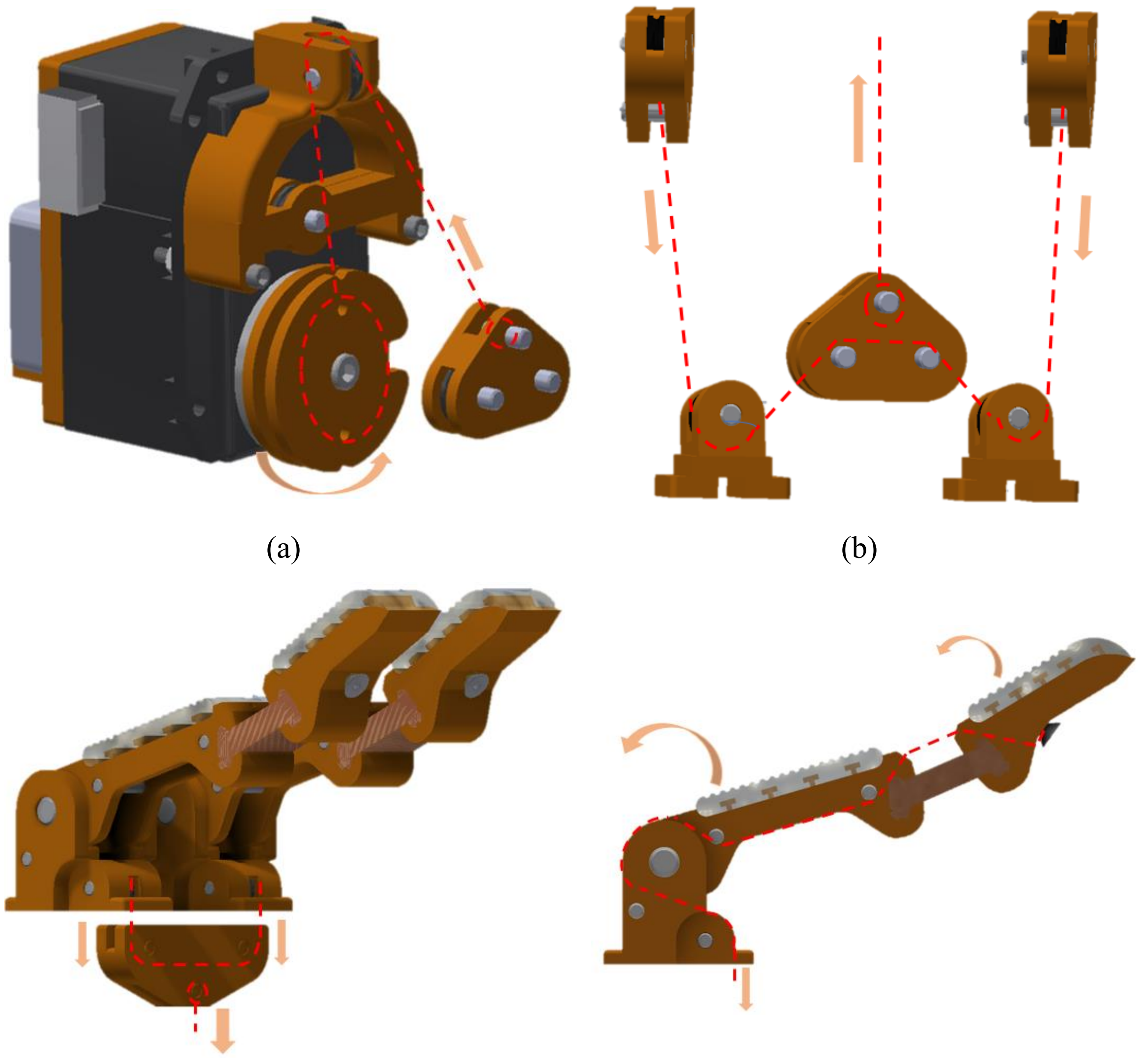
Figure 30- Detailed view of the flexure joint.

Figure 31- Finger flexion demonstration.

Another beneficial feature in the operation of the robotic gripper is its cable routing, which makes the whole operation extremely flexible. The movement of the hand begins with the rotation of the motor, which rolling the tendon, pulls the first component of the transmission (Figure 27 (a)), which is attached at the other end (Figure 32 (a)). Another tendon, which extremities are attached to other components (Figure 27 (c)), passes through the two pulleys of this first component. Since the passage of the wire in the two pulleys does not have any restriction, the movement of the two tips of the wire is not necessarily the same, adjusting the position of the two pairs of fingers to the object (Figure 32 (b)). This system repeats itself on each side of the hand, where the tendon starts on the tip of a finger and travels through the floating pulley block (Figure 27 (c)) until it reaches the end of the other finger. In this way, each of the lateral subsystems also has the above-mentioned interdependence, allowing that even after one of the fingers stops, the other one proceeds until contacting the object (Figure 32 (c)).

This internal pulley mechanism allows to transform the command of a single motor into an independent motion of the robotic gripper fingers, causing all of them to contact the object during its operation.

The Figure 32 presents the tendon path from the motor to the fingertips, using arrows to describe the movement of the thread and its result in the various parts of the mechanism. Finally, in Figure 32 (d), the tendon path along the finger is shown in detail, in order to facilitate the perception of its functioning.



(a) (b)

(c) (d)

Figure 32- Complete sequence of robotic gripper motion; (a) Connection from the motor to the first component; (b) Floating pulley transmission; (c) Floating pulley block connecting two fingers; (d) Tendon path along the finger.

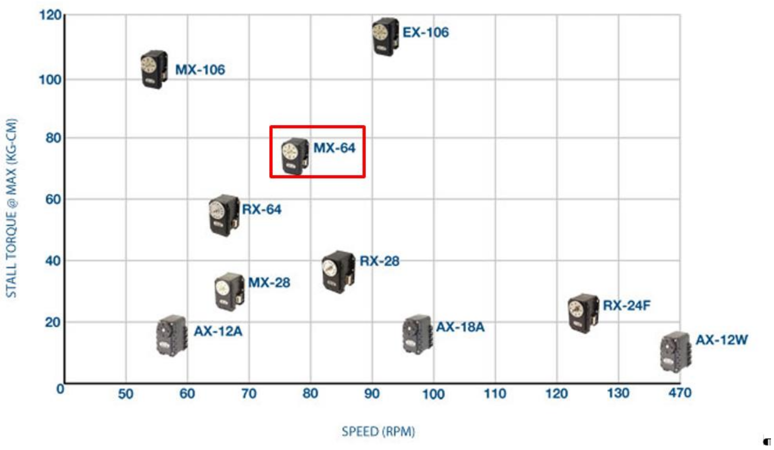
4. ACTUATOR

A mobile system needs actuators to perform its task properly, with the most common option being the use of motors. Although there are several types of motors, it was used in this project an electric motor, responsible for converting electric energy into mechanical energy.

The operation of the motor consists of applying a certain torque to an axis connected to a servo horn. The maximum torque, the speed and the direction of rotation can be modified in order to achieve the desired result as efficiently as possible.

This project consists on a tendon driven robotic gripper so the motor is responsible for pulling the cable, turning its rotational movement into a translation one, using a 3D printed piece that connects with the servo horn where the tendon will be rolled. Despite the various options available in the market, the model chosen was the Dynamixel MX-64AR, presented in Figure 33, which shows to be a good option.

This chapter seeks to detail the operation of the engine, starting with a presentation of the physical characteristics and ending with its inclusion in the robotic gripper.



(a) (b)

Figure 33- Dynamixel choosen Motor; (a) MX-64AR; (b) Comparison between Dynamixel MX-64 and other models [64].

4.1. Important Data

This engine, composed of metal gears and engineering plastic body has a mass of 135 grams and the dimensions of 40.2 x 61.1 x 41.0 [mm], presenting a good compactness and constructive quality. It works with an operating voltage between 10 and 14.8 V, the recommended value being 12 V. Depending on the voltage supplied to the motor, the speed of rotation and the stall torque varies, increasing as the voltage increase, as shown in Table 6 [65].

Table 6- Comparison between different voltages [65].

Operating Voltage	14.8V	12V	11.1V
Stall Torque	7.3 N·m	6.0 N·m	5.5 N·m
No-load Speed	78 rpm	63 rpm	58 rpm

The motor has the ability to track its temperature, shaft position, voltage, load and speed.

The Figure 34 compares the value of current, efficiency, and speed with increasing torque. Obviously, a higher torque, requires a higher current and a lower speed. The maximum level of efficiency, occurs for torque values of 0.75 Nm.

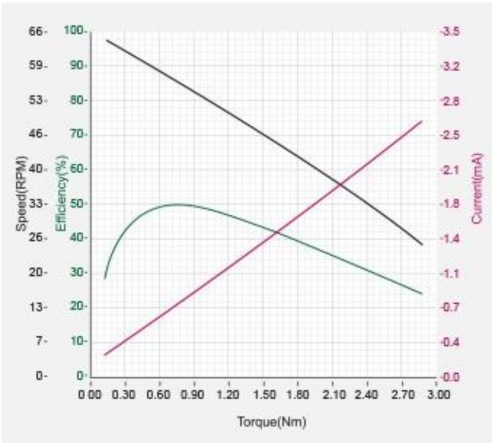


Figure 34- Dynamixel MX-64AR performance graph [65].

The operation of the motor depends on the motion of moving parts, dissipating heat to the outside. High temperatures tend to damage the engine and other components so they must be avoided at all costs. In this project, the motor is in the interior of a "box", surrounded by other components, in a zone designated as the wrist of the robotic gripper, which makes the heating even more drastic. The lack of air circulation in this place associated with the effort of the motor during the normal operation, causes a rise in temperature.

