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DESIGN AND ANALYSIS OF DIRECTIONAL ANTENNA STRUCTURE FOR UNMANNED SURFACE VESSEL

Tampere University
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ABSTRACT

CARLOS MORON ALGUACIL: Design and analysis of directional antenna for unmanned surface vessel
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The purpose of this thesis is to design and analyse the structure of a directional antenna. The directional antenna is part of The Autonomous and Collaborative Offshore Robotics project, an exercise developed by the Tampere University of Technology.

The new structure design is introduced as a replacement of the solution prior to the realization of this thesis. After running protocol test to the original structure, several malfunctions were appreciated. These problems were related to the accuracy of the rotation system and its resistance to mechanical loads.

The realization of the mechanical design has been performed using Solidworks 2017. It is a CAD tool that allows the optimization of all the tasks related to this matter such as solid design, assemblies or blueprints. The process carried out to achieve the final structure has been to make iterative modifications until reaching the final product. As a result, the directional antenna is mounted in a birotational structure, allowing to modify the yaw angle around the z axis and the pitch angle around the y axis.

The control of the structure has been made by using an Arduino based microcontroller. It is in charge of powering and directing the actuators that rotates the components of the structure. The outcome has been obtaining full control by an operator of the aim direction of the antenna.

After building the structure, a series of tests has been carried out in order to measure the improvements of the new structure. The precision when rotating the structure around the yaw axis has been satisfactory. The maximum deviation observed from the target aim direction has been inferior to 0.5°. The accuracy around the pitch axis shows more disparity than the previous case, as the precision fluctuates regarding of the aim direction and the direction of the rotation. The values obtained vary in the range of 0.5-3.8°.

Keywords: Directional antenna, design, analysis, CAD, Solidworks, Arduino

PREFACE

This Master's Thesis has been performed in the Laboratory of Mechanical Engineering and Industrial Systems at the Tampere University of Technology, as part of my Erasmus program.

I would like to thank my supervisor Jussi Aaltonen for granting me the opportunity to perform my Master's Thesis as an exchange student. I would like to thank him for the treat, guidance, help and ideas that have greatly helped all along the process.

To José and Tuomas, who greatly helped me during my work in the department. Without them this project would have been an entirely different experience.

Finally, I would also like to thank my friends and family, who supported me through my whole formation process, as well as encouraging me to never give up and keep going forward.

Tampere, 10 August 2019

Carlos Morón Alguacil

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LIST OF SYMBOLS AND ABBREVIATIONS

aCOLOR	Autonomous and Collaborative Offshore Robotics
AUV	Autonomous Underwater Vehicle
CAD	Computer Aided Engineering
DC	Direct current
DIN	Deutsches Institut für Normung, German Institute for Standardization
DRG	Dragged subsystem
DSRC	Dedicated Short Range Communication
DVN	Driven part of the transmission
DVR	Driver part of the transmission
FTDI	Future Technology Devices International
HTD 3M	High Torque Drive, 3 millimetres pitch profile
HTD 5M	High Torque Drive, 5 millimetres pitch profile
ID	Identifier
IDE	Integrated Development Environment
M	Metric according to ISO 724:1993
MCU	Microcontroller Unit
MEI	Laboratory of Mechanical Engineering and Industrial Systems
PAN	Represents yaw angle servomotor in control programming
PID	Proportional-Integral-Derivative controller
Servo	Servomotor
SS	Subsystem
TILT	Represents pitch angle servomotor in control programming
TTL	Transistor-Transistor Logic
UAS	Unmanned Aerial System
USB	Universal Serial Bus
USV	Unmanned Surface Vessel
3D	Three dimension

C	*Distance between centres*
L	*Length of the belt*
N_i	*Number of turns for cogwheel i*
Z_i	*Number of teeth for cogwheel i*

1. INTRODUCTION

The development of the information technologies occurred during the last decades have resulted in a large increase in the possibilities to solve complex problems and tasks in an autonomous way, increasing the safety of operations while increasing efficiency and speed by eliminating the human factor. Cases of use of these advances could be tasks related to underwater mining or offshore renewable energy plants.

The Autonomous and Collaborative Offshore Robotics project (aCOLOR) is part of this framework, an exercise developed by the Tampere University of Technology in collaboration with the Tampere University of Applied Sciences and the company Alamarin-Jet Oy.

The aCOLOR system consists in the creation of a series of autonomous vehicles working independently but being interconnected, sharing information among them to guarantee the correct functioning of the system with high reliability.

The System is composed of three different vehicles operating in a different environment. On one hand, the Unmanned Aerial System (UAS) operates by air. On the other hand, the Unmanned Surface Vessel (USV) operates at sea surface, while below sea surface the Autonomous Underwater Vehicle (AUV) operates.

This document will include a new design and analysis of the directional antenna of the unmanned surface vessel. With the initial design, after the start-up of the system, different malfunctions were appreciated as a result of a poor material selection and a deficient initial state, causing the necessity to elaborate a new structure to solve the problems encountered. The work on this matter includes an analysis of the structure to identify the causes of the malfunctions and correct them.

The control of the antenna has been developed using an Arduino-based controller. The choice for the Arduino system has been made in accordance of its easy learning curve, the material already available to elaborate it and its upgradability.

The new mechanical design accompanied to the control has resulted in a fully mechanically operational directional antenna, which the action of the system is to follow a previously set reference.

2. RESEARCH METHODOLOGY

In the following lines, the methodology used to carry out this Master's Thesis is presented. The purpose of the methodology is to facilitate the approach to the engineering problem, and the necessary steps to solve successfully the given task.

The methodology is based on three mains aspects: Analysis, synthesis and laboratory testing. First, the initial design to be improved is analysed to set the requirements of the solution, that it is reached by synthetizing the product based on the conditions and requirements set before. Finally, The solution is tested and the results are analysed to value the quality of the final product.

The detailed steps that constitute this methodology are:

- Problem statement. Introduction to the problem and analysis of the initial state of the system. The goal of this phase is to understand and comprehend the main operation principle of the system and to identify the causes of system failure.
- Definition of system conditions. Once the problem has been defined, the requirements and expected performance of the solution are introduced. The solution must be devised in a way that complies with what is established during this phase.
- Design phase. During this phase the necessary changes are made to the system in order to adapt to the requirements and conditions imposed previously. Thanks to the available resources that allow the realization of computer assisted modifications, the design is perfected through successive iterations to overcome the drawbacks and limitations that arise during the process. These drawbacks can have their origin from different sources, such as spatial limitations, impossibility of assembly or fabrication processes.
- Prototype construction.
- Testing. Final phase in which all the necessary tests are performed to ensure the correct operation of the final system.

This methodology has been used to accomplish the objectives of this thesis, these being the realization of a new structure for a directional antenna, and the design and analysis of its control system.

The software used to carry out this project is composed of two main suites.

For the CAD design the program used has been SolidWorks 2017, provided by Dassault Systemes SE. It allows the creation of new parts components and system model, alongside the creation of drawings. Another important feature is the possibility to perform stress testing simulations. The control part has been programmed using the Arduino platform. It is an open source platform with extended documentation and availability. It allows the creation and programming of the microcontroller using an Arbotix-M board from the company Robotis Ltd.

3. DIRECTIONAL ANTENNA

3.1 Directional antenna principle

An antenna is basically an electric system that creates links between a transmitter device and the space surrounding it, or between the space and the device in the case of a receiver device.

One of the definitions among those that have been given through the years states that "An antenna is any device that converts electronic signals to electromagnetic waves (and vice versa)"[1].

Electromagnetic waves are disturbances to the magnetic and electric fields. It is a relation of cause and effect, as a variation in the electric disturbances produces a changing magnetic field perpendicular to the electric field.

The antennas produce or receive these electromagnetic waves that contain the information transmitted.

Attending to the form pattern of the radiation of the electromagnetic waves, the antennas can be classified as:

- Isotropic antenna.
- Omnidirectional antenna.
- Hemispherical antenna.
- Directional antenna.

An isotropic antenna is defined as an antenna which radiates uniformly in all radiations. Omnidirectional antennas are antennas with the ability to cover the signal requirements regarding of the azimuth direction.

A directional antenna, unlike omnidirectional antennas, directs its energy in one specific direction. Therefore, directional antennas must be accurately aimed in the direction of the signal transmitter or receiver. However, the advantages of this type of antennas are that they count with a very high gain, thus allowing to cover large wireless distance. Directional antennas can be either stationary or active tracking antennas. Active tracking antennas base their operating principle of following the movement of the target compared to stationary directional antennas[1].

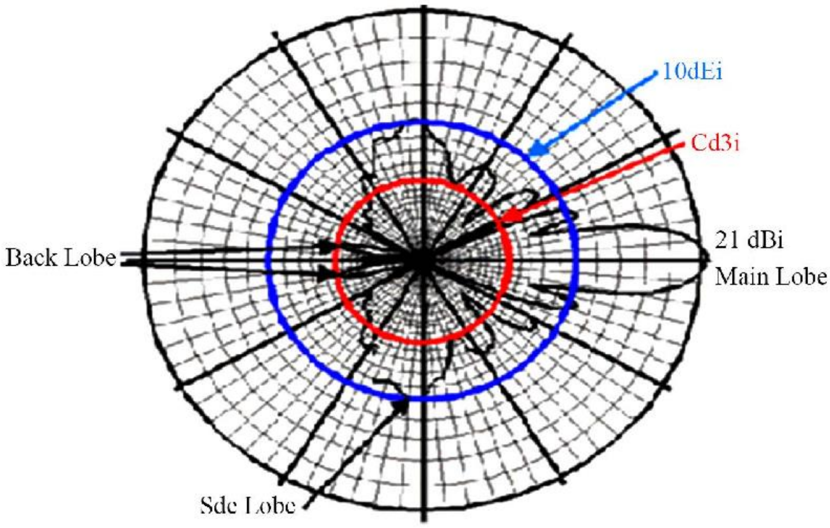


Figure 1. *Typical radiation pattern of a directional antenna*[2].

Figure 1 shows a typical radiation pattern for a directional antenna. It represents the transmittance depending of the azimuth direction. The maximum intensity is given in a certain direction, while in the surrounding zones the intensity is noticeable lower.

3.2 Applications of directional antenna

Directional antennas are widely used in different fields.

An example of this technology is the giant radio astronomy laboratory located in Arecibo, Puerto Rico. It was originally conceived by William Gordon in 1958 as a back-scattering radar system. The purpose of this construction is to measure the density and temperature of the Earth's ionosphere, up to a few thousand kilometres[3].

Suspended at more than 130 metres above the reflector the 900 ton platform is located. The design is similar to a bridge, as it hangs suspended in the air on eighteen cables, which are tied to three reinforced concrete towers. The tallest tower is 110 metres high, while the other two have a height of 80 metres, although the three tops are situated at the same elevation. The three towers combined have a total volume of reinforced concrete of 7000 cubic metres. Each tower is fixed to ground using anchors tied with seven steel bridge cables of 8.25 centimetres of diameter.

Below the triangular frame of the upper platform it is located the circular trach on which the antenna can variate its azimuth direction. The arm is a bow shaped construction 100 metres long[4].

Figure 2. *View of the radio antenna of the Arecibo Observatory*[5].

Another example of the use of directional antenna is the use of this kind of devices for railroad crossing safety applications.

Nowadays, the most common case of railroad accidents are collisions between trains and passenger vehicles at railroad crossings. Due to the speed and size of a train, these collisions generally result in significant damage, and it often leads to even several fatalities.

Current conventional crossing protection systems can be extremely expensive. To protect a two-lane rail crossing path can cost up to approximately 45 000 €.

Figure 3. *Use of directional antennas to prevent railroad accidents*[6].

Wireless technologies, such as Dedicated Short Range Communication(DSRC), can be adapted for its use as collision warning system between the train and passenger vehicles for unprotected grade crossing. Systems formed by directional antennas would transmit warning messages to approaching vehicles. Additionally, this kind of systems could provide feedback to train's operator, alerting them about incoming traffic[6].

Apart from these applications, there are also plenty of uses for directional antennas related to information and communication technologies.

For instance, there has been research for the use of these devices in cybersecurity, such as preventing wormhole attacks.

Wormhole attacks enable an attacker, with limited resources and no cryptographic material, to cause serious damage in wireless networks. A countermeasure to prevent this kind of attacks has been proposed by using directional antennas. The protection system is based in a cooperative protocol where the different connection nodes share directional information, in order to prevent the attacker from masking the attack as false neighbours[7].

Not only directional antennas are being implemented to achieve greater security, but also to improve the quality of wireless networks.

The advantages of directional antennas over omnidirectional antennas in wireless networking are currently being studied. Directional antennas can focus energy in the intended direction, thus automatically improving spatial reuse, an important performance factor in wireless network design.

Additional benefits of using directional antennas come from the fact that they tend to have a larger range while using the same power as omnidirectional antennas because the energy is concentrated in one direction instead of spreading in every direction[8].

3.3 Main working principle

In this section, the kinematic principles of the structure designed and analysed in this project are described.

The directional antenna is a subsystem of the unmanned surface vessel to be incorporated on top of it. The structure is composed of two different rotational mechanisms, giving two degrees of freedom to the system.

The rotation axes are non-coplanar and perpendicular; therefore the design is decoupled and divided into two different mechanical systems, composed of power and transmission systems for each rotation movement.

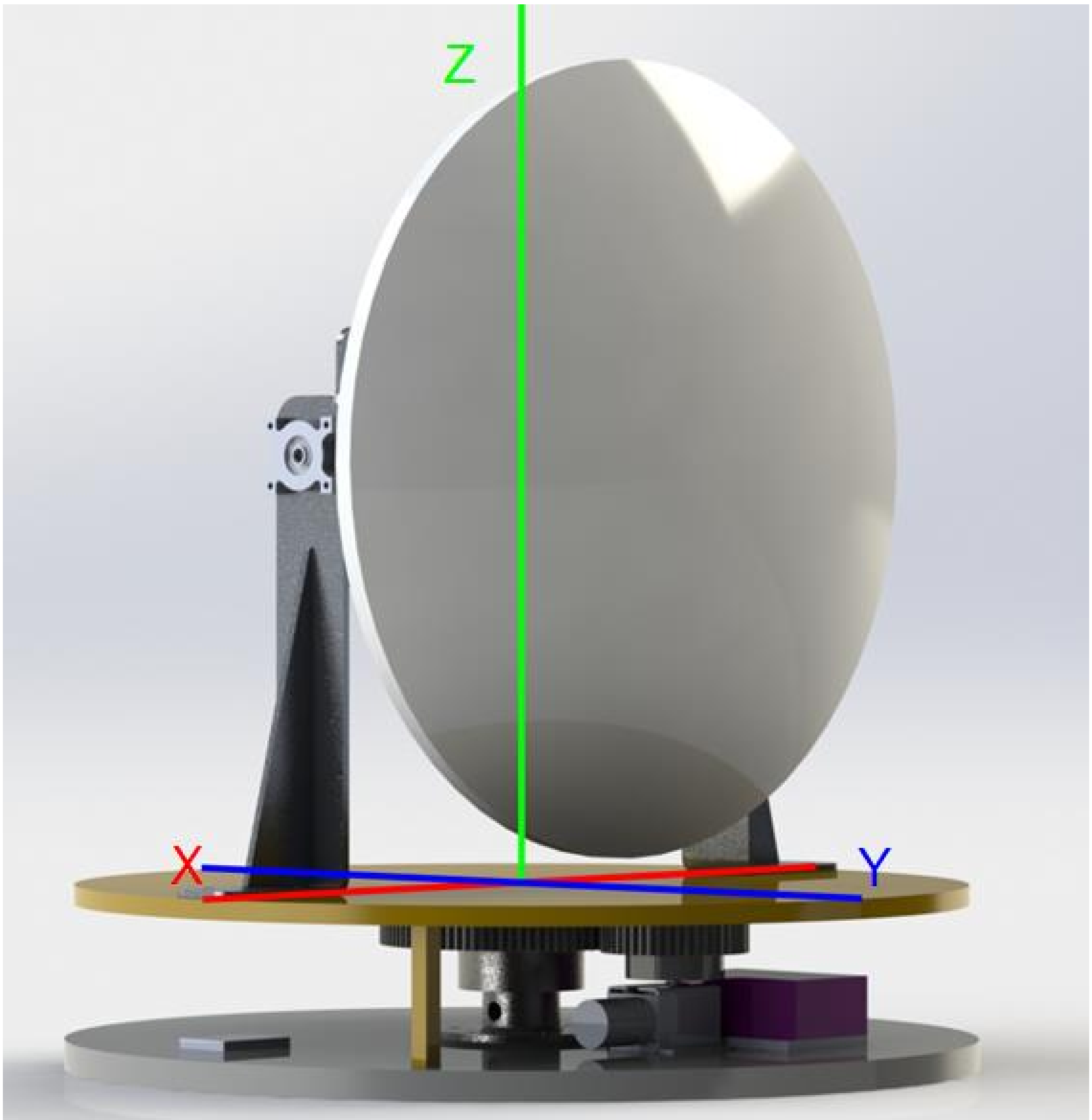


Figure 4. *System reference system.*

A scheme of the system is presented in figure 4. The lines represent the reference system and the rotation axis of the system.

The z axis is also known as the yaw axis[9], as yaw is the name of the rotation around this axis. The rotation around this axis is completely free, since it allows complete turns of 360 degrees. This is due to the fact that the USV where the antenna is mounted can freely move in the x-y plane, and as a result of it the antenna must be able to be redirected.

The y axis, also known as lateral axis[9], and the name for its rotation takes the name of pitch rotation. This movement is limited to a rotation of 90 degrees of amplitude. This adduces for different reasons. On the one hand, the positive turn around the axis is prevented to avoid the collision with the rest of the components of the structure, and on the other hand, the negative turn is limited since directions situated in the back are reached by turning around the yaw angle, redirecting the antenna without influencing the pitch. This arrangement allows for greater ease when designing the control of the structure by having limited one of the rotations and being able at the same time to cover the entire azimuth range as if it was an omnidirectional antenna.