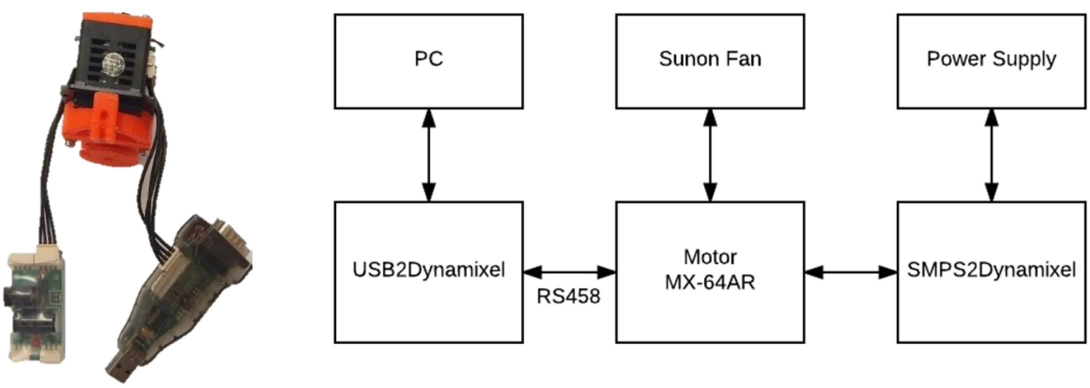
As a precautionary measure for this problem, a fan will be installed in the back of the engine, so that the temperature remains at acceptable levels. This Sunon fan works with 12 V, 0.05 A, has as dimensions 25 × 25 × 10 [mm] and has a rotation speed superior of 10000 rpm [66]. The installation of the Sunon fan is presented in Figure 35.

(a) (b) (c)

Figure 35- Installation of the fan; (a) Sunon fan; (b) Motor Mx-64AR with fan socket; (c) Assembly of the fan on the motor.

4.2. Connection Diagram

The motor connection is ensured by two cables, one for power supply and one for signal passing, which are connected on the sides of the motor, to two 4-pin sockets. On the other end of the cables are two devices, one SMPS2Dynamixel adapter and one USB2Dynamixel (Figure 36 (a)). The Figure 36 (b) provides a simplified diagrammatic view of the entire connection.



(a) (b)

Figure 36- Motor connection; (a) Photo of the connection; (b) Dynamixel MX-64AR connection diagram.

SMPS2Dynamixel consists of a switched-mode power supply (SMPS) and is responsible for the passage of electric current between the power supply and the motor (Figure 37 (a)).

USB2Dynamixel, is fundamental in this connection because it is through it that information and signal are shared between the computer and the engine (Figure 37 (b)). This component has several ports (TTL, RS232, USB2.0 and RS485) but in this project only the USB2.0 and the RS485 port (4 pins) was used, being necessary to define, through the lateral switch, which of the connections are being used [67].

As a future work, it is possible to simplify this construction by replacing the USB2Dynamixel, to a Wavesharer RS485 port, presented in Figure 37 (c), making the whole connection more compact, efficient and economically viable.

(a) (b) (c)

Figure 37- Motor connection; (a) USB2Dynamixel; (b) SMPSDynamixel; (c) RS485 Wavesharer.

4.3. Installation on the Gripper

In the previous chapter the robotic gripper assembly was described, in which the presence of the motor was mentioned. It is now presented in more detail, the inclusion of the motor in this device.

As mentioned before, the motor is placed inside the wrist of this robotic hand and, despite the fact that it is responsible for the action of the hand, creating motion and vibrations, it is also an element sensitive to humidity, heat and obviously to shock. As such it has to be completely motionless, well fixed inside the wrist, always keeping space around it for air circulation.

To secure it properly was moulded in the horizontal surfaces of the gripper the shape of the motor, fitting it between them and using the threaded rod and the self-locking nuts to ensure its immobilization (Figure 38).

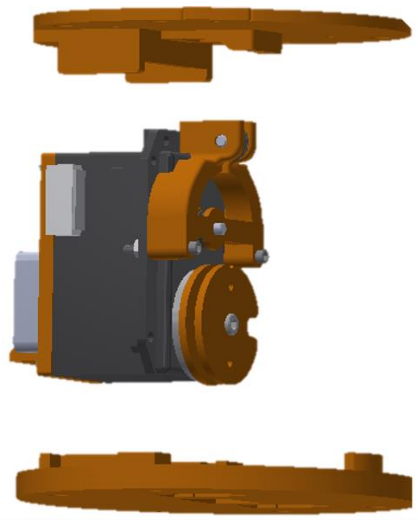


Figure 38- Installation of the motor in the gripper.

4.4. Operation

Like any other electric motor, the operation is based on converting electrical energy into rotational mechanical energy by spinning a shaft inside of it, which is attached to a servo horn. In this specific case, the rotation of the servo horn rolls the tendon, which through a set of pulleys, makes the fingers close. Some considerations such as the maximum torque, the direction of rotation, the speed and the amount of tendon to be pulled, are controlled from the motor programming.

This robotic gripper only has one actuator so the possible moves to control are the hand closing and the hand releasing, which correspond to the same command but in opposite directions.

4.4.1. RoboPlus

Dynamixel actuators have a set of pre-defined characteristics and values, which can be viewed using a software called RoboPlus. This program allows the manipulation of Dynamixel products and also provides an overview of all the relevant values about the actuator, which are presented in Table 7.

Table 7- Dynamixel MX-64AR Parameters.

Addr	Description	Value	Addr	Description	Value
0	Model Number	310	27	I Gain	0
2	Version of Firmware	36	28	P Gain	32
3	ID	2	30	Goal Position	3284
4	Baud Rate	34	32	Moving Speed	1032
5	Return Delay Time	250	34	Torque Limit	1023
6	CW Angle Limit	0	36	Present Position	3284
8	CCW Angle Limit	4095	38	Present Speed	0
11	The Highest Limit Temperature	80	40	Present Load	0
12	The Lowest Limit Voltage	60	42	Present Voltage	119
13	The Highest Limit	160	43	Present Temperature	43
14	Max Torque	1023	44	Registered Instruction	0
16	Status Return Level	2	46	Moving	0
17	Alarm LED	36	47	Lock	0
18	Alarm Shutdown	44	48	Punch	0
20	Multi turn offset	0	68	Sensed Current	2048
22	Resolution divider	1	70	Torque Control Mode	0
24	Torque Enable	0	71	Goal Torque	0
25	LED	0	73	Goal Acceleration	0
26	D Gain	0			

The motor has various operating modes such as a stepper motor (joint) or a normal motor (wheel), which can also be tested using RoboPlus. Operation as a stepper motor causes the motor to rotate a certain angle in a certain direction, which, in the case of MX-64AR, is limited to 360°.

4.4.2. Python Code

The control of the motor is achieved by sending commands to it from the computer through USB2Dynamixel connection. In this specific design, USB2Dynamixel makes the connection between the motor and a Raspberry Pi3, which, on its memory card, contains all the code necessary for the correct actuation. The programming of this robotic gripper could only be based on a command that would cause the motor to rotate a certain number of degrees, in a certain direction, closing or opening the hand. However, choosing this motor allows access to a set of sensors and data that can be very useful to improve the operation of the gripper, so, it would be a waste of resources not to use its full capabilities. In turn, the code becomes too complex and extensive so it will be used as the base, the opensource code available in GitHub, for the Yale OpenHand Project.

4.4.2.1. GitHub OpenSource Code

The code provided on GitHub consists of a set of libraries capable of properly controlling MX and RX series servos, directed to all models of robotic grippers of the Yale OpenHand Project.

Available on the platform are the following libraries:

- dynamixelhandkontrol.py
- dynamixelkontrol.py
- lib_pololu.py
- lib_robotis_mod
- maestrokontrol.py
- nanokontrol.py
- openhand.py

Using this motor to manipulate the hand began by placing the folder with the code of the Yale OpenHand Project as the primary path, which allowed to access the data required through Python. The code entered in the Raspberry Command Line was:

- cd /home/pi/Desktop/ModelT/openhand-software-master
- python -i openhand.py

After accessing the code, it is necessary to provide the system with some information such as the model of the hand that is being used (Model_T), the port number (/dev/ttyUSB0) and the name given to the actuator (2). The introduction of these variables is done as follows:

- T = Model_T("/dev/ttyUSB0",2)

With the system initialized and the motor recognized, it is now possible to send the desired commands. To close the gripper, the following command is used:

- T.close([desired torque for closing grasp])

The torque can vary between 0.0 and 1.0, but it is recommended values in the order of 0.3. The opposite command corresponding to the hand opening is entered as follows:

- T.release()

In the Appendix C it is presented the basic usage of the motor, as well as an exemple.

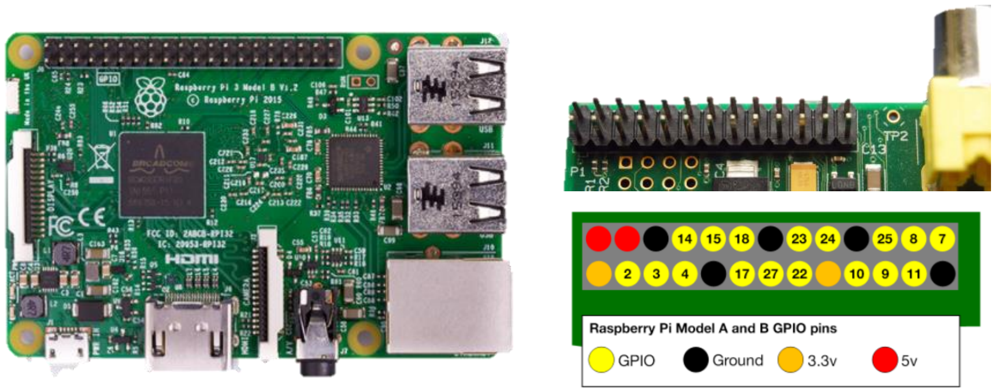
5. RASPBERRY PI 3

The robotic gripper of this project uses a motor, which, like any other robotic component, requires control, so that it can act as desired. As mentioned before, a camera and a proximity sensor were also installed in the robotic hand, so, instead of controlling everything remotely and with a lot of electric wires, it was decided to use another mechanism. This new approach, called embedded control (EC), consists of using the microcontroller responsible for the various tasks required in this case. Despite the existence of several options in the market, Raspberry Pi3 was chosen for this function, providing some advantages such as integrated Wi-Fi, functional operating system with an excellent graphical interface, compactness and above all, allowing to run Python in a practical and effective way.

5.1. Data and Principles of Operation

The Raspberry Pi 3 is a compact single board computer that features several interesting features such as integrated wireless LAN and Bluetooth so it was chosen to control the robotic gripper (Figure 39 (a)). Despite its small size (85x56x17 [mm]), this device has a wide range of ports such as an HDMI port, 4 USB2.0 ports, a camera interface, 40-pin General Purpose Input / Output (GPIO) (Figure 39 (b)) and others, which allows you to connect to a wide variety of other devices. It also has a 1.2GHz Quad Core processor coupled with 1Gb of RAM, which makes this microcomputer a powerful working tool.

To operate under proper conditions, it is necessary to supply a current of 2.5A with a voltage of approximately 5V [68].



(a) (b)

Figure 39- Embedded control; (a) Raspberry Pi 3; (b) GPIO connection [69].

5.2. Installation on the Gripper

As mentioned before, one of the advantages of choosing the EC in the robotic hand is the production of a simplified system with fewer cables and, if possible, more compact. Some geometric modifications in the robotic hand were made in such a way that it is possible to fix a Raspberry Pi 3 box on its side, keeping it still and safe during the operation of the hand (Figure 40). This box is located on the opposite side to the motor in order to prevent possible temperature increases, and, in a zone that allows the electrical wires to reach all its components.

(a) (b)

Figure 40- Installation of Raspberry Pi 3 in the robotic gripper.

5.3. Pi Camera

As mentioned before, this project includes a camera so it is possible to give the operator the robotic gripper point of view. The camera should be installed in the gripper, always ensuring an unobstructed view of the object and without influencing its work. In this way, it is essential a small camera with low mass. Taking advantage of the fact that the control base of the motor is Raspberry, which has a specific camera slot, the device chosen for obtaining the image was the Raspberry Pi Camera V2.1.

Figure 41- Raspberry Pi Camera V2.1.

5.3.1. Data and Principles of Operation

The Raspberry Pi Camera Module V2.1 is an imaging device and was placed in the robotic gripper in order to ensure that its point of view reaches the operator. This camera has an IMX219 sensor from Sony with 8 megapixels guaranteeing good video and photos quality. It weighs 3 grams, has dimensions as 25 x 23 x 9 [mm] and connects to the Raspberry via a short ribbon cable (Figure 42 (a)) [70].

As this camera is designed from scratch to work with Raspberry, the bonding is completed without problems and it is just necessary to enable the camera on Raspberry.

5.3.2. Installation on the Gripper

In order to obtain a good quality video, it is important that the camera stays in a favourable position, free of any physical interference between itself and the object. It is also important to remember that the use of the camera slot in Raspberry Pi 3 requires the flat cable which have a limited size. Finally, since the objective of the gripper is to be used in the robotic arm, its compactness should be sought to the maximum, which makes it necessary to position the camera as close as possible to the centre of mass of the robotic gripper.

Taking advantage of the Raspberry Pi3 printed box, a structure was designed to fix over raspberry serving as protection for the camera and allows the instant adjustment of your viewing angle (Figure 42 (b,c)). In Appendix E, is presented the drawing sheet of each part.

(a) (b) (c)

Figure 42- Installation of the camera; (a) Connection between the Pi Camera V2.1 and the Raspberry Pi 3; (b) Camera support; (c) Camera assembled on the gripper.

5.4. HC-SR04 Ultrasonic Sensor

As it was previously mentioned, to establish a perfect grip, it is important that the object fits correctly inside of the gripper fingers so they can embrace it better. This project consists in a production of a gripper capable of grabbing objects of different sizes and shapes and consequently there is not a predefined optimum distance between the hand and the object.

Ultrasonic ranging module HC-SR04 (Figure 43) is a non-contact measuring device that can give in real time the distance between its lens and an object. This instrument is connected directly to the Raspberry and attached to the gripper so the ultrasonic wave could be reflected on the object.

Figure 43- Ultrasonic Ranging Module HC- SR04.

5.4.1. Data and Principles of Operation

An ultrasonic sensor sends ultrasonic waves that travels in the air and, after reflecting in an object, returns to the sensor.

HC-SR04 sensor, from Elecfreaks (Figure 43) has a range between 2 cm and 400 cm (4 meters) with a maximum error of 3 mm and works with a current of 15 mA and DC 5 V. The measuring angle is 15 degrees and the trigger input signal is 10 μS pulse.

It all starts with the Trigger receiving a 10μS 5V input which generates an 8-cycle ultrasonic burst. When these waves find an object, they reflect on its surface echoing back to the sensor altering the Echo pin to High (Figure 44). Different distances will create a different delay so it is possible to calculate the gap between the device and the object by the following formula [71]:

$$Distance = \frac{high\ level\ time * velocity\ of\ sound\ (340\frac{m}{s})}{2}$$

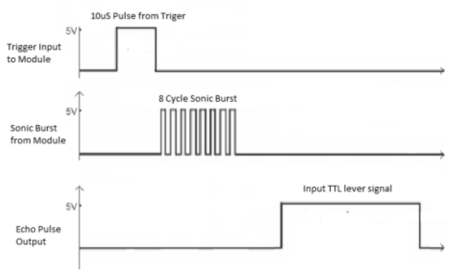


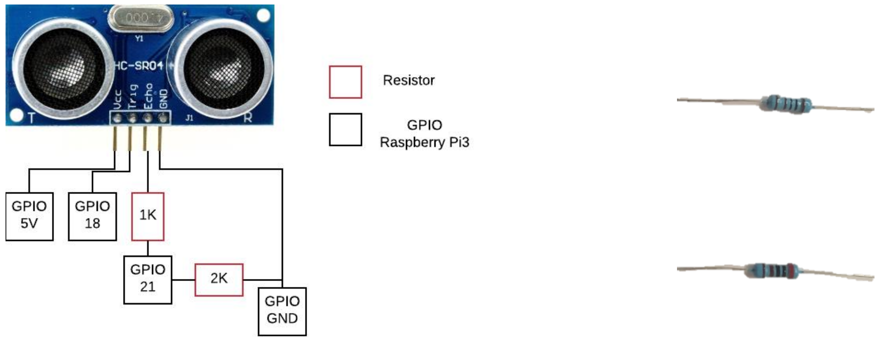
Figure 44- HC-SR04 diagram [71].

The code required to the operation of the sensor is shown in the Appendix D. The Trig and Echo pins of the sensor are connected respectively to pins 18 and 21 of the GPIO, enabling the passage of information. As result, the sensor returns to the operator the distance, in centimetres, that separates it from the object.

5.4.2. Installation on the Gripper

To use properly the ultrasonic sensor, first, it is necessary to connect it to Raspberry Pi3, which is possible using the GPIO pins. HC-SR04 has 4 pins as said on the beginning of this chapter which are Vcc, Trig, Echo and GND.

Since the voltage admitted on Raspberry Pi 3 is 3.3V and HC-SR04 works on 5V, it is necessary to apply some electronic knowledge as presents in the diagram of Figure 45 (a). The red square represents the resistors, presented in more detail in Figure 45 (b).

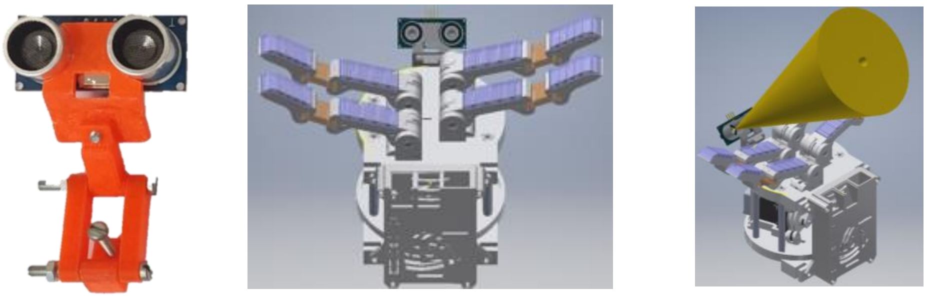


(a) (b)

Figure 45- Installation of Ultrasonic Sensor; (a) Connection diagram between EC and HC-SR04; (b) Resistors.

Since the ultrasonic sensor is not capable of distinguish the object which is echoing, it is necessary to guarantee that nothing will be between his sensors and the object. To solve this problem, needed to join some data as the measuring angle, the position of the sensor when attached to the hand and even the expected position of the object. For obvious reasons, the ultrasonic sensor support (Figure 46 (a)) must be placed on one of the laterals of the hand, sending the ultrasonic waves through the closing point of the fingers. This support was designed on Inventor and all measures are shown in Appendix E. Considering that one of the laterals is already occupied by Raspberry Pi3 and Pi Camera, it is necessary to use the other side (Figure 46 (b)).

To ensure that any component of the gripper is affecting the “field of vision” of the sensor, it was drawn a cone on Inventor, starting on the sensor and passing through the middle of the fingers. This cone has 30º degrees from side to side so it represents the maximum oscillation of the ultrasonic waves (HC-SR04 has a measuring angle of 15º degrees). As shown in Figure 46 (c), ultrasonic waves emitted by HC-SR04 does not touch on the gripper.



(a) (b) (c)

Figure 46- Installation of ultrasonic sensor;(a) Ultrasonic sensor support (b) Position chosen for the HC-SR04; (c) HC-64AR measuring angle.

6. MYO

As previously stated, control of robots through programming is usually complex, time-consuming and requires extensive knowledge in the field. In turn, the advances of technology reduce the distance between man and the machine, imposing better communication between them, and increasing the versatility of work. In collaborative robotics, for example, it is fundamental that human-machine interaction (HMI) flows smoothly, the robot being an extension of human capacity. In this way, it is impracticable that the control of these robots be done in real time, through programming. Some alternatives are voice and gesture control.

Control by gesture recognition is normally based on vision systems, which present some problems such as limited area of action, due to the fact of using fix sensors to control mobile actions. Other option is to use sensors, placed on the body surface, such as the data glove or the magnetic tracker device [72], [73]. In turn, for a device to be used effectively, it must be comfortable, not influencing for any reason the movement of the operator. One possible solution is Myo armband.