The direction the antenna is pointing to is important to guarantee its performance, as it has been previously stated.

Because of this, it is necessary to maintain a continuous control over the state of the rotation of the antenna. This is carried out by establishing a system formed by the proper antenna and the target device to be connected to, where the variable to control is the direction that links both components of the system. This variable takes the name of target reference, or reference for short.

Changes in the direction of the reference, either due to disturbances or movements from the components that form the global system, have to be compensated by rotating the antenna.

The basic control structure is shown in figure 5.

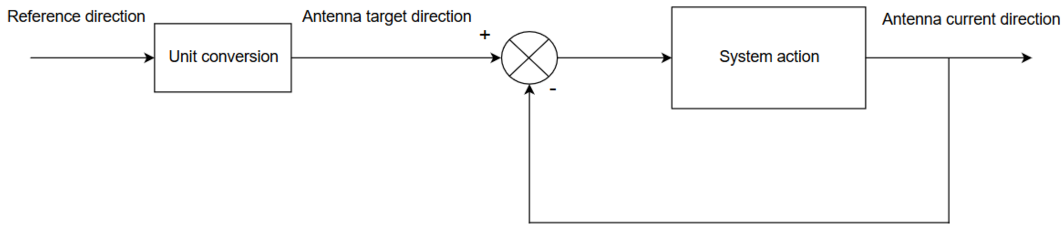


Figure 5. *Diagram of the control of the structure.*

The control of the aim direction of the antenna is based in two steps.

First, it is necessary to obtain information about the relative position of both devices, so the aim direction can be calculated. Once this is known, the parameters are converted to the antenna control system units. This is represented in the first block.

Once the target direction is known, the actuators in the structure modify the aim direction by the rotation movements defined previously, represented in the second block.

4. MECHANICAL DESIGN OF THE DIRECTIONAL ANTENNA

In the present chapter, all the details regarding to the mechanical design are introduced. The state of the original system is firstly stated. Later, the considerations taken and requirements that the new design must meet will be detailed. Finally, it shows the design process carried out to reach the final solution and its subsequent assembly.

4.1 Analysis of the previous system

This point contains the description of the original system, as it was previously built prior to the formulation of this thesis. In order to ease the comprehension of the system, it will be divided in two different subsystems, each one being dominated by only one rotation movement.

Figure 6. *Directional antenna structure original design.*

4.1.1 Yaw angle subsystem

This subsystem is formed by the elements located at the bottom, and these are responsible for the rotation along the z axis of the system.

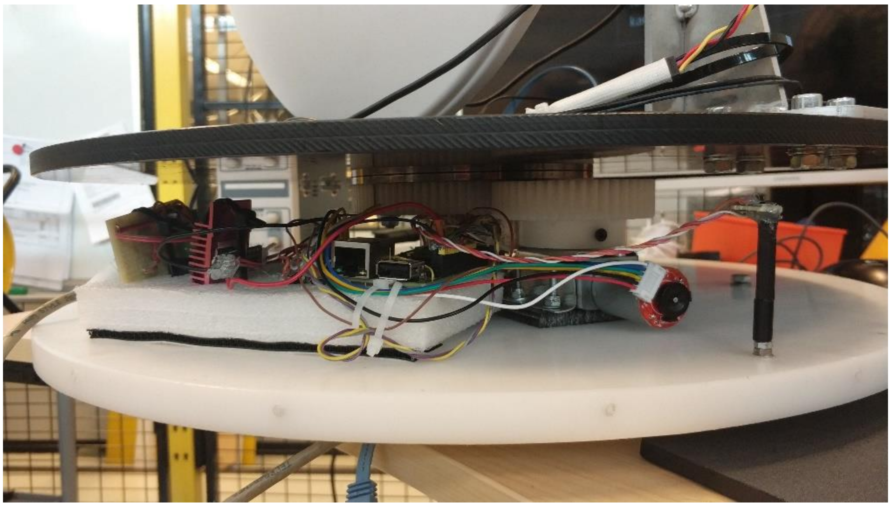


Figure 7. *In detail view of the bottom part of the directional antenna*

The elements corresponding to this subsystem are detailed in the list below:

Table 1. *Elements of the yaw angle subsystem.*

Category	Item	Model	Quantity	Denomination
Mechanical	Base		1	ACO-Y-Base
	Rotation gears	Mekanex OY	1	ACO-Y-Gears
	DC motor	CHIHAY GM4632-370	1	ACO-Y-Motor
Control	Communication board	Raspberry Pi	1	ACO-Y-Board

The base has a circular shape and it is made of plastic. Its measures are 470 mm for the diameter 15 mm for the thickness. The purpose of the base is to host and locate the different elements that form the subsystem, additionally, it serves as the connection of the directional antenna to the USV.

The communication board is a raspberry pi board, which not only contains the necessary code to allow communication of the antenna with the SUV, but also it controls the actions of the motors. The communication protocols according to the aCOLOR Project specifications are beyond the scope of this thesis. Therefore, this component will be ignored in the analysis.

The motor is a brushed DC motor GM4632-370. The motor has an encoder to know the angle of rotation of the shaft. The motor is connected to the controller by means of a 6-pin cable as can be seen in the image.

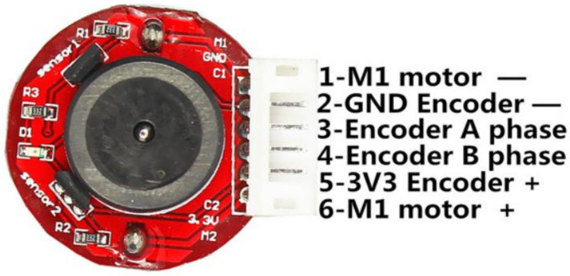


Figure 8. *Pin layout DC motor GM4632-370*[10].

The action of the motor is transmitted to the system using a pair of driven wheels, *ACO-Y-Gears*. They are two cog wheels with straight teeth. The smallest is the driver and is directly coupled to the motor. This gear has 48 teeth and it has a 13 mm hub that serves to facilitate the coupling with the motor shaft. The union between the driver cog and the shaft is achieved by making a hole in the hub and inserting through it a pin to create pressure and friction, allowing the transmission of movement from the motor shaft to the gear.

The second wheel, the largest with 95 teeth, is the driven one. This is attached to a cylindrical block. Said cylindrical block is divided into two coaxial cylindrical elements. The inner element remains fixed and is coupled to the base by using six nut-bolt unions. The outer element is where the gear is attached. Both elements are connected by a bearing that supports the static loads and allows this outer element to rotate around its axis. The block contains a cylindrical hole along its longitudinal axis to allow the insertion of the wiring. The rotation of this element is what constitutes the complete movement of rotation over the yaw angle of the system.

4.1.2 Pitch angle subsystem

The second system is formed by the components at the top of the system, those that are responsible for the rotation along the y axis of the system, the pitch angle.

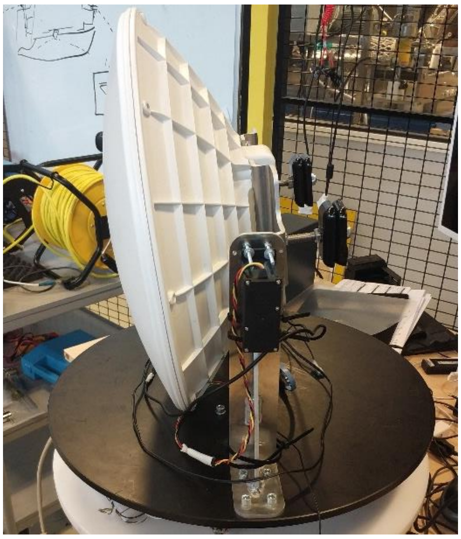


Figure 9. *In detail view of the top part of the directional antenna.*

The elements that form this subsystem are listed below:

Table 2. *Elements of the pitch angle subsystem.*

Category	Item	Model	Quantity	Denomination
Mechanical	Base		1	ACO-P-Base
	Vertical Support		2	ACO-P-Support
	Servomotor	HITEC HS-805BB+	1	ACO-P-Motor
	Shafts		2	ACO-P-Shaft
	Bearing	Axial bearing	1	ACO-P-Bearing
	Antenna		1	ACO-P-Antenna

The base as its homologous component in the other subsystem has circular shape and it is made of plastic. In this case, the base is slightly smaller, with a diameter of 460 mm and wall thickness of 10 mm. It contains a hole in its centre of 30 mm, to align the hole of the ACO-Y-Gears block, and thus to allow the connection of the wiring that controls the servo motor that controls the pitch angle.

The supports consist of two solids made of 4 mm wall thick aluminium sheet metal. They contain a welded vain to provide greater rigidity and resistance to flexion.

The motor is a Hitec HS-805BB+ servomotor. The motor is directly located in one of the supports. The transmission of movement from the motor shaft to the antenna is achieved by coupling a plastic shaft that connects to the antenna. This connection is made through a hole in the shaft where the servomotor is directly inserted. The other end of the piece of plastic is attached to one of the hooking plaques of the antenna.

To complete the movement, in the other L-shaped support, another shaft made of plastic is attached in order to move along the rotation movement of the antenna. It is coupled with an axial bearing with dimensions 10x26x8 mm.

The antenna is then connected to both shafts by using two aluminium plaques, while at the same time allows the connection between both shafts, completing the structure and allowing the movement around the pitch angle.

4.1.3 System failures

The need to devise a new structure for the antenna is due to the fact that, once it was put into operation, different malfunctions in the System were observed, up to the point of causing the rupture of its elements.

Tests were successful with low USV speeds. However, the waves had a huge impact in pitch rotation of the antenna mechanism and there was a relevant gap in the yaw rotation due to DC motor lack. Furthermore, couple of servos were destroyed during the tests (plastic gears got broken while testing high-speed pitch rotation of the directional antenna).

Hence, a second design was necessary to be implemented to have a reliable antenna mechanism. By using a more reliable instrumentation, the mechanism is stronger against impacts offshore and the control improves to get more accurate position of the directional antenna.

5. DESIGN AND DEVELOPMENT OF THE NEW ANTENNA STRUCTURE

In this chapter, it is presented the Development of the new structure that is proposed as the solution to the problem covering this thesis.

It contains all the procedure carried out until reaching the resolution, in chronological order, with the successive modifications until reaching to the final design. In the following pages, the new components and their subsequent modifications are explained in the appropriate cases.

5.1 Initial version

In the following image, the preliminary version of the new structure is shown:

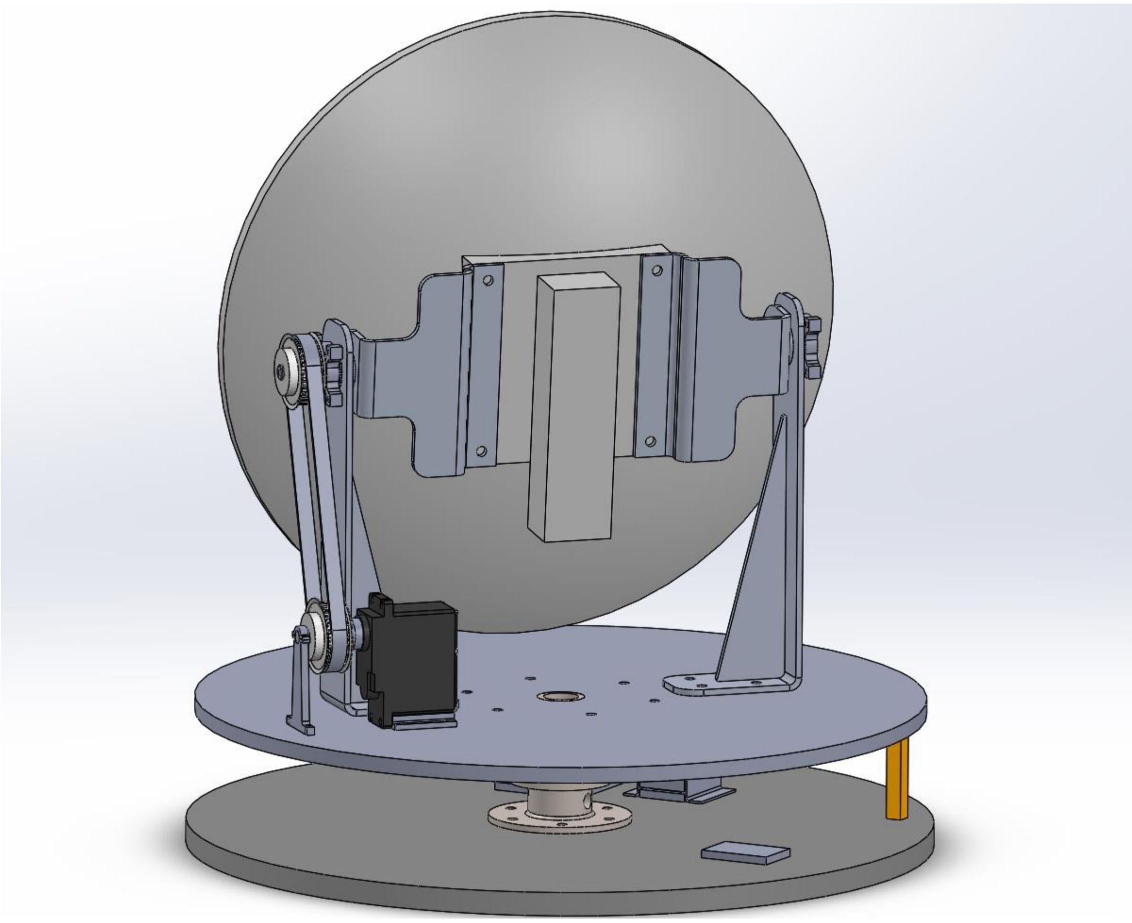


Figure 10. *Solidworks model of the preliminary version of the solution.*

The initial version focuses on changes made to the pitch angle subsystem, leaving the yaw angle subsystem pending for a later revision.

The supports that hold the antenna remain intact, but with a change of orientation, with the aim of occupying less space in its anchorage to the base, in order to reduce the size of the base. These changes were proposed in order to obtain a greater rigidity due to a greater distribution of loads caused by the weight and the flexion momentum that the uncentered weight produces.

As previously discussed, the original system failed among other reasons due to the precarious transmission system used. Therefore, for the new structure it has been decided to introduce a new concept in this part, by adding a synchronous belt.

The purpose of the new transmission is to prevent the previous causes of failure, while ensuring the correct functioning of the system. This is achieved thanks to a better distribution of efforts, by separating the production of the movement with the driven element.

With this approach, the axis of the servomotor is not as solicited as it was in the original system, because the antenna is not directly attached to the servomotor in this occasion. It needs to be able to resist the forces of the driver pulley and the weight of the elements attached, being smaller and lighter elements than in the original case.

In addition, the momentum produced by the weight of the antenna is supported in this case by the driven shaft. The results are that the servomotor now it is less loaded.

Next, the components of the new Transmission System are presented in detail.

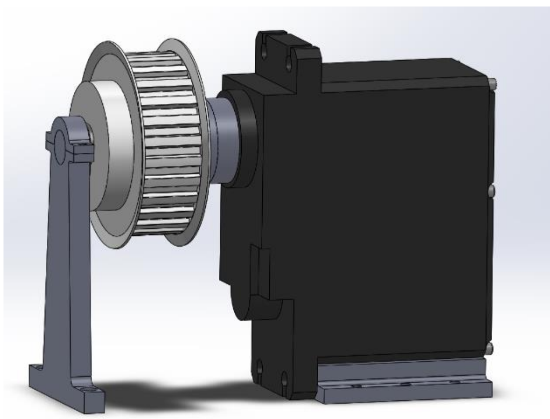


Figure 11. *Driver part of the transmission.*

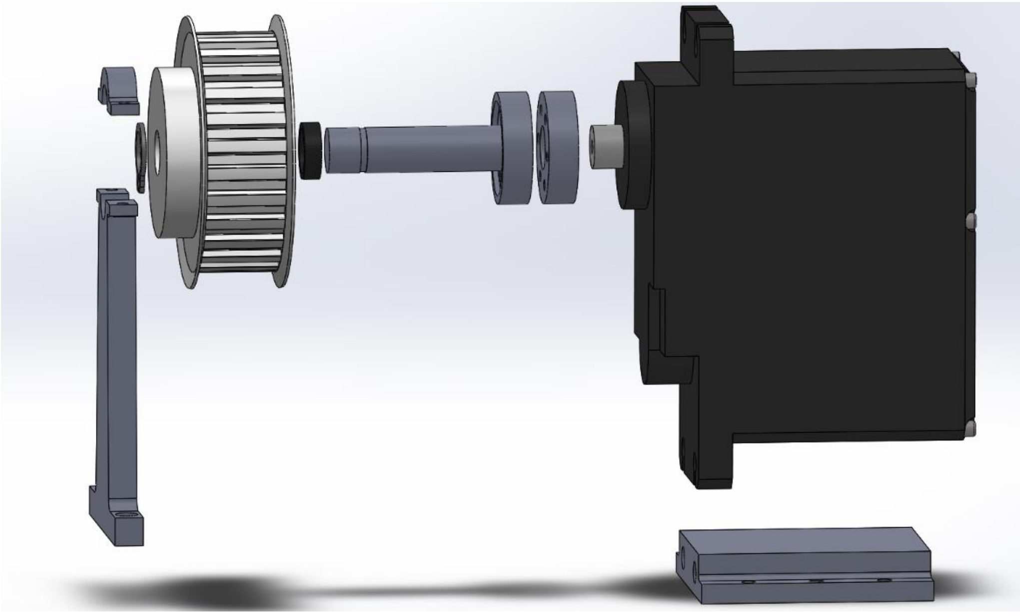


Figure 12. *Exploded view of the driver part of the transmission.*

The elements that form the driver part of the transmission are shown in figures 11 and 12. The addition of the new transmission implies that the servo motor must be changed of position, being placed directly on the base.

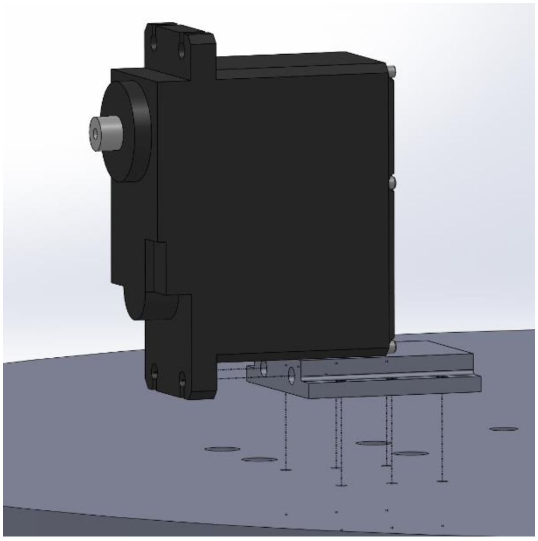


Figure 13. *Fixing of the servomotor to the base.*

To fix the servo in the base, a new solid has been designed to function as the seat of the servo. The seat has a prismatic shape, with two protuberances to provide a surface in which to make the holes that allow the servo to be fixed to the base. The servo is fixed to this element by two M2.5 holes. The metrics measurements used in this project are in accordance to the norm ISO 724:1993 for metric screw threads.

A new shaft has been designed to replace the previously used plastic shaft. The shaft has a main diameter of 8 mm, with a length of 31 mm. The shaft is connected to the servo by using six M2 screws. The shaft contains a groove at 23.30 mm from the servo-motor, to allow the insertion of a circlip for 8 mm shafts, to lock in place the pulley and prevent the movement along the shaft. The circlip specifications are contemplated under the norm DIN 471 for retaining rings.

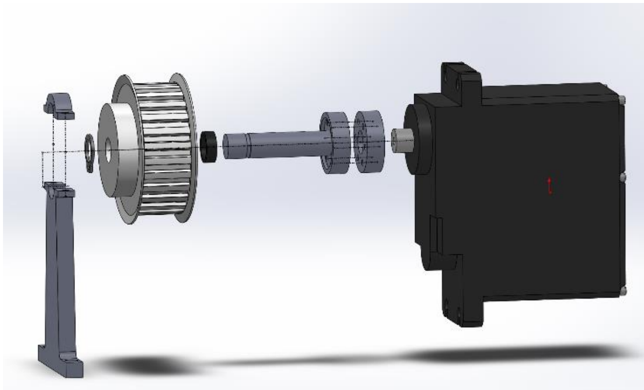


Figure 14. *Component distribution for driver part.*

The pulley is designed for shaft of 8mm of diameter, with T5 profile. It has a total length of 21 mm, being 6mm for the hub and 15mm for the toothed part. In one of the sides, the circlip is placed in the groove of the shaft as it has been previously mentioned to block the movement of the pulley along the shaft longitudinal axis, while on the other side a sleeve of 2 mm thickness is inserted between the shaft-servo connection and the pulley. In this way, the restriction to the movement according to the longitudinal axis is totally restricted.

Finally, the decision to add a support at the free end of the shaft has been made to provide greater rigidity. This element is implemented so the bending tensions due to weight are relieved, as well as the stress concentration that would occur in the servo-axis connection in the absence of this support. The distribution of these elements is shown in figure 14.

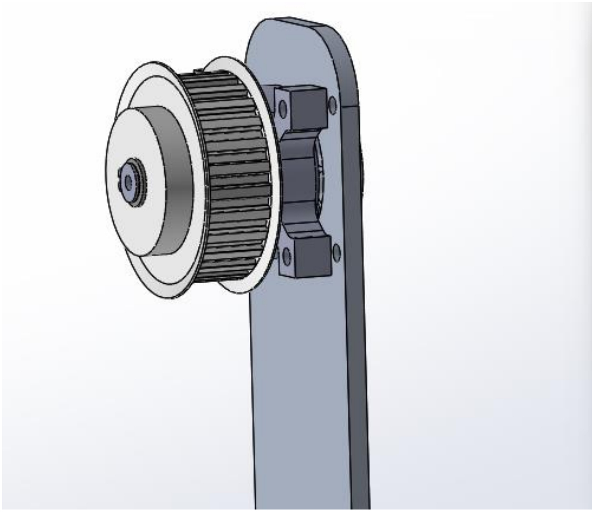


Figure 15. *Driven part view of the transmission.*

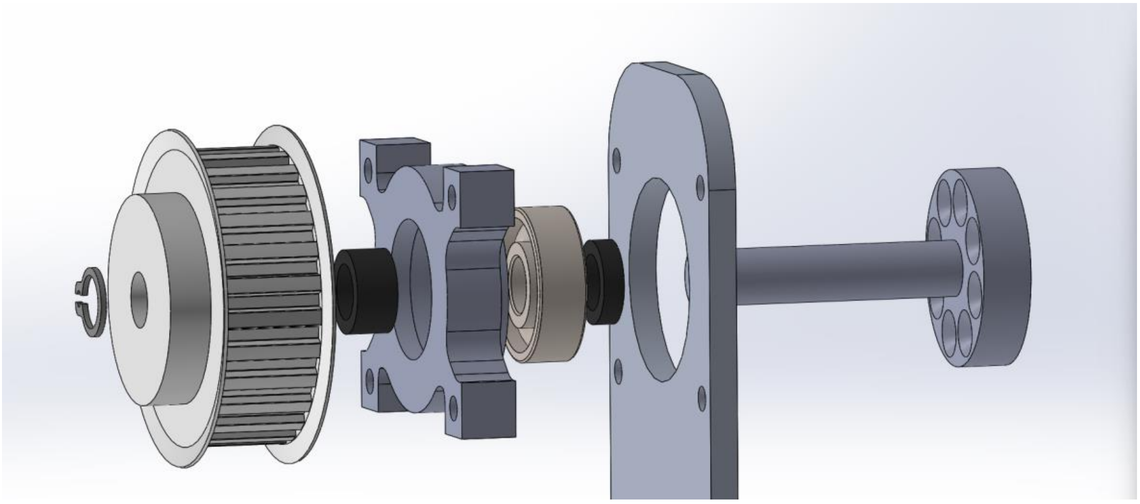


Figure 16. *Exploded view of the driven part of the transmission.*

The driven part of the synchronous belt is presented in figures 15 and 16. The elements corresponding to this set are a shaft, a pulley attached to it with the intention to transmit its movement to the antenna. Accompanying this set it is also added several auxiliary items such as a bearing, several sleeves and a retention clip.

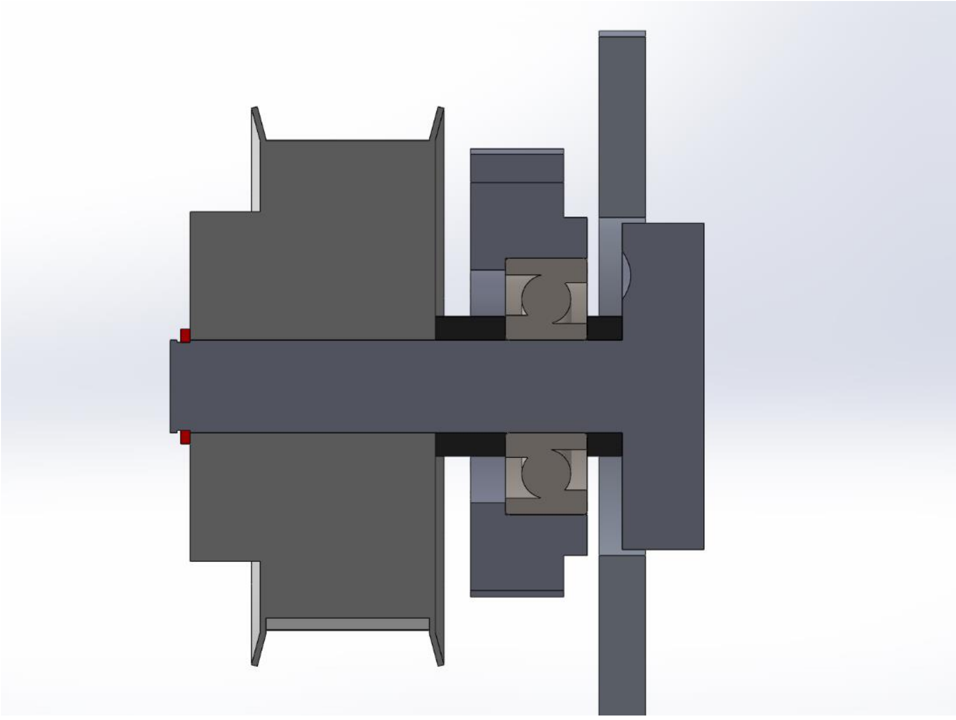


Figure 17. *Cross section of the driven part of the synchronous belt.*

The way the elements are distributed and combined is shown in figure 17.

The shaft measures consist of 8 mm for the diameter and 38.70 mm long, resulting as the same diameter as the shaft before but with an increase of its length. On one hand, in the end that goes attached to the antenna there is a stretch with diameter of 28 mm and 7 mm long. The stretch contains 8 M3 through holes as union method to the antenna.

On the other hand, the free end contains a groove similar to the one performed to the driver shaft to accommodate an 8 mm DIN 471 retention clip to prevent translation movement of the pulley. An axial ball bearing for 8 mm shaft has been introduced to facilitate rotational movement, as well as to absorb axial forces and facilitate axial blockage of the pulley.

For the driven part, two different sleeves are necessary for the separation between the different components. These have different wall thickness, being 3 mm thick for the couple bearing-shaft, while for the combination bearing-pulley is 6 mm thick.

Finally, for the pulley, the exact same model has been chosen as in the driver counterpart. This choice has been made based on the following considerations:

- Availability: Using the same model results in greater ease to obtain them commercially.
- Size: Due to the conditions of the shafts, size and weight limitations, both pulleys have been chosen for their small size, being the smallest available for the shaft

size. Choosing a larger pulley for the driven part would have resulted in the necessity to resize the components of the driven part, resulting in a much larger overall size and weight, creating excessive loads.

- By having two pulleys with the same number of teeth, the transmission ratio becomes 1:1. Therefore both shafts will rotate at the same speed. Due to the servomotor specification, it is easy to know and modify the servomotor speed, therefore it provides greater ease when programming the control. Knowing the operating parameters of the servomotor, the angle and speed of rotation of the antenna itself are obtained directly.

Finally, the element that connects both parts, driver and driven set, is the transmission belt. The length of the belt is calculated according to formula (1).

$$L = 2C + \frac{t*(Z_1+Z_2)}{2} + \frac{t^2*(Z_1-Z_2)^2}{\pi^2*4*C}, \tag{1}$$

The denotation is as follows:

- L: Length of the belt in mm.
- C: Distances between centres in mm.
- t: pitch of the profile in mm.
- Z_1: Number of teeth for the first pulley.
- Z_2: Number of teeth for the second pulley.

Introducing the values for each value, the result is 471 mm for the belt length, as it can be seen in formula (2).

$$L = 2 * 168 + \frac{5*(27+27)}{2} + \frac{5^2*(27-27)^2}{\pi^2*4*168} = 471, \tag{2}$$

The final elements are the antenna and the dragged set located in the other support of the antenna. These two sets of elements are not discussed at this point as they have not been modified, and they remained intact from the original structure, explained in detail during section 4.1.2.

The complete list of components of the global structure is shown in the table 3. The table contains all the important mechanical components, skipping control elements as they will be discussed in the next chapter and the normalized elements for construction, like bolts and nuts.

Table 3. *Antenna structure part list.*

Name	Part of	Quantity	Denomination
Base	Yaw rotation SS	1	ACO-Y-Base
DC motor	Yaw rotation SS	1	ACO-Y-Motor
Rotation gears	Yaw rotation SS	1	ACO-Y-Gears
Cylindrical block	Yaw rotation SS	1	ACO-Y-Block
Base	Pitch rotation SS	1	ACO-P-Base
Servomotor	Pitch rotation SS - DVR	1	ACO-P-Motor
Servomotor seat	Pitch rotation SS - DVR	1	ACO-P-Seat
Servomotor shaft	Pitch rotation SS - DVR	1	ACO-P-SShaft
Sleeve	Pitch rotation SS - DVR & DVN	3	ACO-P-Sleeve
Pulley	Pitch rotation SS - DVR & DVN	2	ACO-P-Pulley
Retention clip	Pitch rotation SS - DVR & DVN	2	ACO-P-Clip
Shaft support	Pitch rotation SS - DVR	1	ACO-P-SSupport
Antenna Support	Pitch rotation SS	2	ACO-P-ASupport
Driven shaft	Pitch rotation SS - DVN	1	ACO-P-DShaft
Bearing 8mm	Pitch rotation SS - DVN	1	ACO-P-8Bearing
Bearing 10mm	Pitch rotation SS - DRG	1	ACO-P-10bearing
Bearing housing	Pitch rotation SS - DVN & DRG	2	ACO-P-Housing
Dragged shaft	Pitch rotation SS - DRG	1	ACO-P-DRShaft
Antenna plaques	Pitch rotation SS	2	ACO-P-Plaque
Antenna	Pitch rotation SS	1	ACO-P-Antenna

Legend
SS → Subsystem
DVR → Driver part of the transmission
DVN → Driven part of the transmission
DRG → Dragged subsystem

5.2 Early modifications

During this section, the modifications that were introduced progressively and in chronological order to the first version of the design are presented.

The initial changes focus on two aspects primarily.

First, the decision to change the supports of the antenna was taken, and not only changing their orientation as it was considered during the preliminary design process. This decision was made considering the following reasons.

On the one hand, one of the design premises was to preserve as many original components as possible. Both bases are found in the category of reused components. Therefore, because the size would not be reduced as it was initially planned, the change of orientation lost one of its purposes as it has been described in the previous section. On the other hand, due to the low base-to-body ratio, excessive deformations were observed in service. It is then decided to change them, considering greater wall thickness and a larger size, using the available space in the base to increment the size of the mounting plate, thus providing greater robustness overall.

The second main modification is based on the motors used for the movement of the antenna. After the tests performed to the original system, the servomotor in charge of the pitch movement initially installed broke, due to the poor construction materials and added to the weight supported by it. Moreover, the motor in charge of the yaw movement, resulted to be a motor of low quality, whose control and precision does not meet the requirements of precision. Therefore, it is decided to change both motors for two Dynamixel MX-28 servomotors.

The choice of the use of these servomotors adduces to several reasons.

They are two servos of this model that were prior to the development of this project purchased by The Laboratory of Mechanical Engineering and Industrial Systems (MEI), for their use in a concluded previous project, resulting in immediate availability.

Moreover, the construction materials are superior to the previously used motors, as they count with steel gears for the movement of the shaft.

A great feature of these motors is that they incorporate their own control framework compatible with the Arduino platform, which facilitates the control programming. They incorporate integrated PID controllers for the shaft rotation, allowing greater control by adapting its torque to the load conditions automatically.

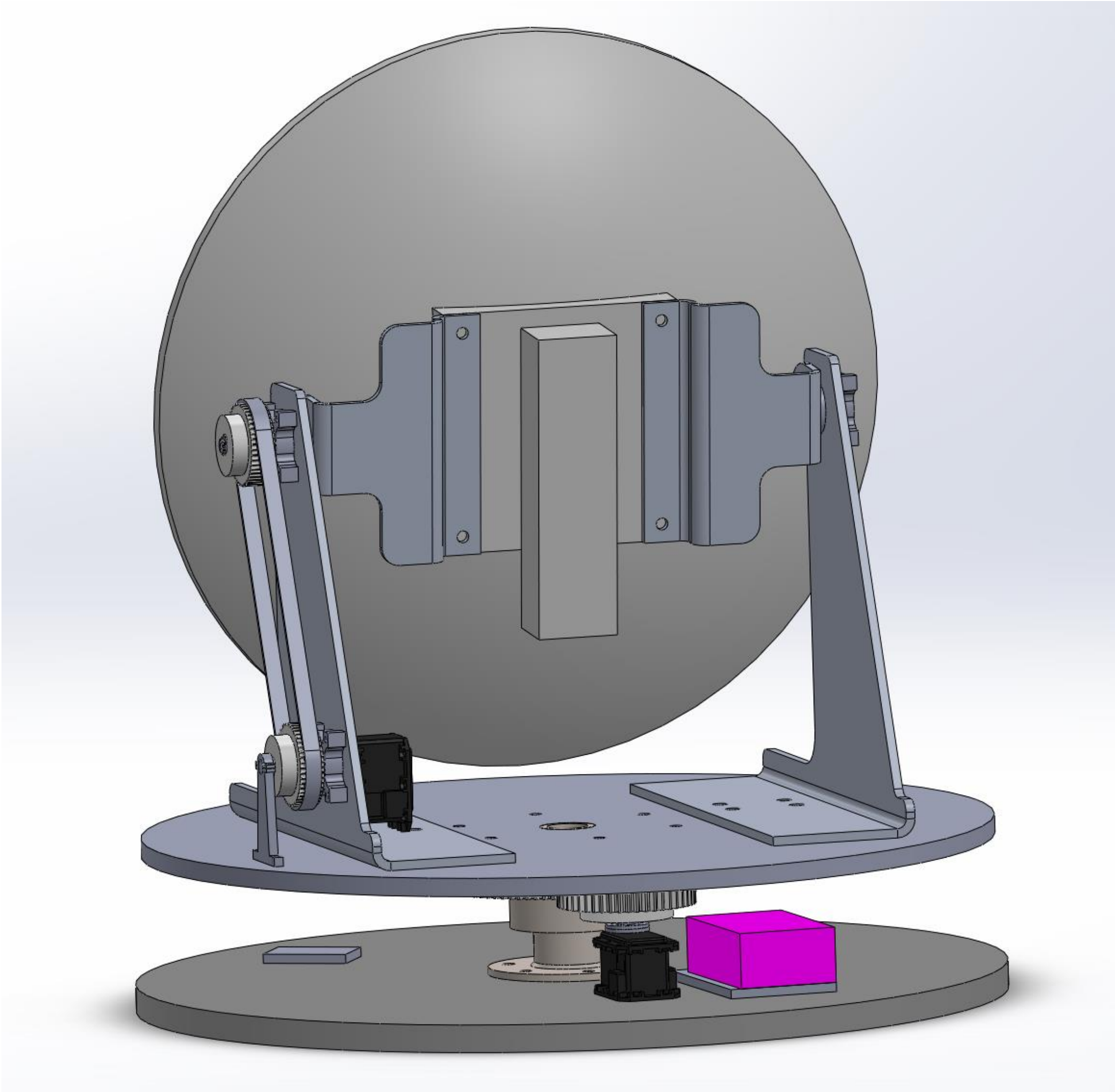


Figure 18. First modifications applied to the design. Bigger and thicker supports and new motors.