6.1. EMG

Electromyographic (EMG) sensors consist of devices capable of acquiring the neuromuscular electrical signals that occur during the contraction of the muscle [74], and can be made in an invasive manner, in which needles are placed in the muscular tissue, or in a non-invasive way, through superficial electrodes, placed on the skin surface [75]. Despite the best results obtained through the intramuscular (imEMG) sensors (invasive method), it is uncomfortable and impractical, so surface (sEMG) sensor (non-invasive method), is more usual [76].

One of the great applications of EMG sensors is in amputees, who, despite not having the hand, continue to have the muscles of the forearm responsible for its movement. In this way, it is still possible to control the prostheses by muscular impulses [77]. However, not all are advantages, being this method negatively influenced by the electrode position variation on the surface of the skin, by the position and movement of the limb during the performance, among others [78], [79]. As such, a good calibration, training and consistency of service conditions are essential [80].

6.2. Myo Armband

Myo armband (Figure 47) is a device developed by Thalmic Labs, which recognizes hand gestures and arm movements using two sensors (inertial measurement unit (IMU) and electromyography (EMG)). The IMU sensor, responsible for the analysis of arm acceleration and orientation, is irrelevant for this project, so it will not be studied.

Figure 47- Myo armband [81].

This armband is composed of 8 modules, each of which has a non-invasive electrode (sEMG). When correctly placed, these electrodes are arranged around the forearm, capturing the signals of its muscular activity. As these muscles are responsible for hand movements, it is possible to collect through them hand gestural date. If the signal obtained by armband corresponds to any of the predefined gestures in the system, it can be used to perform an action.

These predefined gestures are 5 and correspond to double tap, fist, fingers spread, wave left and wave right. It is possible to increase the range of possibilities combining various gestures in sequences and even adding to them IMU data. It is also possible for the operator to create new gestures.

The armband has 1 full day of autonomy and can be charged using a Micro-USB cable. The connection between PC and Myo is established through Bluetooth [81].

Figure 48- Hand gestures recognized by Myo armband [81].

6.3. Robotic Gripper Controll

The purpose of this subchapter is to describe how to control this robotic gripper. As explained before, this robotic hand consists of 4 underactuated fingers, which, through the principle of tendon-driven robots, are connected to a single motor. In this way, the motor acts by closing the robotic hand, which reopens when the motor runs in the opposite direction. Despite the great complexity of the code, detailed in chapter 4 by the large number of sensors that the motor has, the gripper control was achieved through the application of only two commands:

- T.close (Torque Value)
- T.release ()

The control of the robotic gripper from Myo was accomplished by associating each of the two commands to the predefined gestures. A third gesture was also used for unlocking the gripper. This unlocking gesture is important because it confirms that it is supposed to operate the gripper, serving as a protection measure.

The gesture chosen to deblock the system was the "double tap" (Figure 49 (a)), for the simple reason of being the most unlikely to happen by chance. For the performance of the gripper itself the most obvious gestures were chosen in order to make everything more intuitive. As such, "fist" (Figure 49 (b)) is the command to close the hand, while "fingers spread" (Figure 49 (c)) is the command to open the hand.

(a) (b) (c)

Figure 49- Myo gestures to control the robotic gripper [81].

7. CONCLUSION

This dissertation describes the production of a low cost robotic gripper for the autonomous manipulation of objects with different sizes and shapes. This component must then be coupled to a robotic arm, and resort to gesture control to perform its function effectively.

The components obtained from 3D printing have good quality and precision. On the other hand, the other materials needed to produce the hand were not found, and it is necessary to improvise with the available equipment. The solution found for the structural part, which consisted of using threaded rod cut to size and fixed by self-locking nuts, performs its function perfectly, giving the gripper an excellent stability and consistency.

Also, the fingers, produced by the HDM process, demonstrate excellent physical characteristics, which allow, as promised, a good compliance.

Following the first tests run, it is possible to check that the whole system works correctly. The information transmission is done without any problems and the 4 fingers simultaneously articulate on the object, wrapping it totally. However, there are some failures in the reopening of the fingers due to the malfunction of the torsion springs and the intermediate pulley system. In the case of springs, the fact that they are produced manually, makes them all different from each other, so that the fingers do not open at the same time. Although this failure does not present complications in the operation of the hand, the same cannot be said of the pulley system. Due to a set of dimensional and geometrical characteristics, such as the thickness of the wire and the angle with which the pulleys of the base are constructed, sometimes the wire is trapped between the pulley and the structure, blocking the return of the fingers.

The solid construction of the gripper allows free manipulation by the robotic arm, and the position of the sensors does not represent any obstacle in the grasping process. The camera features a high-quality image, which allows the operator to identify without any problem the object to be grasped, as well as its orientation in space. Due to the fact that the camera image is obtained through an internet connection, it is subjected to suffer some lag, which should be taken into consideration. The ultrasonic sensor allows to obtain the distance (in centimetres) between the object and the gripper. Its movable stand causes the distance between the sensor and the palm of the hand to vary, which must be taken into account during normal operation. It is recommended to keep the sensor in a fixed position and calibrate it to reduce the associated error.

7.1. Future Work

This dissertation documents the construction, assembly and operation of a underactuated robotic gripper. The area of soft robots, which include flexible grippers is constantly expanding, so everyday appears new problems to be solved.

In the specific case of this robotic gripper, the future work should focus mainly on solving the problem referred before, in which the wire clamps between the pulley and the structure. One possible solution would be to use a thicker wire, which requires a change throughout the CAD. Another recommendation is the installation of industrial torsional springs instead of the ones made by hand. Although not a problem, ensuring that all fingers are subjected to the same force, they allow them to open together, creating a smoother operation.

In evolutionary terms, some proposals of future works would be the experimentation of several geometries of fingers, keeping the base of the hand identical. Fingers such as “fin ray finger”, would certainly be successful. It is also proposed a change of the actuator used by a simpler and cheaper model, modifying the internal structure of the hand so that this new motor can be installed.

Finally, combining a linear laser with the existing camera in the robotic gripper, it is possible to scan the surface geometry of objects. This system can be useful in obtaining information about the objects to be grasped.

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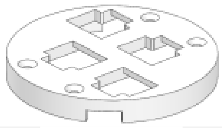
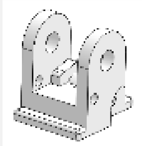
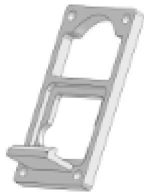
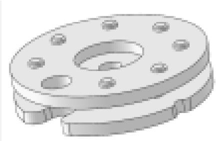
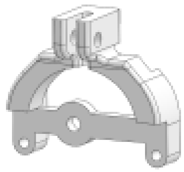
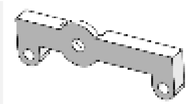
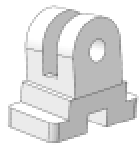
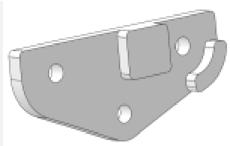
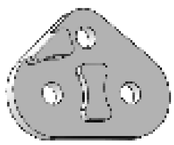
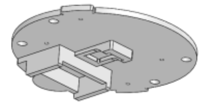
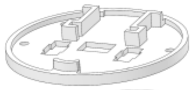
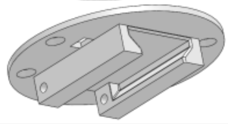
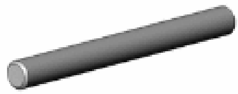
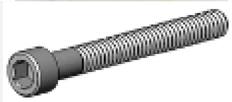
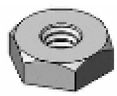
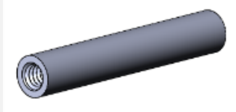
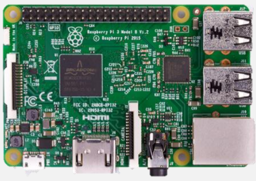
APPENDIX A (LIST OF 3D PRINTED PARTS)

Nº	List of components		Quant.	Print duration	Figure
1	Pivot-Flexure Finger		4	2h:18m:4s	
2	Wrist Top Plate		1	3h:33m:11s	
3	Finger Base		4	1h:13m:21s	
4	Fan Support		1	50m:42s	
5	Servo horn adapter		1	31m:22s	
6		Part 1	1	48m:5s	
7		Part 2	1	14m:28s	
8	Tendon pulley transmission	Part 3	2	35m:41s	
9		Part 4	4	22m:11s	
10		Part 5	2	12m:41s	

11	Top mounting plate for motor		1	2h:48m:27s	
12	Lower mounting plate for motor		1	3h:4m:24s	
13	Wrist lower plate		1	3h:41m:0s	
14	Pulley		14	5m:13s	
15	Raspberry Case	Bottom Case	1	2h:37m:14s	
		Top Case	1	2h:43m:53s	

APPENDIX B (LIST OF COMPONENTS)

Nº	List of components	Quant.	Figure
1	PMC-780 Urethane	-	
2	Vytaflex 30 Urethane	-	
3	Heat Inserted Screw	4	
4	3 mm Steel Dowel Pin	25	
5	7mm Steel Dowel Pin	4	
6	Part	4	
7	Part 3	1	
8	Sunon Speed Fan	1	
9	M3 Screws	2	
10	M3 Nuts	2	
11	5 mm Threaded rod	4	

12	Spectra Tendon	1	
13	USB2Dynamixel	1	
	SMPSDynamixel	1	
14	Raspberry Pi 3	1	
15	Raspberry Pi Camera V2.1	1	
16	Ultrasonic sensor HC-SR04	1	
17	Myo armband	1	

APPENDIX C (MOTOR USAGE)