The modifications mentioned in the previous page, as well as other minor modifications that will be explained below are showcased in the figure 18.

Attending to the yaw angle subsystem, the main change is the replacement of the motor. The MX-28 has different dimensions compared to the previous DC motor, so it is necessary to make a new union to the base, as well as the coupling to the set of gears.

The servo is fixed to the base by using the 2.7 mm diameter holes for M2.5 screws available in the servo case.

To couple the servo to the driving gear, a new shaft has been designed, which is inserted into the gear hub by one of its ends, while on the other it is directly coupled to the servo, using the holes available in the horn, as it can be seen in figure 19.

This shaft has a length of 10 mm. Positioned in the middle of its length there is a 3 mm diameter pin hole to fix the gear by using a pin through both elements.

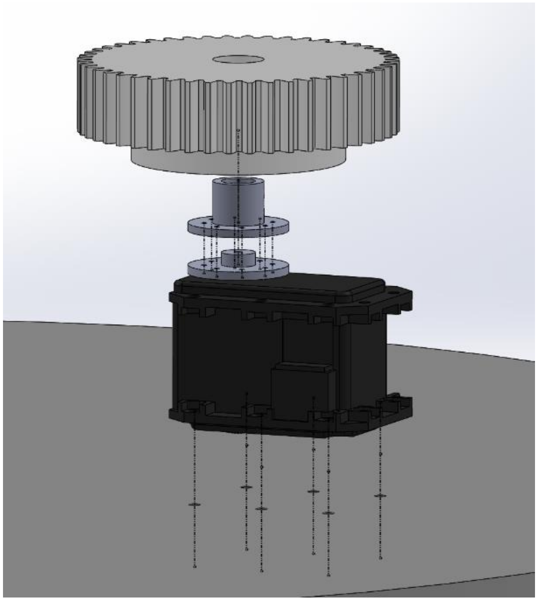


Figure 19. *Attachment of the servomotor to the base.*

To accommodate the driving gear to the new size of the servo, it is necessary to reduce the length of the hub, so that the height and size of the total structure remain constant. This recess magnitude is 6 mm. The hub final length is of 7 mm.

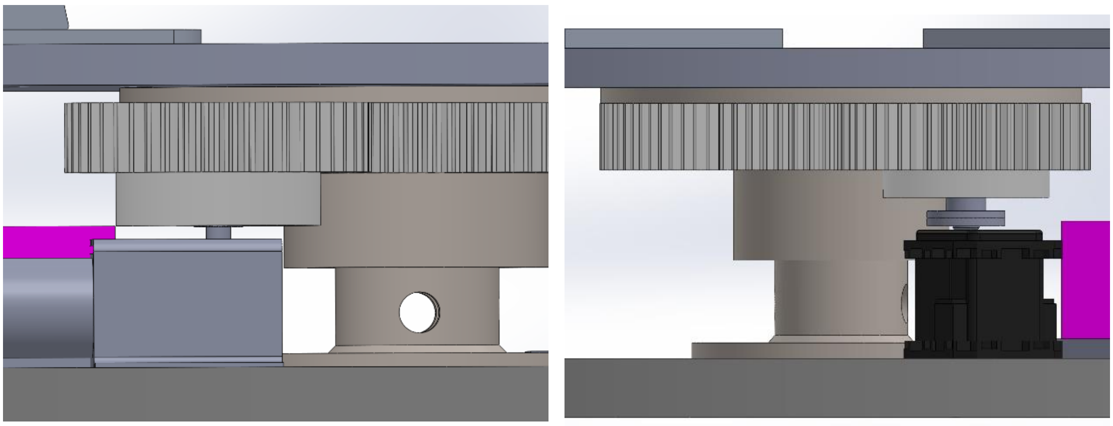


Figure 20. *Zoomed view of the yaw angle subsystem motor disposition. On the left, the former DC motor. On the right, the new servomotor accompanied of the reduced size of the gear.*

As for the pitch angle subsystem, the servomotor location has to be changed again due to changes in both supports and servomotor. The figure 21 shows the changes in the driver part of the pitch angle subsystem.

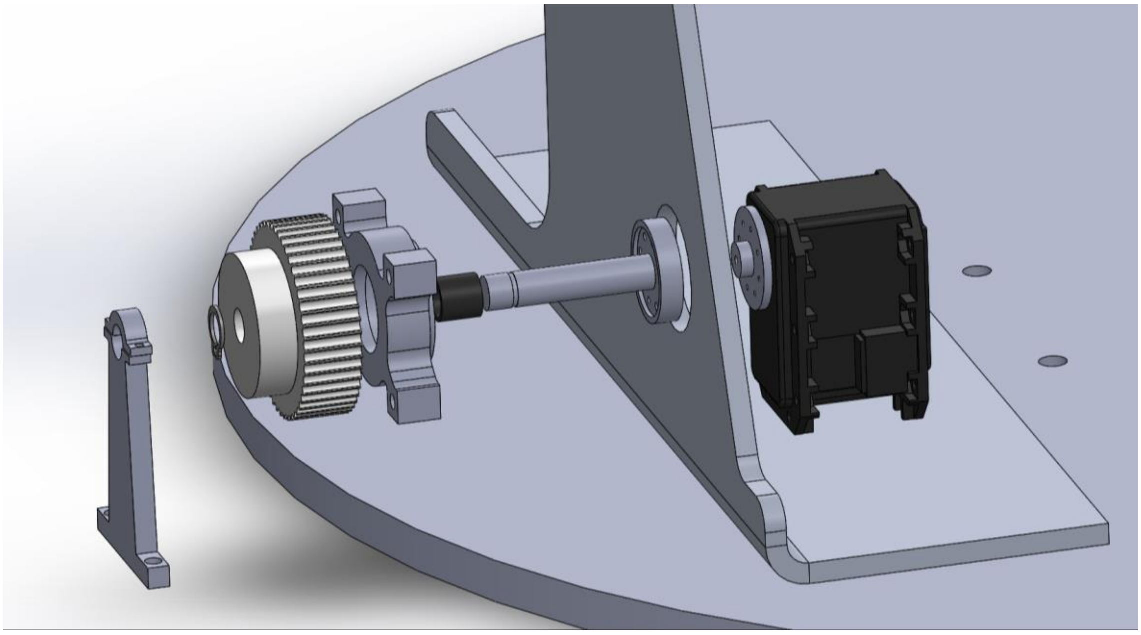


Figure 21. *Exploded view of the modification in the driver part of the pitch angle subsystem.*

The motor is now directly attached to the antenna support. To make this possible, it is necessary to make a hole to allow the insertion of the shaft. The servo attachment uses the same method as in the previous case, by drilling six 2.7 mm holes to introduce M2.5 screws as joining method. A similar part to those used to house the bearing of the driven part has been added without any modification, since it does not satisfy any mechanical requirement, it is only presented as an aesthetic solution.

Another important modification in this phase is the change of type of the synchronous belt pulleys. The reason for this change is due exclusively to the availability when it comes to purchasing this type of components.

The new pulleys are HTD 3M profile, keeping the same shaft diameter. This new pulley retains the same dimensions approximately, having a greater cube length of 8.80 mm but with a shorter length in the toothed part, it being only 13.40 mm.

In the table 4, the list of components updated is shown.

Table 4. *List of components updated.*

Name	Part of	Quantity	Denomination
Base	Yaw rotation SS	1	ACO-Y-Base
DC motor	Yaw rotation SS	1	ACO-Y-Motor
Dynamixel MX-28	Yaw and pitch rotation SS	2	ACO-Y-Motor
Rotation gears	Yaw rotation SS	1	ACO-Y-Gears
Cylindrical block	Yaw rotation SS	1	ACO-Y-Block
Base	Pitch rotation SS	1	ACO-P-Base
Servomotor	Pitch rotation SS - DVR	1	ACO-P-Motor
Servomotor seat	Pitch rotation SS - DVR	1	ACO-P-Seat
Servomotor shaft	Pitch rotation SS - DVR	1	ACO-P-SShaft
Sleeve	Pitch rotation SS - DVR & DVN	3	ACO-P-Sleeve
Pulley	Pitch rotation SS - DVR & DVN	2	ACO-P-Pulley
Retention clip	Pitch rotation SS - DVR & DVN	2	ACO-P-Clip
Shaft support	Pitch rotation SS - DVR	1	ACO-P-SSupport
Antenna Support	Pitch rotation SS	2	ACO-P-ASupport
Driven shaft	Pitch rotation SS - DVN	1	ACO-P-DShaft
Bearing 8mm	Pitch rotation SS - DVN	1	ACO-P-8Bearing
Bearing 10mm	Pitch rotation SS - DRG	1	ACO-P-10bearing
Bearing housing	Pitch rotation SS - DVN & DRG	3	ACO-P-Housing
Dragged shaft	Pitch rotation SS - DRG	1	ACO-P-DRShaft
Antenna plaques	Pitch rotation SS	2	ACO-P-Plaque
Antenna	Pitch rotation SS	1	ACO-P-Antenna

Legend
SS → Subsystem
DVR → Driver part of the transmission
DVN → Driven part of the transmission
DRG → Dragged subsystem

In red → Components removed
In blue → Components updated
In green → New components

5.3 Final modifications

In this section the final modifications are introduced, once again in chronological order. The final changes of the design focus in the synchronous belt and the parts associated to it. The aim of these final changes is to accommodate the design to manufacturing and assembling requirements.

For the correct operation of the synchronous belt, it is necessary that the belt has enough tension. If the belt does not have enough tension, the transmission effort is insufficient resulting in problems of movement of the antenna in the form of hitches and inaccuracies.

The strap is not very flexible, so its length has to be calculated before mounting it, the distance between the centres being a factor to be taken into account. This fact has been previously discussed in the section 5.1.

In order to be able to regulate the tension of the belt, while facilitating the assembly, it is decided then to modify the attachment of the servo.

Initially, it was planned to make 6 holes to accommodate the servo. Extending this method, two millings are made to hold the servo, and a larger milling for the shaft. Thanks to this, the position of the servo can be modified to vary the distance between the centres of the pulleys, thus allowing the adjustment of the tension of the belt

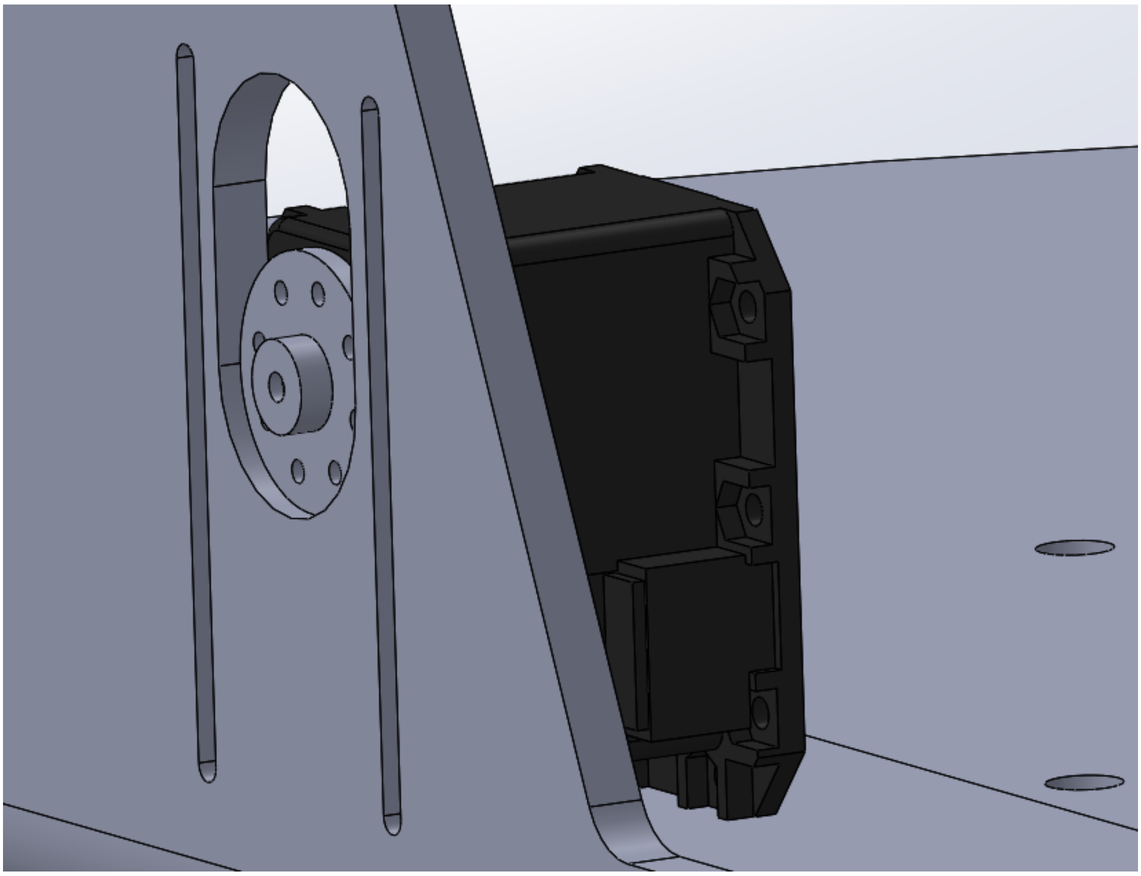


Figure 22. *Millings performed in the support for the new attachment method.*

To accompany these changes, the additional bearing housing previously added as an aesthetic solution is eliminated. In its place, a prismatic piece with matching servomotor holes is inserted. This way, the friction caused by this type of joint will be enough to keep the servo locked in the desired position.

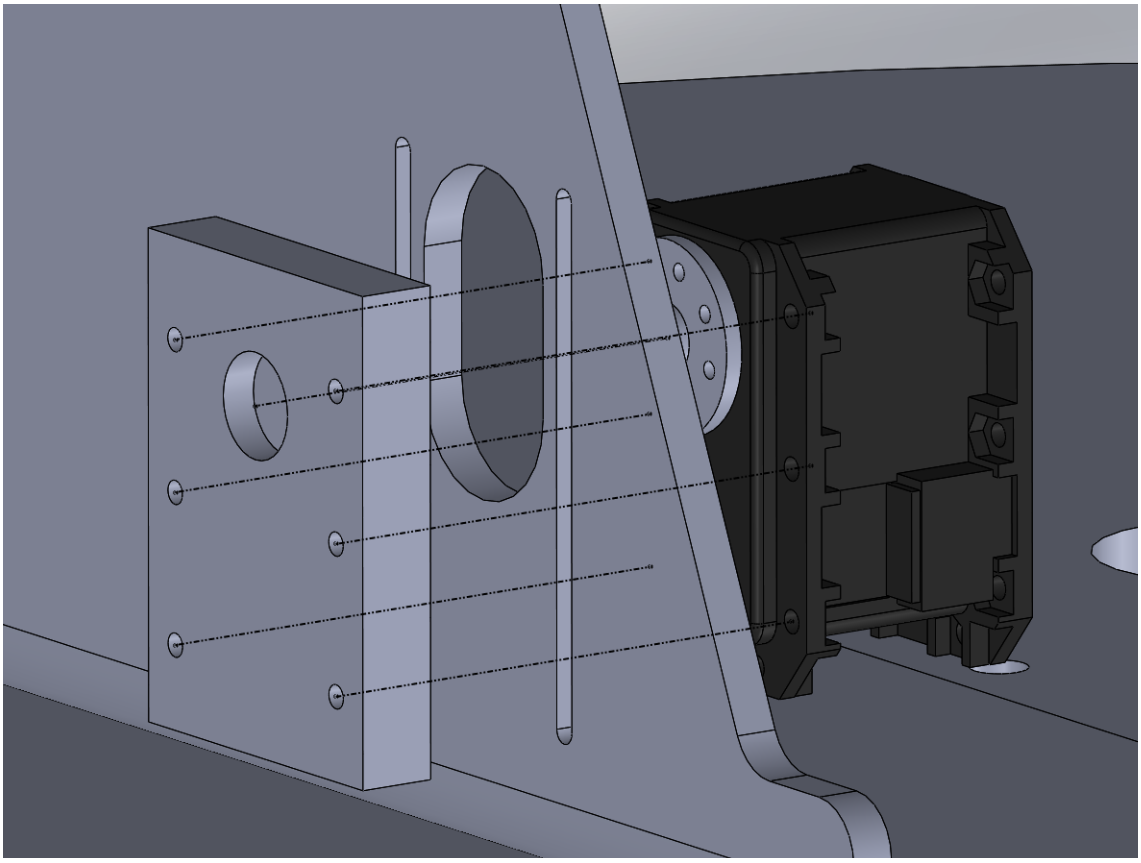


Figure 23. *Detailed view of the new servo attachment method.*

Several changes are made in the transmission driver assembly as well. The shaft where the pulley is mounted, is resized in such a way that it contains two sections of different diameter. From the free end, the first section is 22.25 mm long and diameter 8 mm. In this section is where the pulley is located. The second section is 8.75 mm long and 10 mm in diameter. This new design is introduced to avoid the use of sleeves to fix the pulley on the shaft, thereby making this second section work as a separator. The shaft will be manufactured by turning, so it is easy to make stretches of different thickness and thus avoiding the use of additional elements.

To prevent the belt from misalignment in service, it is decided to change the pulleys once again. The design of the pulleys chosen so far does not consider this problem, as it does not have any type of belt retention.

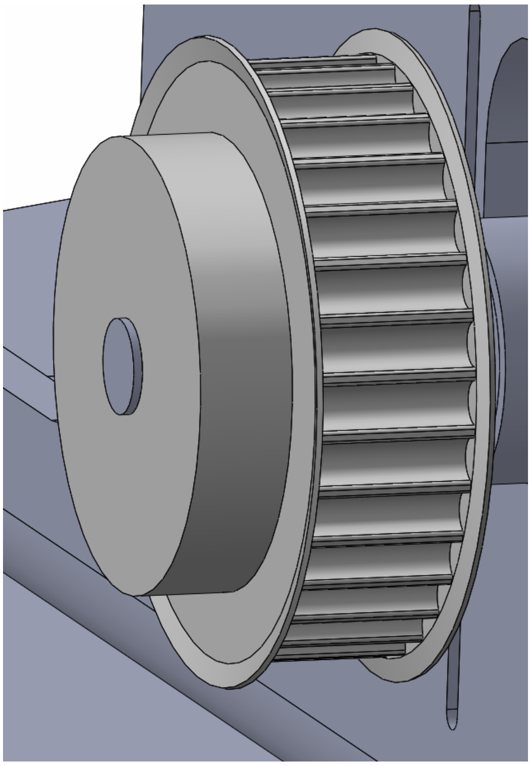


Figure 24. *Final model of the pulleys.*

The pulleys used are finally HTD-5M profile, with a hub length of 8 mm and the toothed part has a length of 14.50 mm, being only 0.3 mm longer than the previously used pulleys. The main difference to the previous set, and the reason they have been chosen, is because this set contain exterior tabs along the perimeter that allows the fixing of the belt in the teeth of the pulleys.

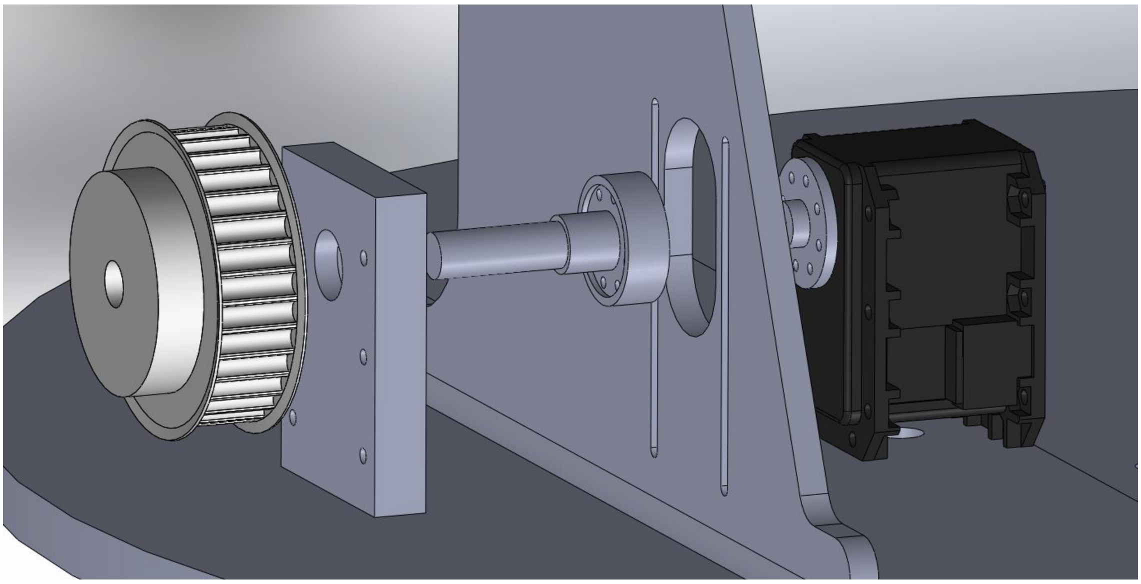


Figure 25. *Exploded view of the driver part of the timing belt after the modifications mentioned above*

Similar changes are also introduced to the driven part of the synchronous belt. The pulley is replaced by another of the same model as the one in the driver assembly, maintaining the 1:1 transmission ratio.

Following the same reasoning used in the driver part, modifications are made to the shaft, introducing different stretches to avoid the use of additional elements as separators. In this case, it is made up of a first section of 23.70 mm long with a diameter of 8 mm, where the pulley will be located.

The second section is 12 mm long and 10 mm diameter. This section contains the axial bearing, which has been resized maintaining the same characteristics and functionality. However, the dimensions are now 10x26x8 mm. This decision is made based on the availability of this bearing is immediate due to excess stock in the department. The bearing seat is resized along it to adapt to the new bearing size.

The last section is 3mm long and diameter 12 mm, to give the necessary clearance and avoid contact between the parts.

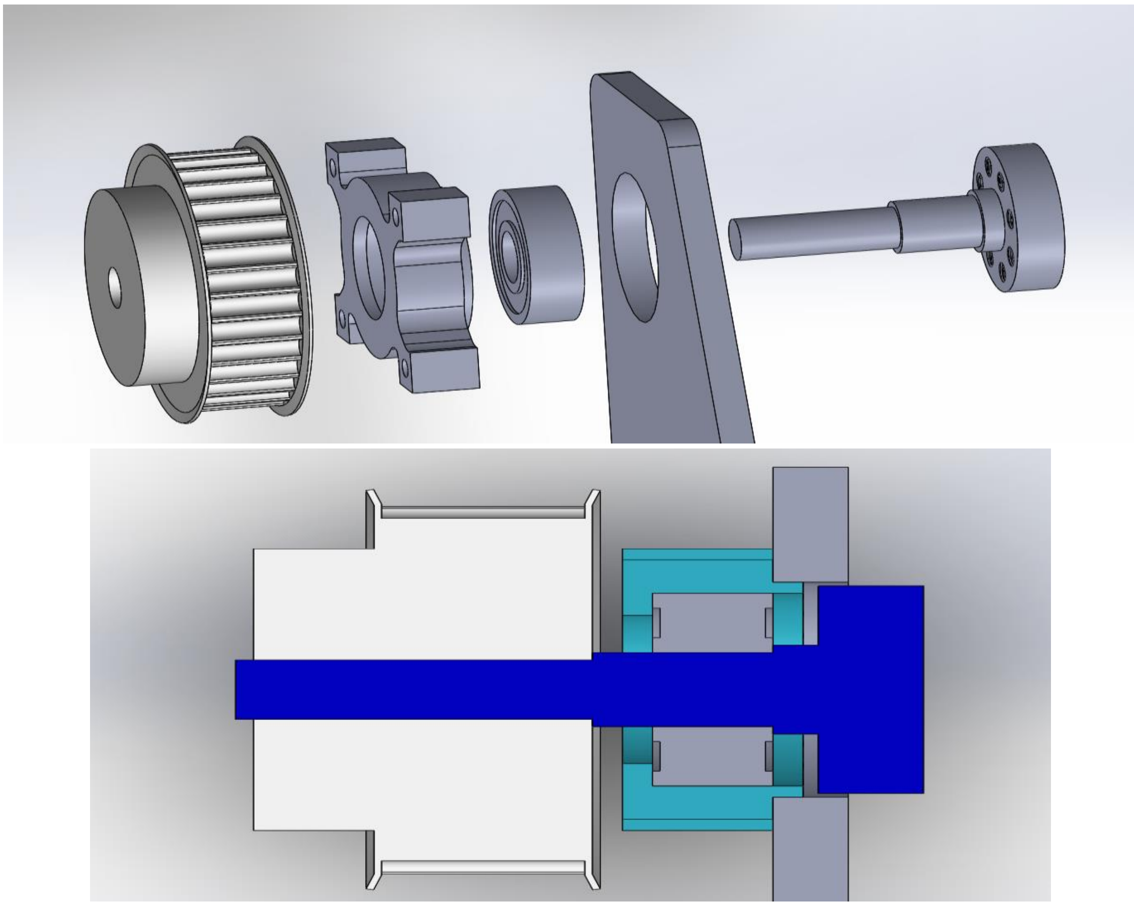


Figure 26. *On top, exploded view of the driven assembly. On the bottom, the cross section of the assembly.*

The last change made to the design is located in the driven part of the synchronous belt. Initially, the use of a support attached to the base was planned in order to alleviate the static efforts on the shaft and servo. However, the use of said method is finally ruled out due to modifications of the driven part. The position of the servo is finally not determined, as it is possible to modify its height according to the need for the belt, as it can be seen in the figure 22.

Due to this, the new model contains a bracket support with adjustable height by hooking it up directly to the antenna support as shown in the figure 27.

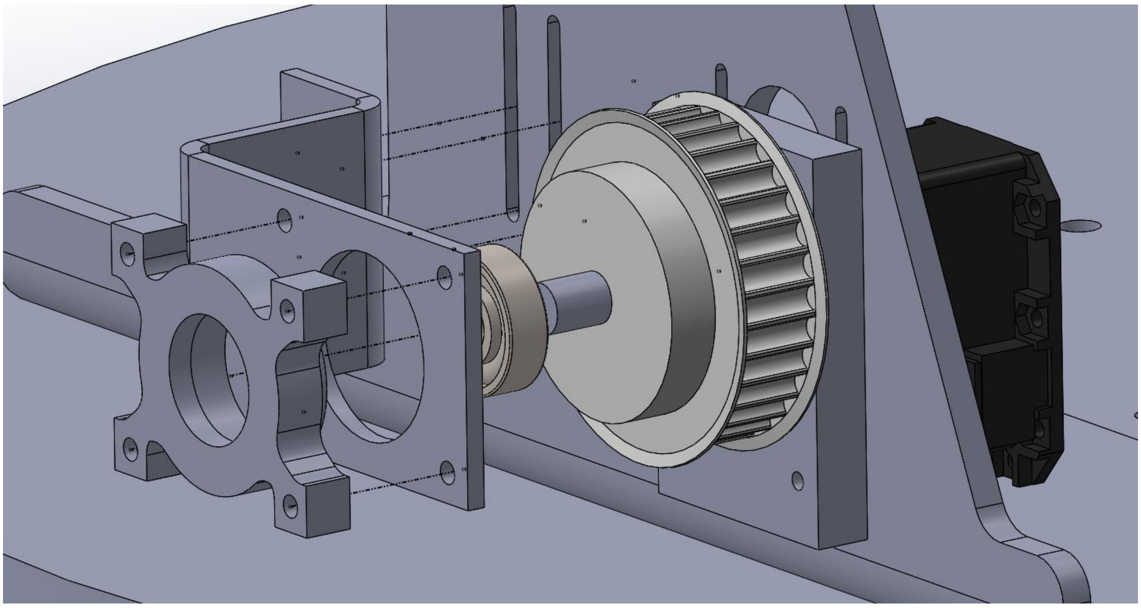


Figure 27. *Introduction of a bracket support with adjustable height. It is attached to the antenna support through new millings.*

The bracket is fixed directly to the antenna support by milling two slots for M3 screws. This way, said support can be adjusted in height in solidarity with the shaft position.

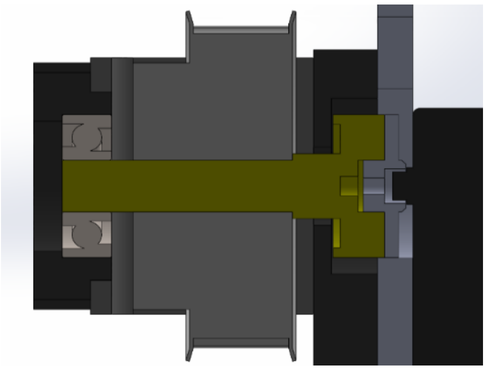


Figure 28. *Cross section of the final driver set of the timing belt.*

It has been also included an axial bearing to support the shaft axial loads, which measurements are 8x22x7 mm. The bearing is located in a housing solid similar to those used in the other shafts but adapted to the size of the new element.

How the elements combine can be seen in the figure 28. It shows the cross section of the assembly using different colours for visualization.

The final list of components is showed in the table 5.

Table 5. *Final list of components.*

Name	Part of	Quantity	Denomination
Base	Yaw rotation SS	1	ACO-Y-Base
Dynamixel MX-28	Yaw and pitch rotation SS	2	ACO-Y-Motor
Rotation gears	Yaw rotation SS	1	ACO-Y-Gears
Cylindrical block	Yaw rotation SS	1	ACO-Y-Block
Base	Pitch rotation SS	1	ACO-P-Base
Servomotor shaft	Pitch rotation SS - DVR	1	ACO-P-SShaft
Sleeve	Pitch rotation SS - DVR & DVN	3	ACO-P-Sleeve
Pulley	Pitch rotation SS - DVR & DVN	2	ACO-P-Pulley
Retention clip	Pitch rotation SS - DVR & DVN	2	ACO-P-Clip
Shaft support	Pitch rotation SS - DVR	1	ACO-P-SSupport
Antenna Support	Pitch rotation SS	2	ACO-P-ASupport
Driven shaft	Pitch rotation SS - DVN	1	ACO-P-DShaft
Bearing 8mm	Pitch rotation SS - DVN	1	ACO-P-8Bearing
Bearing 10mm	Pitch rotation SS - DRG	2	ACO-P-10bearing
Bearing housing	Pitch rotation SS - DVN & DRG	3	ACO-P-Housing
Dragged shaft	Pitch rotation SS - DRG	1	ACO-P-DRShaft
Antenna plaques	Pitch rotation SS	2	ACO-P-Plaque
Antenna	Pitch rotation SS	1	ACO-P-Antenna
Pitch servo fixing part	Pitch rotation SS	1	ACO-P-Fixer
Bracket support	Pitch rotation SS	1	ACO-P-Bracket

Legend
SS → Subsystem
DVR → Driver part of the transmission
DVN → Driven part of the transmission
DRG → Dragged subsystem

In red → Components removed
In blue → Components updated
In green → New components

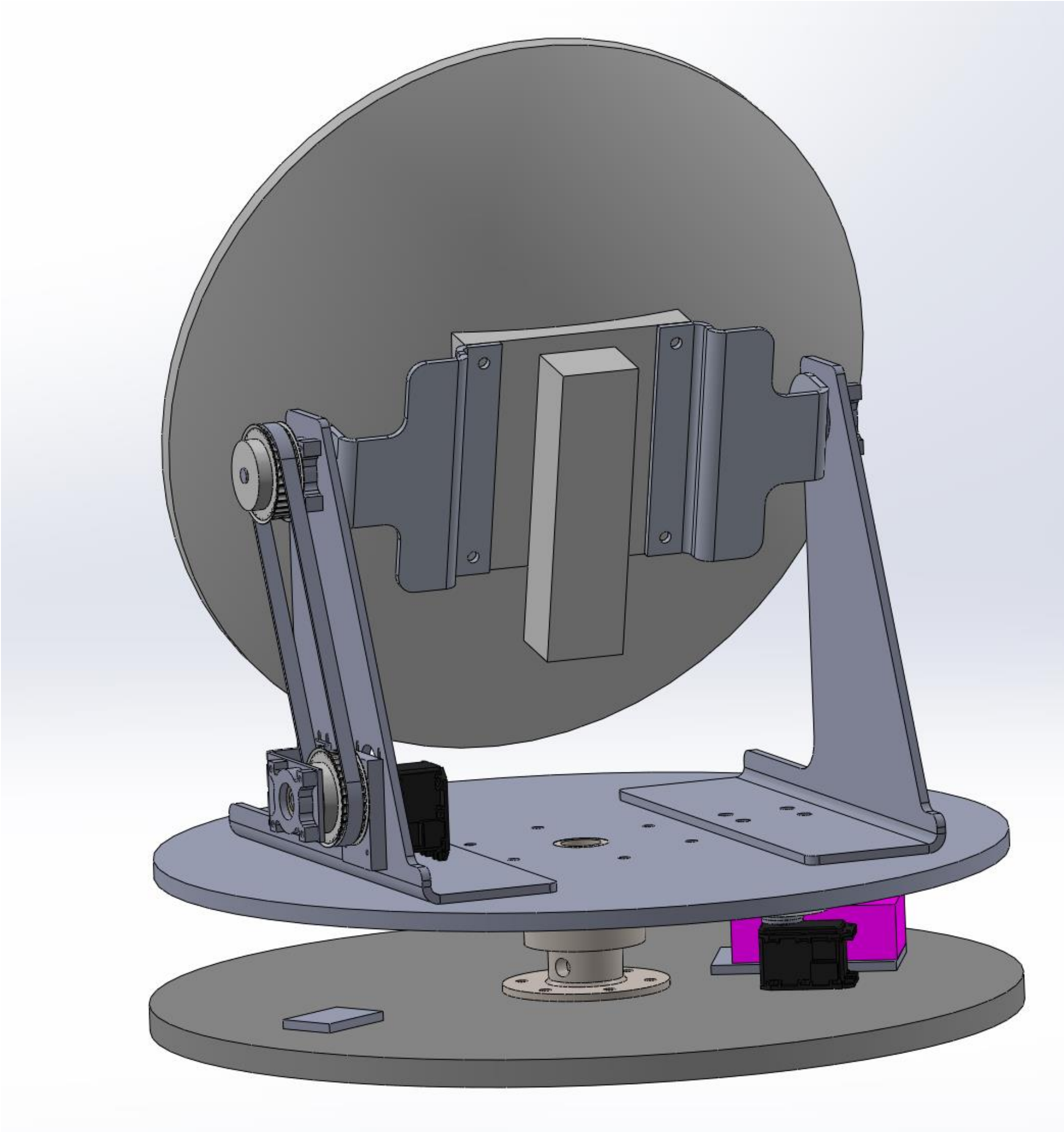


Figure 29. *Final design of the directional antenna structure*

In the figure 29, the final design with all the modifications discussed is shown.