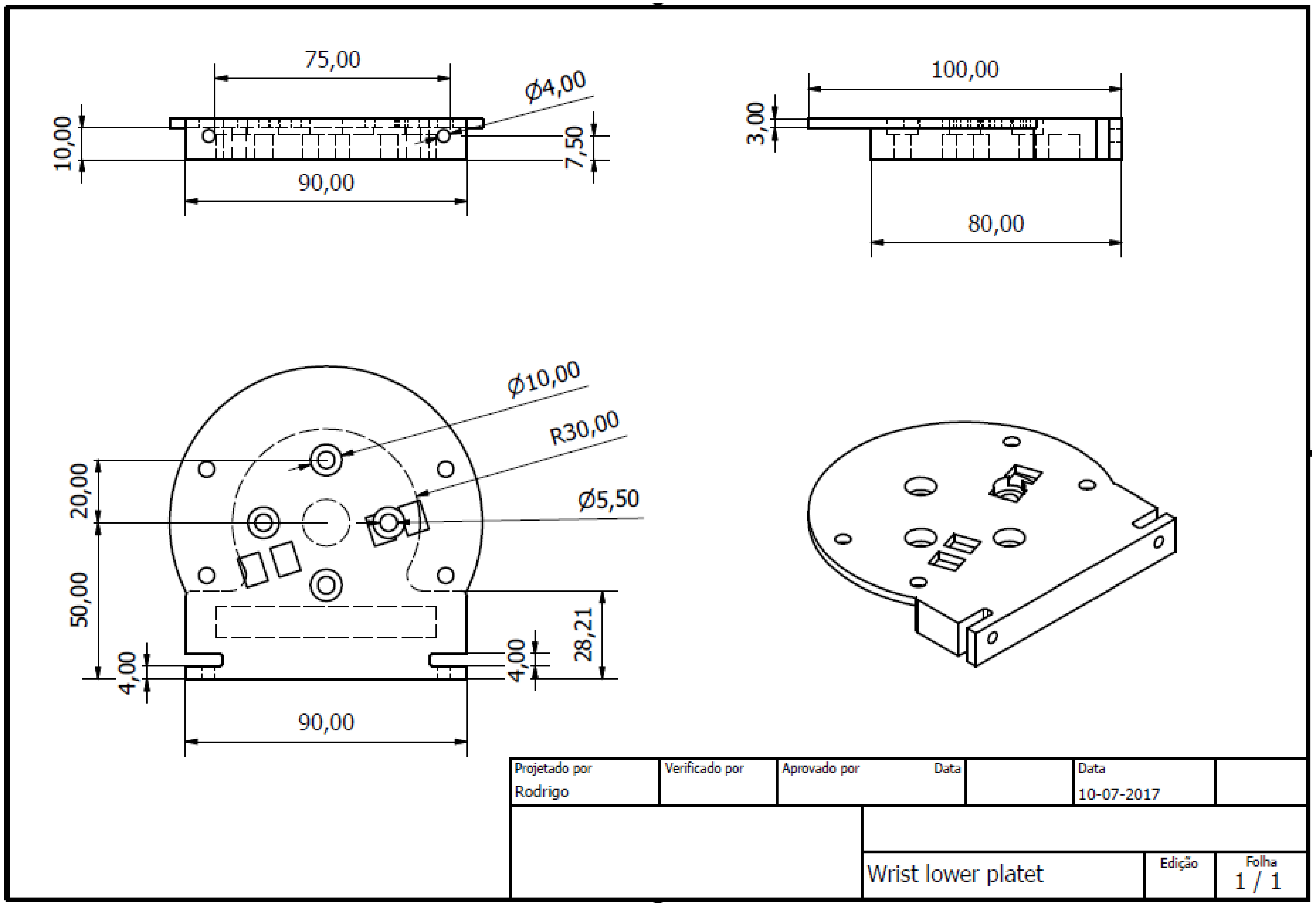
```
Basic Usage:

python -i openhand.py

>> T = Model\_T([port name], [main servo id])
>> T.close([desired torque for closing grasp (0.0-1.0)])
>> T.moveMotor([index of servo], [desired position (0.0-1.0)])
>> T.release()
```

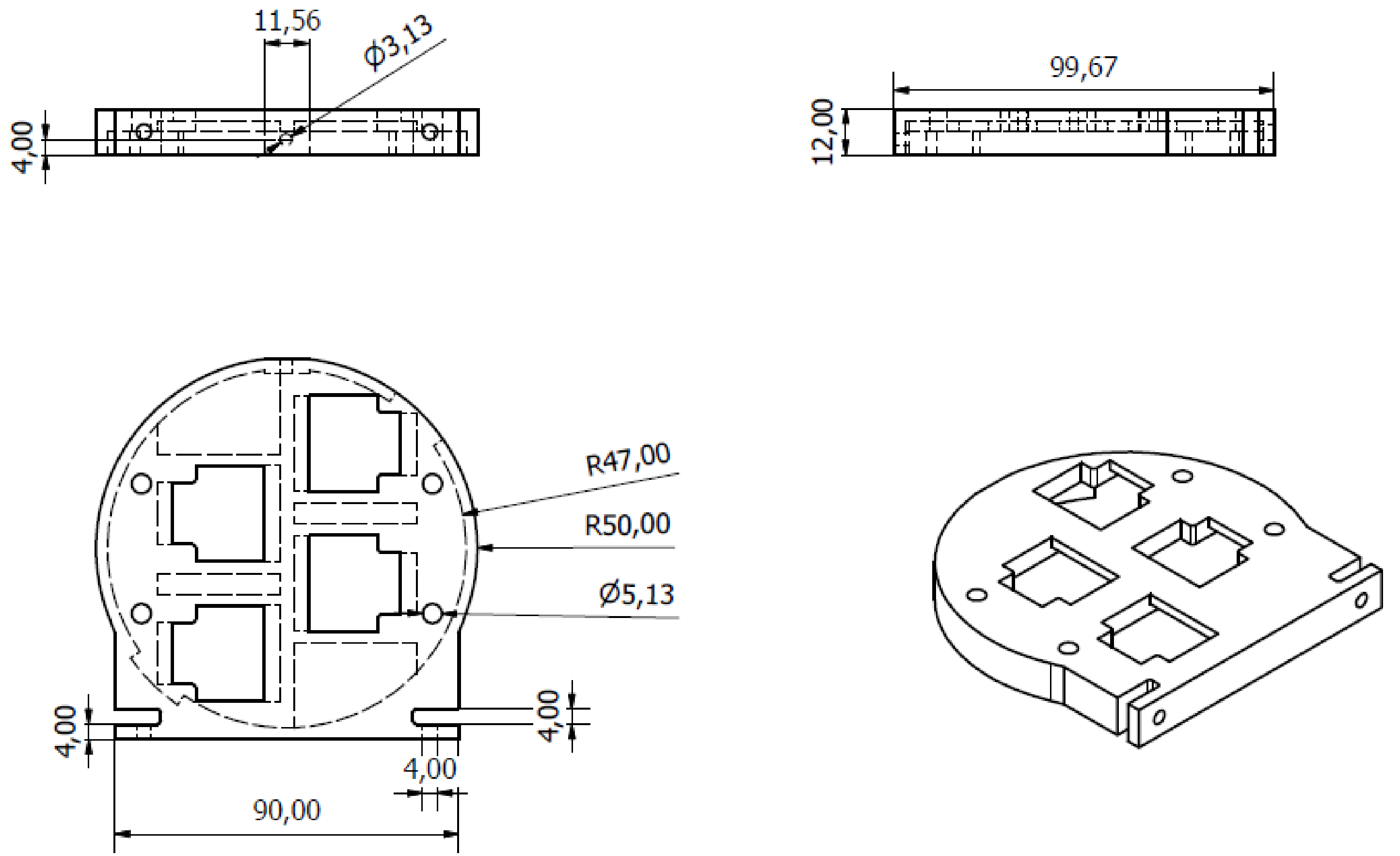
```
Example Usage:

python -i openhand.py

>> T = Model\_T("/dev/ttyUSB0",1)
>> T.close(0.3)
>> T.release()
```

APPENDIX D (HC-SR04 CODE)

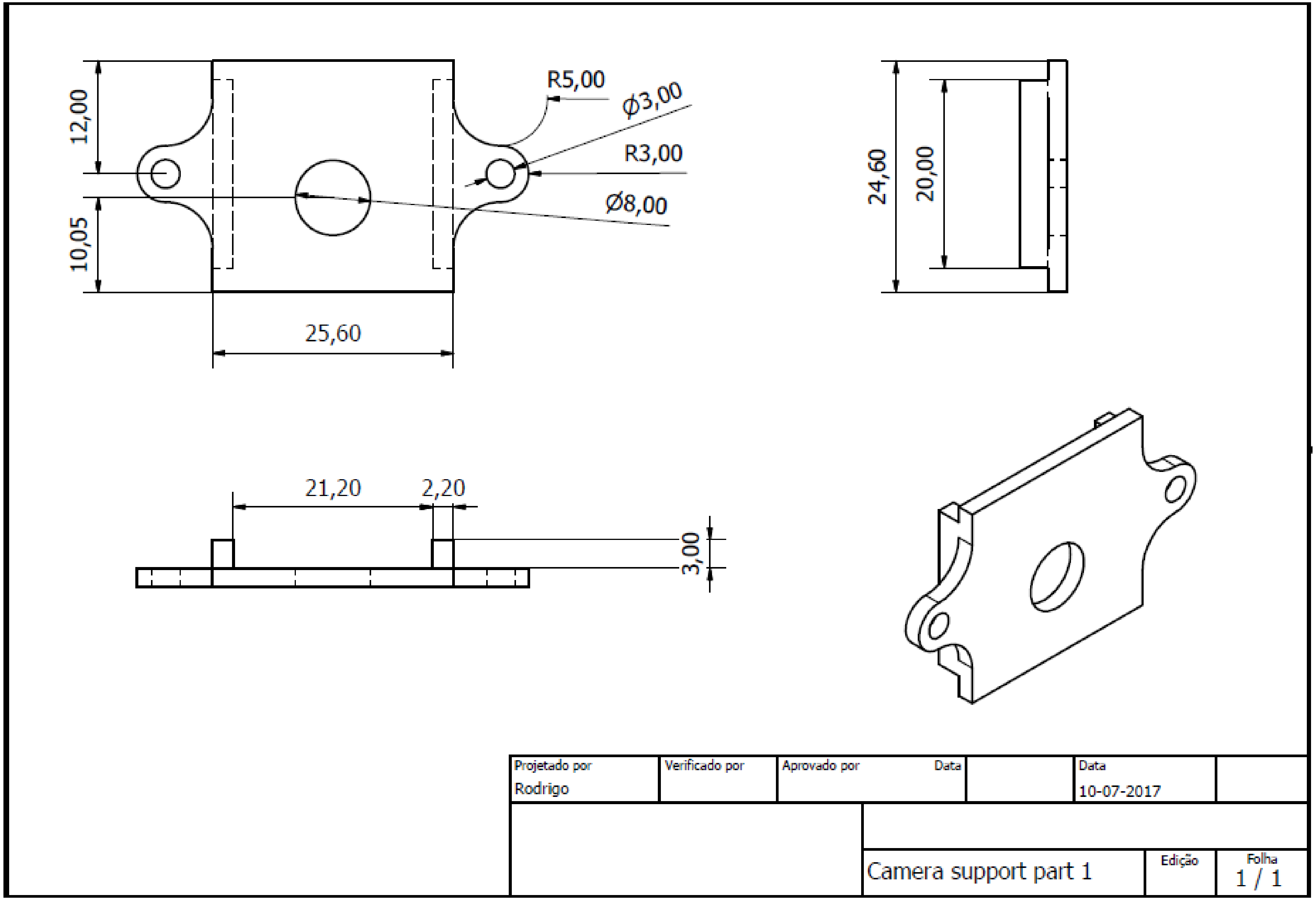
```
import RPi.GPIO as GPIO
import time
GPIO.setmode(GPIO.BCM)

TRIG = 18
ECHO = 21

print "Distance measurement in progress"

GPIO.setup(TRIG,GPIO.OUT)
GPIO.setup(ECHO,GPIO.IN)

def distance():
  GPIO.output(TRIG, True)

  time.sleep(0.00001)
  GPIO.output(TRIG, False)
  StartTime = time.time()
  StopTime = time.time()

  while GPIO.input(ECHO) == 0:
    StartTime = time.time()

  while GPIO.input(ECHO) == 1:
    StopTime = time.time()

  TimeElapsed = StopTime - StartTime

  distance = (TimeElapsed * 34300) / 2

  return distance

if __name__ == '__main__':
  try:
    while True:
      dist = distance()
      print ("Distance od the object = %.1f cm" % dist)
      time.sleep(0.1)

  except KeyboardInterrupt:
      print("STOP")
      GPIO.cleanup()
```

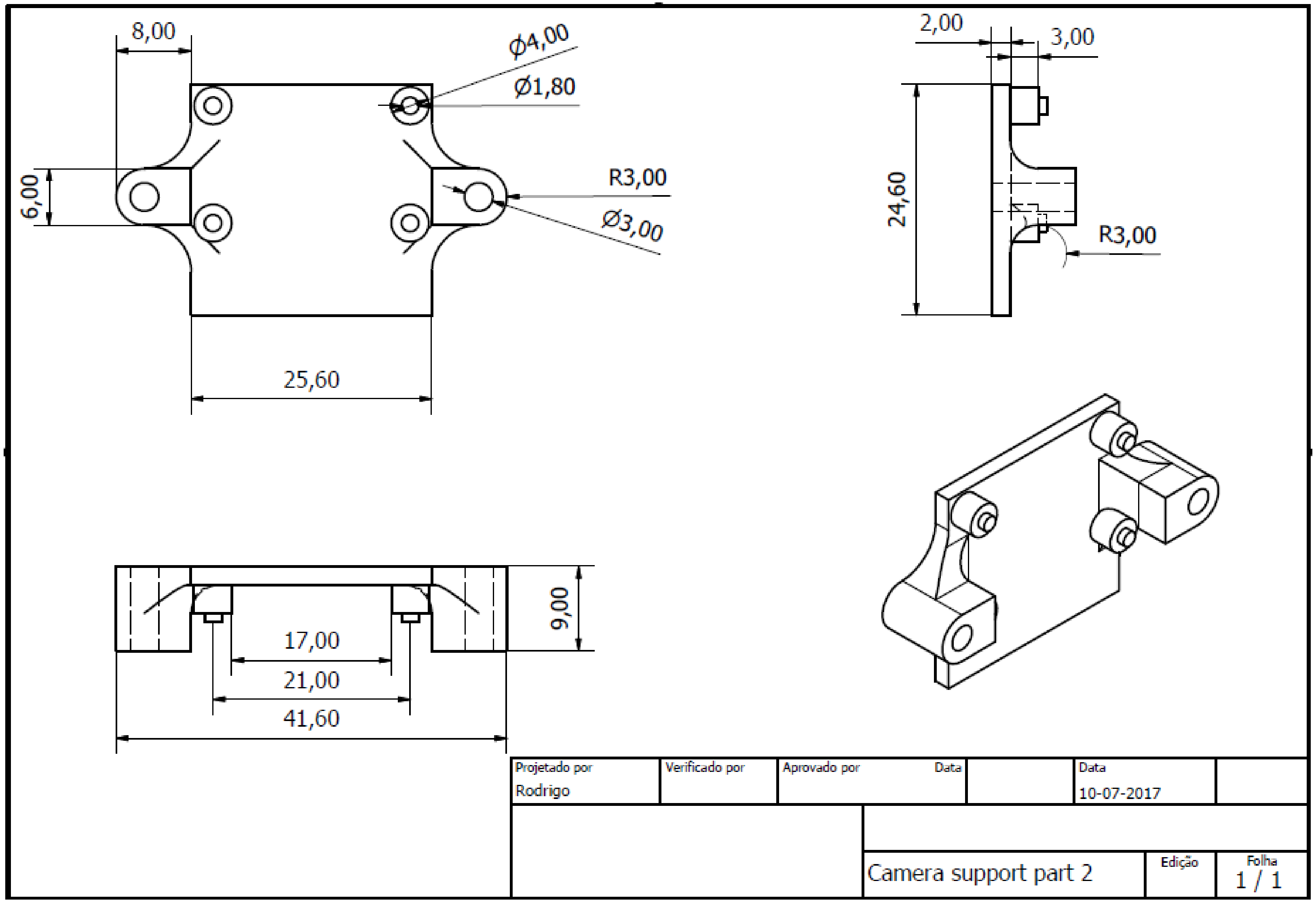
APPENDIX E (CAD FILES)