APPENDIX A. STATIC SIMULATIONS contains the static forces studies performed to the shafts in order to assure their reliability while on service.

APPENDIX C. DRAWINGS contains the drawings of every new part manufactured. All the normalized elements and the pulleys are excluded as those are acquired through external suppliers whose measurements are included in commercial catalogues.

5.4 Assembling guide

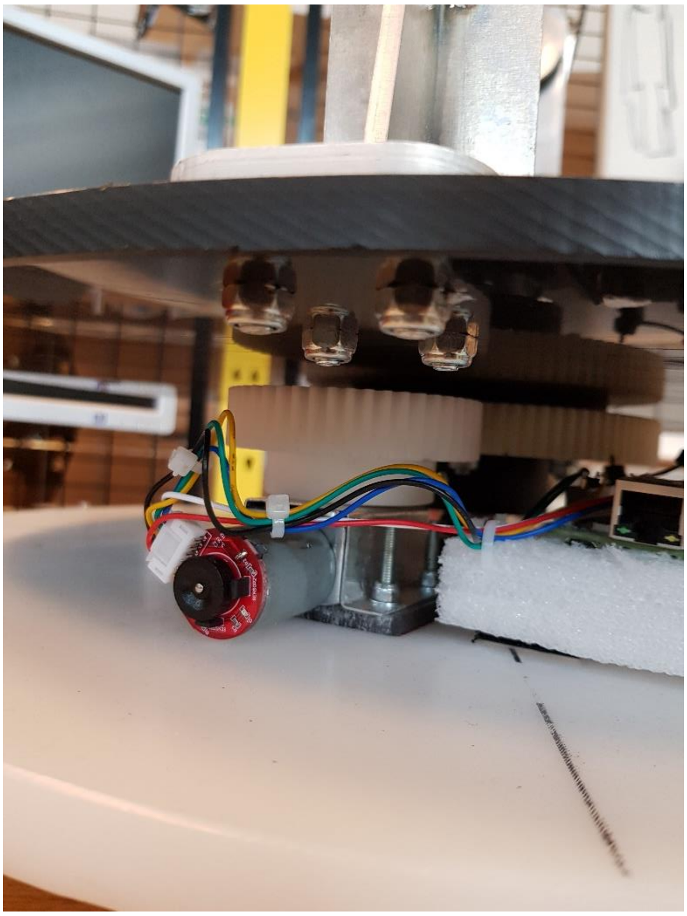


Figure 30. *Initial layout of components in yaw angle subsystem.*

The first step consists of disassembling the previous structure, in order to remove those elements that are not necessary anymore and replace them with the new components. The assembly begins at the bottom base, which supports the weight of the entire system and where it joins to the USV.

The components that must be removed before proceeding to install the new ones are the DC motor GM4632-370, as well as the communications board. The coupling of the motor to the base was formed by four M3 screws, attached to a metal clamp around the motor. The motor sits on an acrylic sheet crossed by the coupling screws, so it must also be removed. The communications board was adhered by a Velcro tape, so its removal is simple.

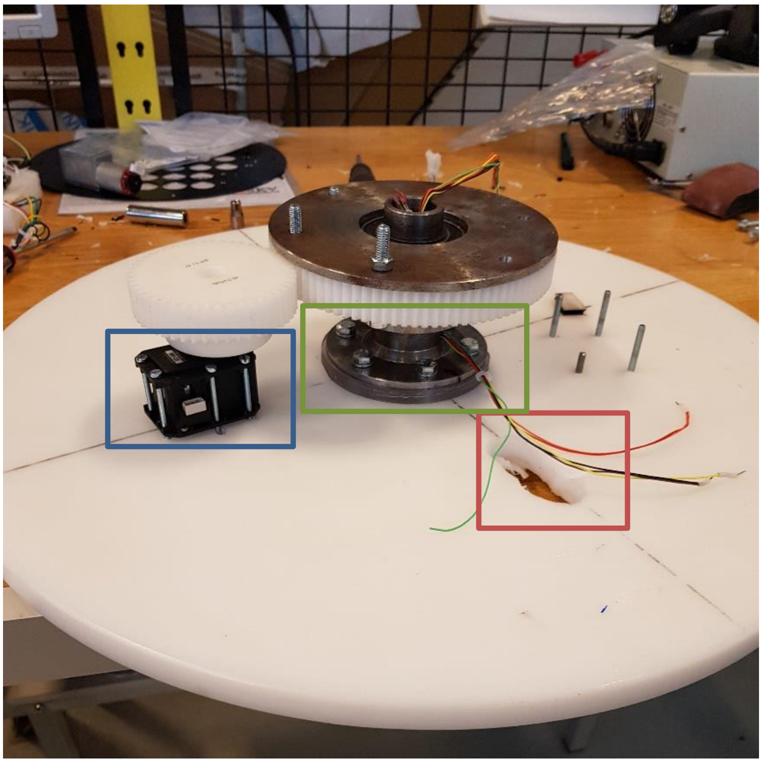


Figure 31. *New layout for the yaw angle subsystem.*

Once everything has been removed, the procedure to add the new servomotor begins. This phase consists of the assembling of the yaw angle subsystems.

The fixing of the servomotor to the base is done by using the existing holes in its case. To do this, the motor is oriented in such a way that its axis of rotation is parallel to the vertical axis of the structure. The problem is that the back part of the case is not completely flat, as it contains a bulge. Said protuberance has the purpose of carrying out a hooking point for different brackets depending of the use of the servomotor.

Because of this, it is necessary to make an incision in the base to accommodate it. A first attempt was made, shown in the red box of figure 31. However, this attempt failed due to the use of inadequate tools. Finally, it was made again in another position (blue box), this time making a single hole to house the extreme of the shaft, instead of trying to reduce the entire surface, and then make 6 through holes to insert the screws.

The screws were initially planned to use M2.5. Nonetheless, making this type of holes on the base resulted in an arduous and complicated work due to the available tools, so in the end the solution taken was to make larger holes, finally being 3.5 mm of diameter to house M3 screws. This modification necessitated widening the holes in the servo housing using a hand drill at low rpm to prevent from damaging the servo.

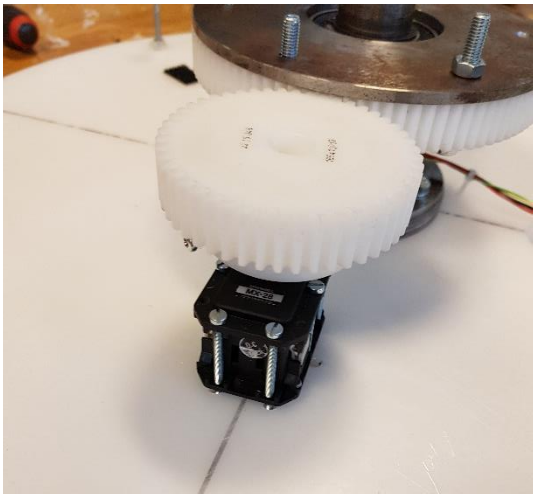


Figure 32. *Locking the servo in its place on the surface of the base.*

Once the servo is fixed, the next step was to adapt the height of the assembly due to the larger size of the motor. Initially, the solution proposed was to reduce the height of the gear. This option was quickly discarded during the assembly phase due to the difficulty of said operation. As the height of the gear cannot be reduced, it is decided to increase the height of the assembly, by adding a seat made in acrylic panel for the cylindrical block thus compensating for the increase in height of the servomotor, as it can be seen in the green box of the figure 32.

The connection between the shaft and the driver pulley is made by inserting a pin of 3 mm in diameter, to ensure the joint movement of the gear and the motor.

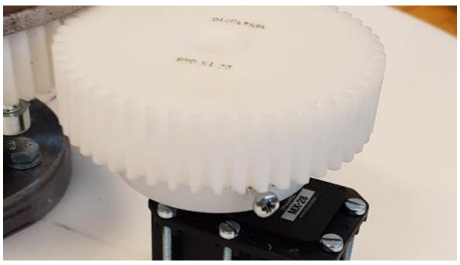


Figure 33. *Pin insertion through both gear and shaft*

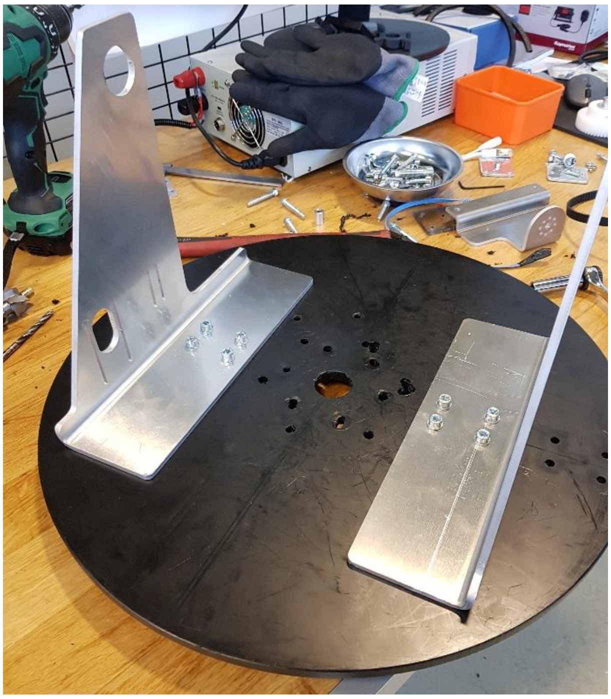


Figure 34. *Antenna supports locked in place showing the old set of holes.*

Figure 34 shows the modifications to the upper base.

On the one hand, it is necessary to make new holes to fix the supports the base. These holes have the same relative arrangement as those holes drilled previously, but at a shorter distance from the centre of the base as it can be seen in the right part in figure 34. The diameter of these holes is 7 mm, to facilitate the introduction of the bolts. The union is made with M6 bolts with hexagonal head. It ends with the use of nut and washer set and thus fix the union properly.

On the other hand, the hexagonal block of the lower gear set is fixed to the base by using other six M6 hexagonal head bolts. In figure 34 it can be seen how there are two different sets of holes in the central part, six holes forming an inner hexagon and other six forming an outer hexagon. The reason for this is that the cylindrical block previously used in this structure is replaced by one used on a homologous system. However, although both blocks have the same purpose and same dimensions, they vary in some of the manufacturing materials, as well as the exact arrangement of the union holes.

The six holes of the inner crown correspond to the block previously used, while those belonging to the outer crown are those to the block that is going to be used in this occasion.

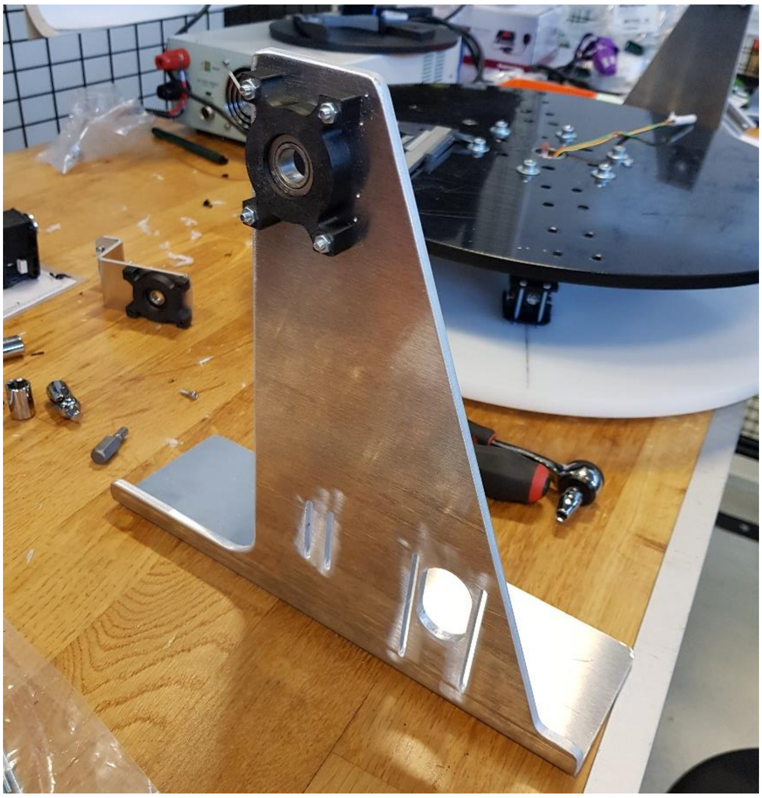


Figure 35. *Bearing and its housing assembling.*

The next step is to mount the synchronous belt.

First, the 10 mm diameter bearing that is located in the driven part of the transmission has to be placed. To do this, the bearing is fitted into its housing, and once this is done, the bearing is inserted into the upper hole of the support. The position is fixed by the 4 holes in the housing.

To do this, it is necessary to make holes in the support to allow the passage of screws. The holes are marked by using a pointer, which leaves a pressure mark to guide the holes. Then, a vertical drill is used to make the drills. The use of the vertical drill is recommended because the antenna supports are made of aluminium, so the additional power compared to the hand drill is suitable.

Finally, M3 bolts are introduced, and these are fixed in place thanks to the joint use of nut and washer of the same metric, with which the assembly is locked in the proper position. The result can be seen in Figure 35.

This same procedure is repeated later on the other antenna support, for the dragged set of components that allow the pitch rotation.

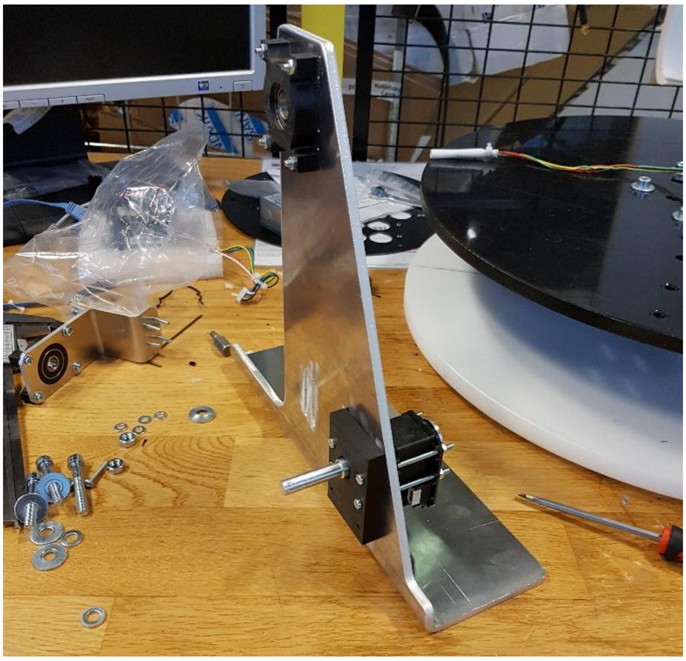


Figure 36. Locking the servomotor in the antenna support.

Next, the servomotor is fixed to the support at the desired height to satisfy the tension needs for the belt. To position the servo in place the holes in the case are used as in a similar way to the previous motor. Once again, it is necessary to enlarge said holes to accommodate M3 bolts. However, the reason for this change is different from the previous case, since the problem lies in that there was no availability to acquire screws from the original metric (M2.5) with enough length, while there was availability for wider and longer screws.

Initially, it was planned to use 6 screws according to the design. Nevertheless, due to the layout of the case, the lower holes are left free, as the use of nut-screw assembly become an impossible task due to the proximity of the electric connections of the servo.

A final modification from the computer design was performed in the central hole of the fixing counterpart element. Due to the precise adjustment between the shaft and the hole, the rotation of the shaft is impeded by the friction produced against the wall of the opening. By using the hand drill, the said hole is widened as it is shown in the figure 37

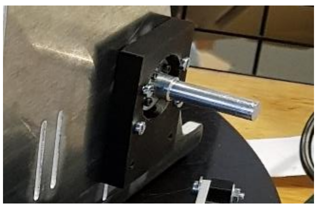


Figure 37. In detail view of the widening of the hole allowing free rotation of the shaft.

Next, the shaft of the driven part is introduced into the bearing, in order to prepare the pulleys' addiction.

The fixing of the pulleys uses the same principle used in the yaw gear system. A hole is made in the hub of the pulleys, in which a pin is then inserted, which exerts the necessary pressure on the shaft so that both elements rotate together.

Once the pulleys are inserted and fixed, the driver shaft is closed by adding its bearing, as well as fixing the housing of this bearing to the bracket support. To finish the assembly of the timing belt, the bracket is fixed to the antenna support four M3 screws.