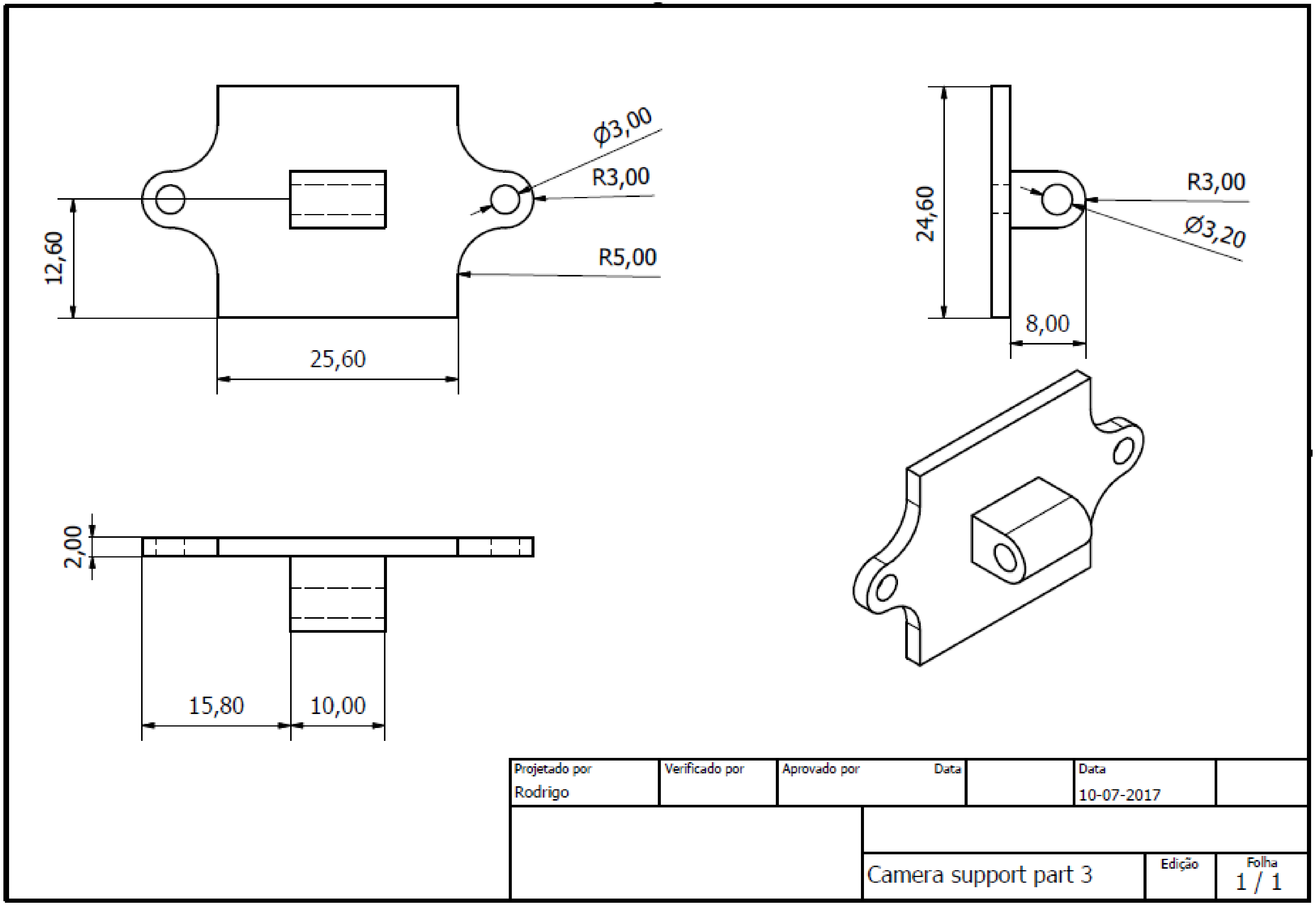


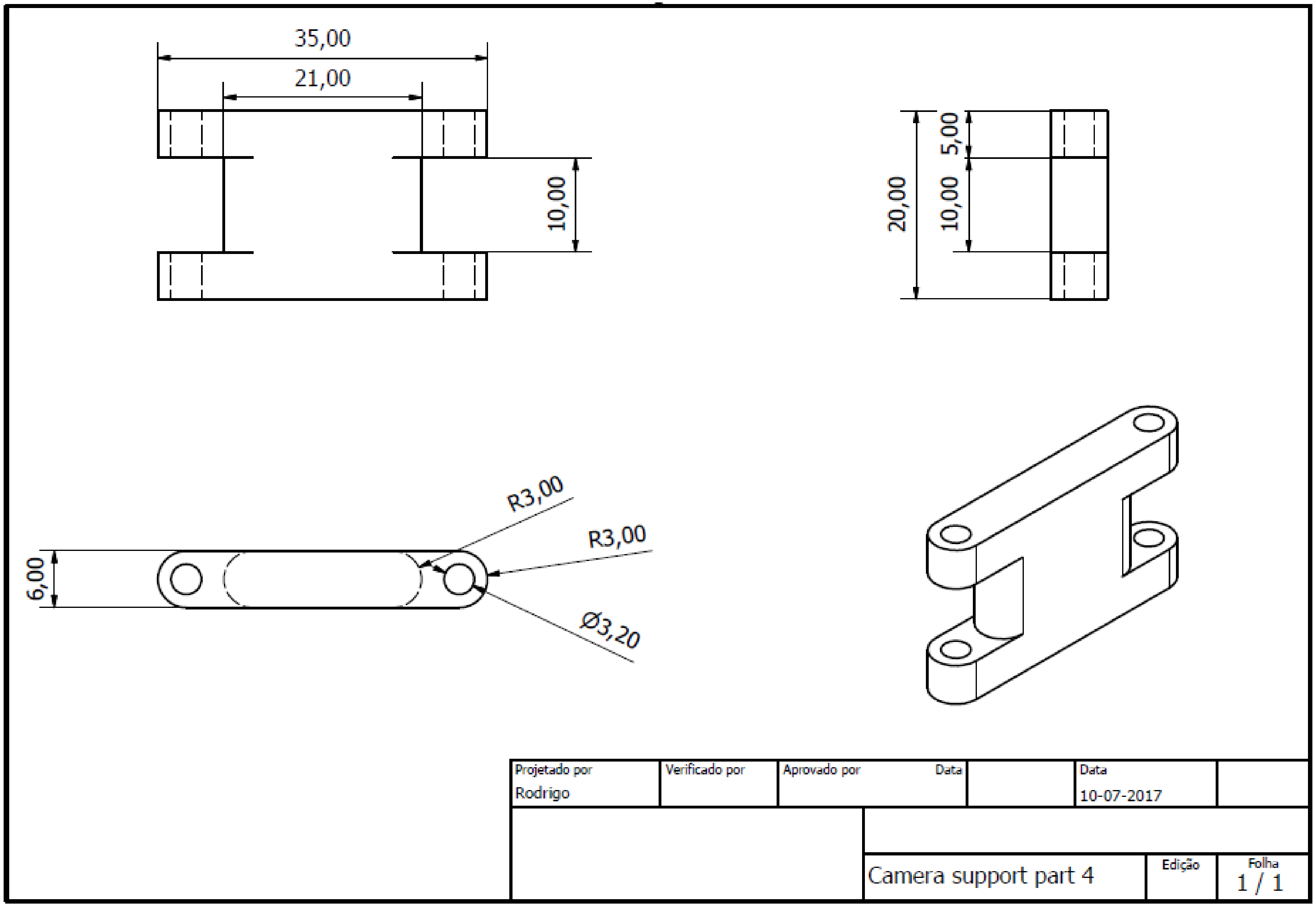


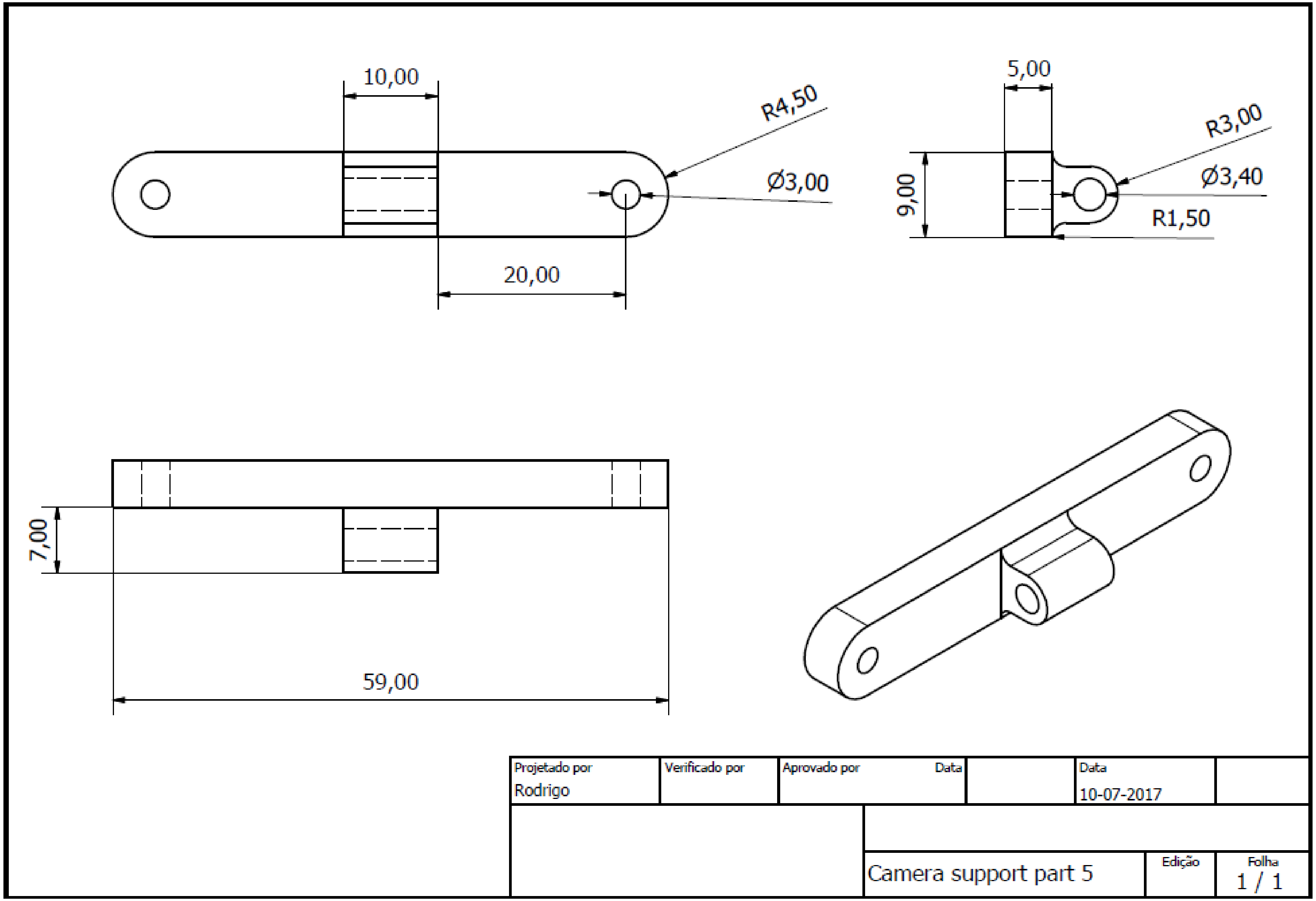
Projetado por	Verificado por	Aprovado por	Data		Data	
Rodrigo					10-07-2017	
	Wrist top plate				Edição	Folha 1 / 1

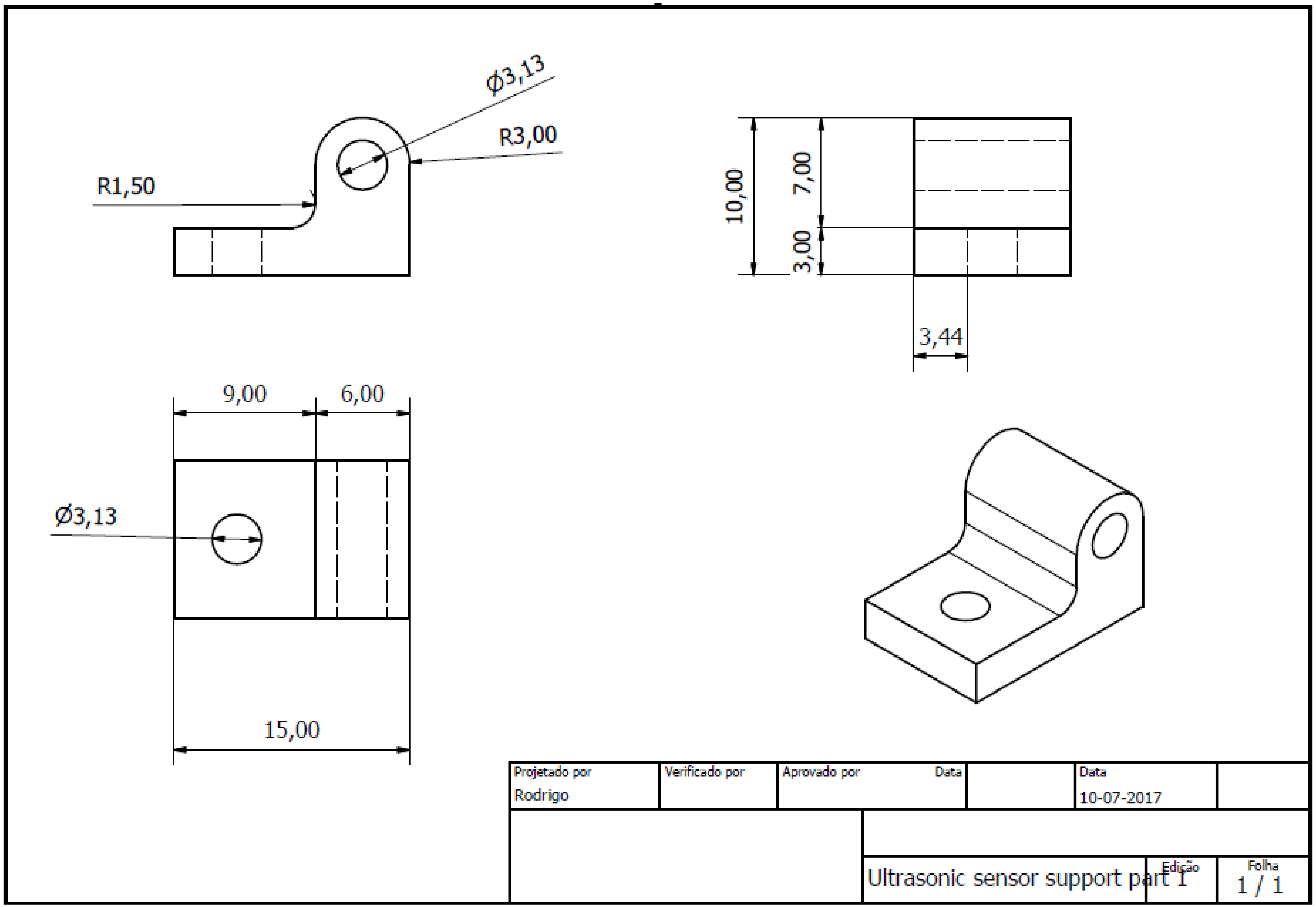

12,00
10,05
25,60
R5,00
Ø3,00
R3,00
Ø8,00
24,60
20,00
21,20
2,20
3,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Camera support part 1
Edição
Folha
1 / 1