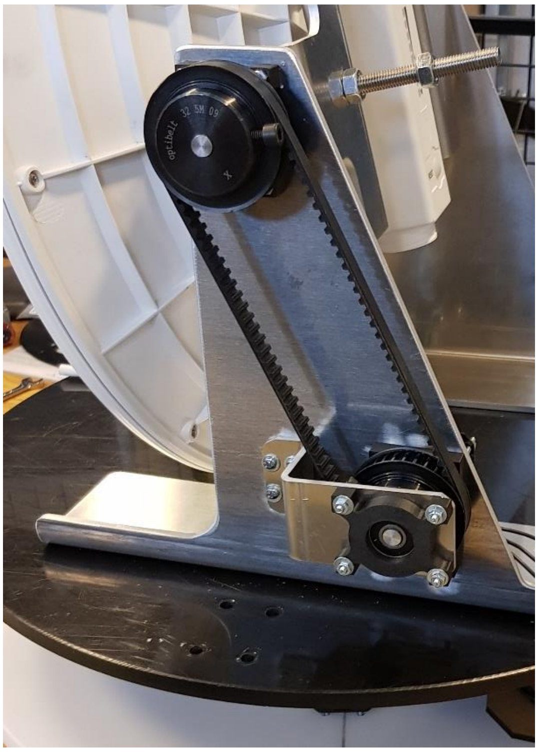


Figure 38. *Synchronous belt assembled.*

The antenna is mounted on two metal plaques. These plates are attached to the shafts in charge of its movement, these being the driven shaft of the belt, and the dragged shaft that follows the rotation.

The union between the shafts and the plaques are made with eight screws. The shaft that is part of the transmission belt is made of aluminium, and these holes contain the thread directly, so it is not necessary to use nuts to retain the screw, it goes directly threaded to the hole.

The second shaft is manufactured by 3D printing. This method allows great flexibility when it comes to obtaining the piece, however it does not have the enough precision nor enough resistance to make the thread directly in the hole, so this side is fixed according to a screw-nut union.

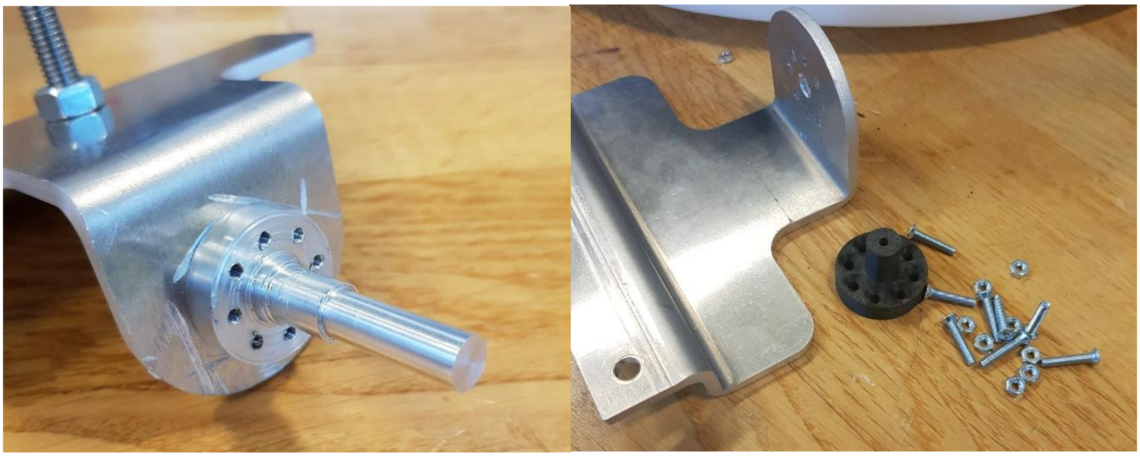


Figure 39. *On the left, the driven shaft fixed to one plaque. On the right, the other plaque, dragged shaft and union elements.*

To conclude the assembly, the antenna is attached to both metal plaques, by using four M6 screws, two for each plaque. The holes in the antenna are threaded, the union is done by just threading the screws in the holes.

Figure 40. *Assembly of the directional antenna completed.*

6. DESIGN OF THE ACTUATION CONTROL FOR ACTIVE TRACKING

The content of this chapter focuses on the elements that control the movement of the structure, as well as the necessary tools and their configuration that allow the communication between said elements, along with the programming of the code for the movement of the antenna to suit the needs of operations.

The control design focuses on enabling the ability to handle the movement of the antenna by manual instructions. At the end of the chapter, the movement of the antenna controlled by an operator will be completely defined. The integration with the communication and operation protocols with the USV would need automating the input of the code presented later in this chapter, leaving this task outside the scope of this project.

6.1 Description of the power system

The list of components responsible for antenna control are detailed below:

- Dynamixel MX-28 servomotors
- Arbotix-M Robocontroller
- 3 pin cable connectors
- 12V DC Power supply unit

The control system is based on two servomotors Dynamixel MX-28. These are the actuators of the system in charge of the rotation of the shafts that allow the movement of the antenna.

The actuators are controlled by a microcontroller board from the same company named Arbotix-M Robocontroller, connected through 3 pin cables that power the motors and transmit the control code from the board to the motors.

The whole system is then powered by a DC 12V power supply.

The specifications of Dynamixel MX-28 are presented in the table below:

Table 6. *Dynamixel* MX-28 Specifications[11].

Item	Specifications
MCU	ARM CORTEX-M3 (72 (MHz), 32Bit)
Position Sensor	Contactless absolute encoder (12Bit, 360 (°))
Motor	Coreless (Maxon)
Baud Rate	8,000 (bps) ~ 4.5 (Mbps)
Control Algorithm	PID control
Resolution	4096 [pulse/rev]
Backlash	20 [arcmin] (0.33 [°])
Operating Mode	Joint Mode (0 ~ 360 [°]) Wheel Mode (Endless Turn)
Weight	72 (g)
Dimensions (W x H x D)	35.6 x 50.6 x 35.5 (mm)
Gear Ratio	193 : 1
Stall Torque	2.3 (Nm) @ 11.1 (V), 1.3 (A) 2.5 (Nm) @ 12 (V), 1.4 (A) 3.1 (Nm) @ 14.8 (V), 1.7 (A)
No Load Speed	50 (rpm) @ 11.1 (V) 55 (rpm) @ 12 (V) 67 (rpm)] @ 14.8 (V)
Operating Temperature	-5 ~ +80 (°C)
Physical Connection	RS485 / TTL Multidrop Bus
ID	254 ID (0 ~ 253)
Feedback	Position, Temperature, Load, Input Voltage, etc
Material	Full Metal Gear Engineering Plastic(Front, Middle, Back) Metal(Front)

Regarding to the specifications included in table 6, It is necessary to explain in depth the meaning of some values of the specifications, in order to facilitate the understanding the control code of the structure that will be presented further on the chapter.

The baud rate indicates the speed at which the motor executes its instructions, including the reading of the data provided by the sensors of the servo. Higher values of this parameter allow more readings per second, at the cost of higher consumption. This is worth noting to improve the autonomy when powering the system using batteries.

The resolution parameter indicates the accuracy of the encoder. The measurement is 4096 pulse / rev, which indicates that the sensor can distinguish between 4096 different positions per turn, which yields an accuracy of:

$$4096\,\frac{pulse}{rev} * \frac{1}{360}\frac{rev}{°} = 11.3778\,\frac{pulse}{°} = 0.088\,\frac{°}{pulse} \tag{3}$$

Operating mode represents the rotation configuration of the servomotor shaft. One of the characteristics of these devices is the possibility of alternating the shaft rotation mode.

- • Joint mode. Default operation mode. It allows the completion of a full turn in the shaft rotation, after this, the motor stops.
- • Multiturn mode. Mode similar to the previous one, with the difference that in this case the rotation is allowed up to 7 full turns both clockwise and anticlockwise direction.
- • Wheel mode. Mode without rotation limit.

The mode used for the servo that handles the pitch angle of the antenna is the default operation mode, the joint mode. This decision is made because the shaft of this servo will not require a continuous rotation, as its requirements are based on small adjustments to compensate perturbations and follow the reference direction.

However, for the yaw angle servo, it is configured to use the second operating mode, the multiturn mode. This decision has been taken since, unlike the previous one, it must allow large-angle rotations. On the one hand, to achieve a complete revolution of the structure requires more than one turn of the shaft due to the gear ratio between the transmission system gears. The equation 4 shows the transmission ratio for the cog wheels attached to the yaw servo. To complete 1 turn in the driven cog the shaft must do almost two complete turns.

$$\frac{z_1}{z_2} = \frac{n_2}{n_1} \rightarrow n_1 = \frac{z_2 * n_2}{z_1} = \frac{95*1}{48} = 1.98 \tag{4}$$

Variables z_1 and z_2 represent the number of teeth of the cog wheels, while n_1 and n_2 represent the number of turns of each wheel.

On the other hand, it must permit large permanent rotations to accompany the movement of the USV without losing the reference. The Wheel mode has been discarded since, in spite of allowing infinite turns, it loses the position control. This mode would only allow continuous turns at a user defined speed, without the possibility to accurately control when it stops.

The stall torque indicates the torque exerted on the shaft when it is not rotating. This value is important to know, since it allows to block the shaft rotation when it is not necessary to move it. It allows to perform a good control against disturbances and unwanted actions. An example of this case is the weight of the antenna, which provides a natural rotation moment in the shaft axis as it can be seen in the previous chapter. The figure 41 shows the real torque curve of the motor.

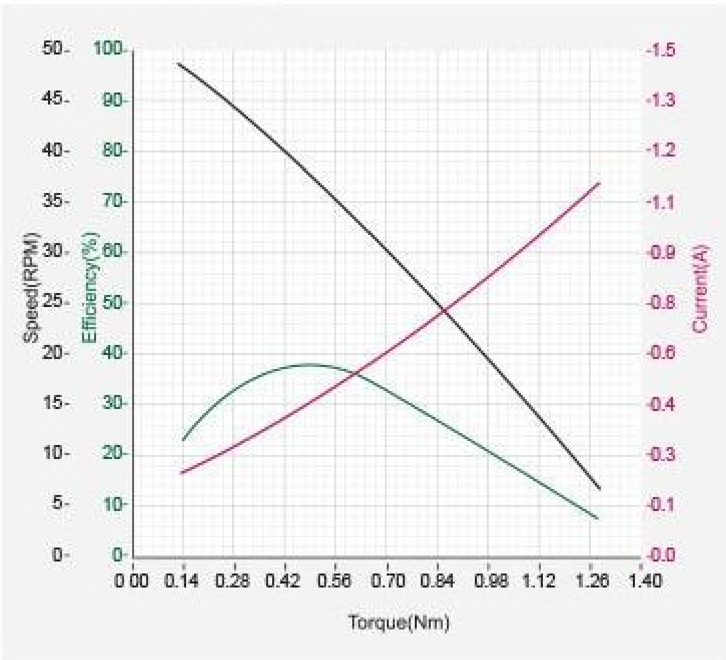


Figure 41. *Torque curve of Dynamixel MX-28*[11].

The Arbotix-m board functions are to provide electrical power to the motors and to control them. This board is compatible with the Arduino environment, which will be used to program the motors.

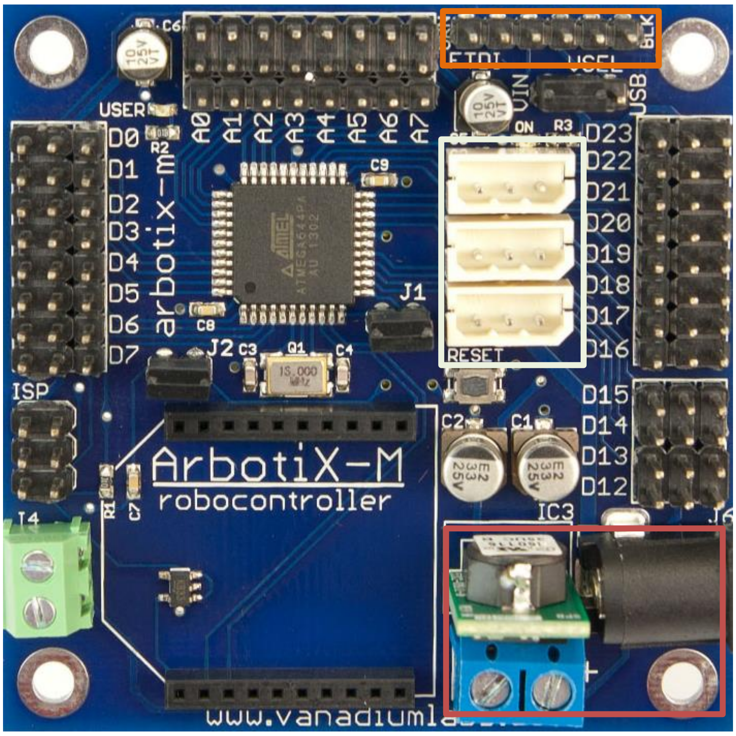


Figure 42. *Arbotix-M pin layout*[12].

The figure 42 shows the layout of the available connections of the board.

The interesting parts in the context of the realization of this project are described below.

The red box in figure 42 frames the power delivery system of the board. It is composed of two elements. On the left and with prismatic shape and colour blue, it is the screw-terminal, to which two cables must be connected to transmit the power: The left pin is connected to ground, while the right pin, under the plus symbol, it is where the positive voltage terminal must be connected. On the right, there is a standard connector 2.1x5.5 mm DC jack. This second will be the method to power the system in this project.

The orange top box in the right of the board frames the FTDI Serial port/programming port. This port has double functionality, since it acts as a connection channel with the computer. The two functions are to load the code on the board that will control the servos and to interact with the code loaded on the board in real time while it is being executed.

Finally, the white box in the middle of the board frames the 3 pin Dynamixel ports. These ports are used to connect the servos, since it allows direct connection, as well as stacking the servos to facilitate wiring. The pin on the left is the data transmission pins, while the one in the middle and the one in the right are those in charge to deliver power to the servos (positive voltage and ground respectively). It should be noted that the voltage that is transmitted through this connection is the same as the one used to power the board. The board admits between 7 and 30 V, while the servomotors only admit voltages up to 15 V, so it is necessary to take special precaution when making the connections to avoid damaging the servos[13][14].

Once the elements that form the control system have been introduced, the procedure for initial configuration of the work environment is described briefly. It includes the installation of the necessary software, including the necessary libraries to establish communication between the control system and the computer.

First, it is necessary to download and install the Arduino IDE. On the date of the realization of this project there are plenty of versions available, although the libraries that need to be used are only compatible with a few of them. For this reason, the version used is 1.0.6, as it is the last stable build compatible with the libraries provided by the manufacturer to control the servos.

Once Arduino is installed, it is necessary to incorporate the drivers that allow communication between the board and the computer. These drivers allow the computer to recognize the protocols used by the Arbotix-M system. The physical connexion between both devices are on one side an FTDI connection to the board, and the other side a USB connection to the computer. The version of these drivers used for this project is 2.12.28.

Next, it is necessary to incorporate the libraries and hardware files. These files are available on the manufacturer website. These files come in three different folders.

- Hardware. This folder contains all the necessary hardware definitions, to allow to adapt the code to the framework so it can be utilized by the components that form the Arbotix-M.
- Libraries. This directory contains the different functions and methods already coded by the manufacturer to allow a greater flexibility to the user.
- Arbotix Sketches. Finally, this folder includes sample codes that can be executed directly on the board.

To install the libraries, it is necessary to copy the folders that contain them and paste them into the Arduino user folder of the computer. This directory is created during the installation of the IDE, and it can be found by default in the next location:

```
C:\Users\user\Documents\Arduino
```

The last parameter to configure before starting to write the code for the control is the internal ID of each servo, as well as the baud rate that the servos will use. The servos have an internal variable of type integer that stores a number that serves to identify them. The value that this variable adopts in each servo must necessarily be different, since the methods and functions to control them contained in the libraries act on the servos according to the value that is introduced based on this variable.

The default value of this variable is equal to 1, so it is necessary to change it in at least one of the servos so that the servos do not share IDs.

To do this, a tool provided by the manufacturer is used. In addition, it also allows to change the baud rate. The name of the tool is DynaManager.

The ID of the servos are set then to 1 and 2, for the yaw and pitch respectively, with a baud rate of 1 000 000 bps.

Once all the components are set up, the board is attached to the lower base, where the previous control board was connected. The servomotors are connected to the board by using the 3 pin cables. The cable connecting the yaw servomotor to the board is hooked up directly, while the cable used for the pitch servomotor is introduced through the passage located in the cylindrical block, allowing the rotation without physical restrictions possibly occasioned by the wiring.

6.2 Controller programming

The code used to control the servos is detailed in this section. It consists of code snippets and the details of the purpose of each command.

```
   //define pan and tilt servo IDs
 2 #define PAN    1
   #define TILT   2
 4
   //Upper/Lower limits for pitch servo to prevent from damaging
 6 //the antenna
   #define TILT_MAX 3072
 8 #define TILT_MIN 2048

10 //Upper/Lower limits for the pan servo
   #define PAN_MAX 28672
12 #define PAN_MIN -28672

14 //Default/Home position.
   #define DEFAULT_PAN 0
16 #define DEFAULT_TILT 2638
```

Program 1. *Definition of constants.*

In program 1 the first lines of code are shown, which correspond to the constants that restrain the movement of the antenna.

Lines 2 and 3 define two constants to facilitate the writing of the posterior code by adding identifiers for both servos. The value to this constant is the value assigned to the ID of the servos. PAN represents the yaw servo, while the constant TILT corresponds to the pitch servo.

Lines 7 and 8 correspond to the limit constants for the position of servo TILT. The values assigned to this set of data attends to the configuration of servo sensors as it was mentioned in the section before. The sensor range is from 0 to 4095 for a full turn, so these values correspond to:

1. TILT_MAX : 3072 corresponds to 270°
2. TILT_MIN : 2048 corresponds to 180°

The servo rotates in the anti-clockwise direction, so the maximum limit, corresponding to 270° would be the lowest position of the antenna, while the lower limit, 180°, is the highest position of the antenna.

Lines 11 and 12 represent the position limits for servo PAN. The values for its limits are much higher, being almost ten times more. The values are set this way to allow the motor to rotate more than one complete turn. Specifically, these values correspond to 7 full turns of the servomotor shaft, both clockwise and counter clockwise.