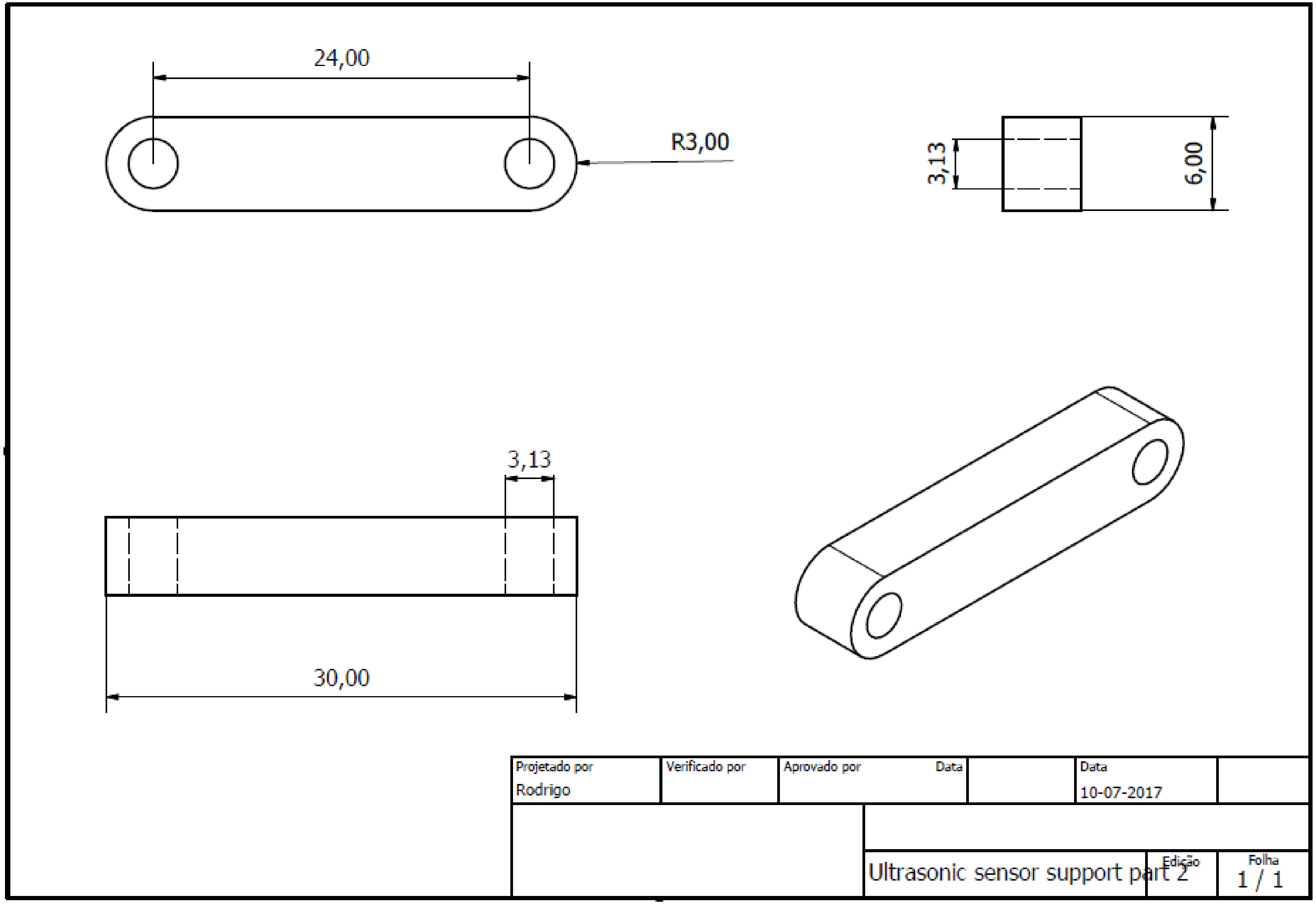

8,00
Φ4,00
Ø1,80
6,00
R3,00
Ø3,00
25,60
2,00
3,00
24,60
R3,00
17,00
21,00
41,60
9,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Camera support part 2
Edição
Folha
1 / 1

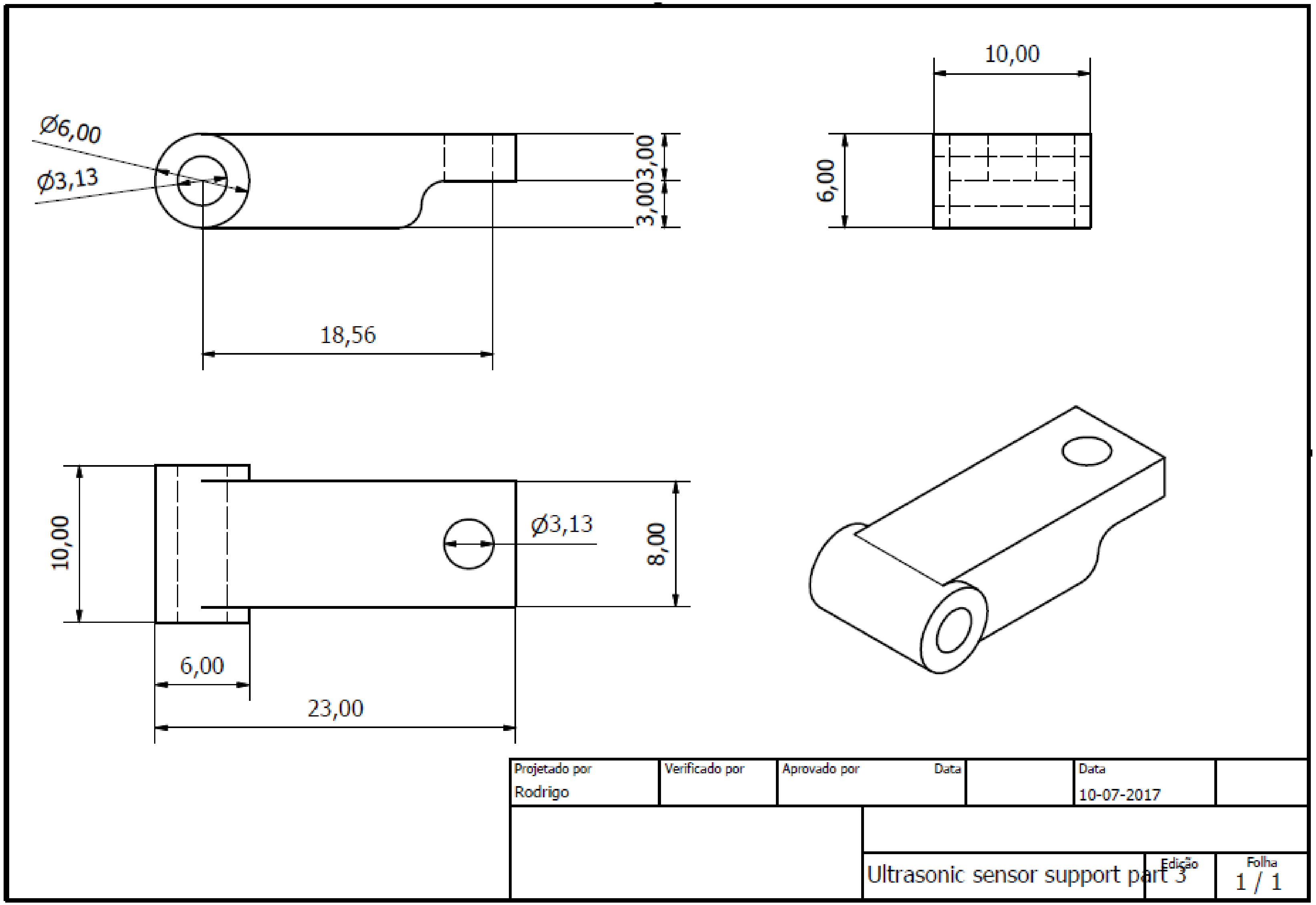

ϕ3,00
R3,00
R5,00
12,60
25,60
24,60
R3,00
Ø3,20
8,00
2,00
15,80
10,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Camera support part 3
Edição
Folha
1 / 1


35,00
21,00
10,00
20,00
5,00
10,00
6,00
R3,00
R3,00
Ø3,20
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Camera support part 4
Edição
Folha
1 / 1


10,00
R4,50
Ø3,00
20,00
5,00
R3,00
Ø3,40
9,00
R1,50
7,00
59,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Camera support part 5
Edição
Folha
1 / 1


ϕ3,13
R3,00
R1,50
10,00
7,00
3,00
3,44
9,00
6,00
Ø3,13
15,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Ultrasonic sensor support part 1
Edição
Folha
1 / 1


24,00
R3,00
3,13
6,00
3,13
30,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Ultrasonic sensor support part 2
Edição
Folha
1 / 1


Ø6,00
Ø3,13
3,00
3,00
18,56
10,00
6,00
10,00
Ø3,13
8,00
6,00
23,00
Projetado por
Rodrigo
Verificado por
Aprovado por
Data
Data
10-07-2017
Ultrasonic sensor support part 3
Edição
Folha
1 / 1