Lines 15 and 16 define the position values that will be used both during the start-up and as the target position of the servos in case the connection between servos and the board is lost.

```
18 //Include necessary Libraries to drive the DYNAMIXEL servos
   #include <ax12.h>
20 #include <BioloidController.h>

22 /* Hardware Construct */
   BioloidController bioloid = BioloidController(1000000);
24
   //Variable definitions
26 int pan;            //Current position of the pan servo
   int tilt;           //Current position of the tilt servo
28 int desiredPan;     //Desired position of the pan servo
   int desiredTilt;    //Desired position of the tilt servo
30 bool control;      //Internal variable to set new servo position
   int conditionPan;  //Variable to set new operating points
32 int conditionTilt; //Variable to set new operating points
   int speed = 6;
```

Program 2. *Introduction of libraries and variables.*

Program 2 introduces the variables and libraries that will be used.

Lines 19 and 20 include the necessary libraries to include the already defined functions that will be used later. These libraries are those that contain the definitions of hardware, in addition to the methods of access to the sensors and shaft rotation. The libraries are formed by 4 files:

- ax12.h: This is the header of the ax12 library. In this file, the access parameters to the different sensors and the definitions of the methods of interaction with said parameters are introduced.
- ax12.cpp: It is the main file of the library, where the methods that define the behaviour of the functions of this library are coded.
- BioloidController.h: It is the header of the BioloidController library. This library contains the hardware definitions. Allows to identify the components that form the servo and the interactions between them.
- BioloidController.cpp. Main file of the BioloidController library.

Line 23 contains the initialization of an object of the Bioloid class from the BioloidController library. This object is created to store the data of the servos and to control them during the start-up process. The parameter of this function is the operating baud rate.

The variables of the code are specified from line 26 to line 33. They are mostly of type int. The first four store the position at each moment and the target position, while the other three serve as auxiliary variables for the control code written later. The use for the bool variable named control will be explained further on the document.

```
void setup()
 {
   pinMode(0,OUTPUT);     //setup user LED
   //turn user LED on to show the program is running
   digitalWrite(0, HIGH);

   //Change in the register to enable multiturn mode in PAN
   //servo
   ax12SetRegister2(1, AX_CW_ANGLE_LIMIT_L, 4095);
   ax12SetRegister2(1, AX_CCW_ANGLE_LIMIT_L, 4095);

   //setup interpolation, slowly raise turret to home positon.
   pan = DEFAULT_PAN;//load default pan value for startup
   tilt = DEFAULT_TILT;//load default tilt value for startup

   //Setting points to follow
   desiredPan = 0;
   desiredTilt = 3000;

   //Variable to establish hierarchy in the code
   control = false;

   //wait for the bioloid controller to intialize
   delay(1000);  //

   //2 servos, so the pose size will be 2
   bioloid.poseSize = 2;

   //Find where the servos are currently
   bioloid.readPose();

   //Prepare the pan servo to the default position
   bioloid.setNextPose(PAN,pan);

   //Prepare the tilt servo to the default position
   bioloid.setNextPose(TILT,tilt);

   //Setup for interpolation from the current position to the
   //positions set in setNextPose, over 2000ms
   bioloid.interpolateSetup(2000);

   //Until we have reached the positions set in setNextPose,
   //execute the instructions in this loop

   while(bioloid.interpolating > 0)
     {
       bioloid.interpolateStep();//move servos 1 'step
       delay(3);
     }
 }
```

Program 3. *Setup() function.*

A typical Arduino code consists of two fundamental functions: the setup() function and the loop() function.

The setup() function is executed only once at the beginning of the operation. This function includes the initialization of the necessary parameters for correct execution.

The loop() function contains the main code of the program. This function is executed once per clock cycle of the processor unit of the board. While the board is connected, this code is continuously executed in a loop until the power is disconnected from the board.

Program 3 shows the system setup function.

In Figure 42 it can be seen in the upper left corner a led with the USER label. This led is set to pin 0 of the board. Lines 37, 38 and 39 show the use of this led as feedback to the user so that the operator knows that the program is at least being executed and that the board is correctly connected to the power system.

The pinmode(pin, mode) function establishes the mode of operation for that pin. The mode is OUTPUT type since it is an output component as it gives feedback to the user. The digitalWrite(pin, value) function establishes the voltage value supplied to the led, with HIGH connected and LOW disconnected. The value is set to HIGH, so the led lights up.

Lines 43 and 44 contain the function ax12SetRegister2 (int id, int regstart, int data) defined in the library ax12. Its parameters represent:

- id: The identifier of the servo to indicate in which servo the function must act on.
- regstart: The registry entry that is set to be modified.
- data. The desired value.

The function acts on the register entry introduced in the regstart parameter, modifying its value and replacing it with the value of the data parameter, for the servo with ID equal to the parameter id. In the header file ax12.h there is the record table, where all the values of the servo parameters are shown. The registry entries can be read or read and write. In the first group are located the sensors registers, while in the second group are the operating parameters of the servos. More information about the servo registries can be found in APPENDIX B. REGISTRY ENTRIES.

In this case, the function is used to change the operating mode of the system. The registry entries that are modified are the rotation limits for both clockwise and counter clockwise movement. By setting both limits to 4095 according to the manufacturer's instructions[11], the restriction of a single rotation of the default operating mode is eliminated, setting the multiturn mode, being this step necessary to the PAN servo.

In lines 47 and 48 the initial position of the system is configured, initializing the variables that control the position of the servos to the default value during the start-up of the system.

Lines 51 and 52 initialize the target position variables of the system.

Subsequently, the control variable is initialized, which will be used later to manually define new points of operation once the target position has been reached.

Line 58 shows the implementation of a 1 second delay, to ensure the correct configuration of the bioloid controller.

Line 61 indicates the number of servos to be controlled by the bioloid object.

The readPose() method of the BioloidController library on line 64 reads the current position of both servos.

On lines 67 and 70 the movement of the servo motors is started in order to achieve the positions defined in lines 47 and 48, by using the setNextPose() method of the BioloidController library.

The last lines from 79 to 83 correspond to the subsequent movement of the servos until the start-up target position is reached, in a period of less than 2 seconds.

```
86  void loop()
      {
88      //Initiate Serial Communication
        Serial.begin(9600);
90
        //Checks position of the servo
92      pan = GetPosition(PAN);
        tilt = GetPosition(TILT);
94
        //When its close enough
96      conditionPan = abs(pan-desiredPan);
        conditionTilt = abs(tilt-desiredTilt);
98
        //Control loop. When the target position is reached new
100     //positions for pan and tilt are introduced
        if(conditionPan <= 10 && conditionTilt <= 10)
102       {
            if(control == false)
104           {
                Serial.println("Enter the new pan point: ");
106             while(!Serial.available())
                  {
```

```
108                   //Do Nothing unless there is a reply!
                    }
110               desiredPan=Serial.parseInt();
                  //desiredPan = random(PAN_MIN, PAN_MAX);
112               desiredPan=max(desiredPan, PAN_MIN);
                  desiredPan=min(desiredPan, PAN_MAX);
114               Serial.println(desiredPan);
                  control = true;
116             }
              if(control == true)
118             {
                  Serial.println("Enter the new tilt point: ");
120               while(!Serial.available())
                    {
122                   //Do Nothing unless there is a reply!
                    }
124               desiredTilt=Serial.parseInt();
                    //desiredTilt = random(TILT_MIN, TILT_MAX);
126               desiredTilt=max(desiredTilt, TILT_MIN);
                  desiredTilt=min(desiredTilt, TILT_MAX);
128               Serial.println(desiredTilt);
                  control = false;
130             }
            }
132
```

Program 4. *Loop() function, Evaluation and main if loop.*

The loop() function of the program consists of two fundamental parts.

First, a series of checks are carried out to acquire the current position sensors of the servos. After this, an if-else structure is introduced. The condition of this structure is dependant of the data collected in the first step: if the target position has been reached, a new target point is established in the if section. If it hasn't reached the target position, then the system continues to move according to the code of the else section.

In program 4 the section of the checks and the content of the if loop are shown.

On line 89, the serial communication terminal is initialized. This terminal will be the one used so that the user can interact with the board while it is performing in real time. This resource will be used to introduce new target operation points once the active target point is reached. The parameter that is entered is the baud rate with which this terminal will work with. The value is chosen from a range of values predetermined by the utility. 9600 is the chosen one, as it grants enough speed with low consumption of resources.

Lines 92 and 93 contain the necessary code to obtain the reading of the position from the servo encoder. The function used is GetPosition(id) from the library ax12, which at the same time it is a definition used to replace the use of the function ax12GetRegister (int, int regstart, int length), and thus be more user-friendly. The parameter regstart in this case is the entry in line 39 in the APPENDIX B. REGISTRY ENTRIES.

Once the position data has been obtained, the distance to the target point is calculated on lines 96 and 97. The distance is compared with a by user set precision value as a condition of the if-else structure. If this value is less than the threshold value, the code in the if loop is executed. If it is greater than the threshold, this part is omitted, and the else loop is executed instead.

The purpose of the if loop is to establish new operating points to continue the movement of the antenna. The content of this loop therefore contains the instructions necessary to alter the position variables manually by the user in real time.

Within the if loop, there are two more if loops. These code blocks are designed to be executed sequentially. In the first, the new target position for the PAN servo is established and in the second the same thing happens, this time for the TILT servo. The sequence is controlled by the control variable, of the bool type initiated to false in the program setup() function. Once the first nested if loop is executed, this variable changes its value, to meet the condition of the next loop. Once this second set is executed, the value of the control variable is reseted for its use on the next occasion.

The actions of these nested if loops are described in the following lines. In the first place, the user is warned to enter the new target position, by an imprint in the terminal of a warning using the println(string) method of the Serial class.

Once the value has been entered, the number entered is set to the desiredPan variable using the parseInt() method of the Serial class.

One drawback of using this method is that if a value for the new position that exceeds any of the limits of rotation is introduced, the program would present a malfunction in which the structure would move until it reaches the limit, without giving the possibility of establish a new point, since the condition of line 101 would never occur, so the system would stop working.

To solve this problem, the code of lines 112 and 113 is introduced. They contain calls to the functions max(value, reference) and min(value, reference) are used, from the Arduino integrated libraries.

With the use of these functions, the new target position is prevented from exceeding any of the limits, by comparing the value entered with the limits and setting the limits as target points if the value introduced by the user exceed the limits.

A different mode of operation has been included, in which the new points are chosen randomly after reaching the target point, and not manually by the operator. To change to this mode of operation, it is necessary to remove the comment from line 111, and comment the rest of the lines of the loop, like it is shown in program 5.

```
            if(control == false)
104           {
                //Serial.println("Enter the new pan point: ");
106             //while(!Serial.available())
                //  {
108                   //Do Nothing unless there is a reply!
                //  }
110             //desiredPan=Serial.parseInt();
                desiredPan = random(PAN_MIN, PAN_MAX);
112             //desiredPan=max(desiredPan, PAN_MIN);
                //desiredPan=min(desiredPan, PAN_MAX);
114             //Serial.println(desiredPan);
                control = true;
116           }
```

Program 5. *Selecting new target points randomly.*

This command makes use of the random(x, y) function of Arduino. What this function does is to obtain an int type number randomly between the x and y limits introduced as parameters.

From lines 117 to 130 is the same principle over the TILT servo instead over the PAN servo.

```
        else
134       {
            if((desiredPan - pan) >= 0)
136           {
                if((desiredPan - pan) <= speed)
138               {
                    pan = desiredPan;
140               }
                else
142               {
                    pan = pan + speed;
144               }
              }
146         if((desiredPan - pan) < 0)
              {
148             if((pan - desiredPan) <= speed)
                  {
150                 pan = desiredPan;
                  }
152             else
                  {
154                 pan = pan - speed;
```

```
            }
        }
      //Enforce upper/lower limits for pan servo
      pan = max(pan, PAN_MIN);
      pan = min(pan, PAN_MAX);

      if((desiredTilt - tilt) >= 0)
        {
          if((desiredTilt - tilt) <= speed)
            {
              tilt = desiredTilt;
            }
          else
            {
              tilt = tilt + speed;
            }
         }
       if((desiredTilt - tilt) < 0)
         {
           if((tilt - desiredTilt) <= speed)
             {
               tilt = desiredTilt;
             }
           else
             {
               tilt = tilt - speed;
             }
         }
      //Enforce upper/lower limits for tilt servo. s.
      tilt = max(tilt, TILT_MIN);
      tilt = min(tilt, TILT_MAX);
      //Send pan and tilt goal positions to the
      //pan/tilt   servos
      SetPosition(PAN,pan);
      SetPosition(TILT,tilt);

      //Delay to allow servos move to the goal position
      delay(10);
    }
}
```

Program 6. *Else loop in the loop() function*

The else loop of the loop() function contains the code responsible for moving the servos. The idea proposed is an incremental procedure to control the position at all times and prevent tracking errors.

Again, the code of this part is structured in two blocks mainly, being these constituted by the same set of instructions, but acting on different servomotor, so it is only necessary to explain the first part of the code.

First, it is necessary to evaluate the relative disposition between the target position and the current position, since depending on this factor the servomotor has to rotate in one direction or in the other. This content is represented in lines 135 and 146 for example.

Once it has been ascertained in which direction the motor has to rotate, the increase of the movement signal is made to try to reach the objective position. The speed of the system is done by controlling the step size of the increment of the position in each cycle by using the variable called speed.

Increasing the value of the variable speed allows to modify the speed of the system. It has been tried values ranging from 1 to 50, what it translates to a range of 1 to 55 rpm. The value is set to 6 due to two reasons mainly.

On the one hand, it grants a speed of approximately of 7 rpm. This speed allows to rotate the pitch from bottom to top in less than 3 seconds. On the other hand, greater speed values provoke greater instability during the transient moments, especially when the motor starts. These values were dangerous to use in the test bench as there was not available mounting and fixing the whole structure, so it could freely move due to the load actions leading to rupture.

Since the movement is performed by discrete short increments, it is necessary to consider the case when the increment necessary to reach the target position is smaller than the step size, so this condition must be added through if-else structures. An example can be seen in lines 137-155.

The commands of lines 158 and 159 are incorporated to avoid exceeding the limits of the servos, in an analogous manner to the code in program 4 in which the target positions were prevented from exceeding the limits. These lines are incorporated redundantly to guarantee the precision of the movement of the servomotors.

Once the increase per cycle and the direction of rotation has been determined, the rotation signal is sent to the servo so the shaft rotates to reach the target position by means of the function SetPosition(id, pos) of the library ax12.

This function has a similar definition to the function GetPosition(id). SetPosition(id, pos) contains in its definition a call to the function ax12SetRegister2(id, regstart, value). In this case, the modified registry entry (line 33 in APPENDIX B. REGISTRY ENTRIES) is the one reserved for the movement of the shaft.

Once the movement is set, a delay of 10 ms is introduced to allow the servos to reach the position set by the increment, and thus be able to start the cycle again, until the target position is finally reached.

7. LABORATORY TESTING OF THE DIRECTIONAL ANTENNA

In order to evaluate the benefits derived of the new structural and control design, it is necessary to perform a series of tests to provide evidence of the improvements. For that reason, this chapter is dedicated to the results obtained after performing a defined sequence of operations to measure the shaft rotation values.

First, the methodology used to carry out the tests is presented, followed by the results of performing the tests.

7.1 Test methodology

In the figure 43 the test bench used is shown:

Figure 43. *Test bench used to test the accuracy of the structure.*

The figure 43 shows the elements used during the tests. These elements are formed by the actual antenna structure, connected to the Arbotix-M board. The board is connected to a laptop with the Arduino IDE installed by an USB connection as it was described during the chapter 5.

The tests will consist of a series of different runs of code to measure the accuracy of the antenna to reach to a desired target location.

For the measurements, the internal sensors of the servos will be used, specifically the encoders that proportionate the information of the rotation values of the shafts.

The tests for every servomotor rotation will be performed individually, so only one servomotor is active in each run of the test, to isolate the results and prevent for wrong reading by the user.

The tool used to get the measurement values is the Arduino Serial Monitor. This tool will be used to set the target points as it was described in chapter 5, and also to read the sensor values.

Due to the fact the tests are made separately for each motor, it is necessary to adapt the code that controls the servomotors.

```
void loop()
  {
    //Initiate Serial Communication
    Serial.begin(9600);

    //Checks position of the servo and then shows its value
    pan = GetPosition(PAN);
    Serial.println(pan);
    //When its close enough
    conditionPan = abs(pan-desiredPan);

    //Control loop. When the target position is reached new
    //positions for pan and tilt are introduced
    if(conditionPan <= 10)
      {
        {
          Serial.println("Enter the new pan point: ");
          while(!Serial.available())
            {
              //Do Nothing unless there is a reply!
            }
          desiredPan=Serial.parseInt();
          desiredPan=max(desiredPan, PAN_MIN);
          desiredPan=min(desiredPan, PAN_MAX);
          Serial.println(desiredPan);
        }
      }
```

Program 7. *Code adapted to get rotations value printed in terminal*

Program 7 shows the code adapted to the PAN servo. For the TILT servo is the same structure but changing the variables belonging to PAN to those analogous for TILT servo.

The difference between the initial code is the values of the position printed in every step of the loop to follow the trajectory, and that the condition for the if-else structure is reduced to only one servo. The changes are highlighted in boldface.

The steps taken for every measurement are presented below.

- Target point, inferior limit point and superior limit point are set.
- System is initialized to default position.
- The movement starts by setting the position to the inferior limit point.
- From the inferior limit point, the system is moved to target point.
- Measurement of the value of the encoder, and it is written down.
- From the target position it is moved then to superior limit point
- Movement from superior limit point to target point
- Measurement of the value of the encoder, it is then written down.

The process is repeated three times more for every target point, yielding 8 different measures for every target point. The target points will be taken arbitrarily.

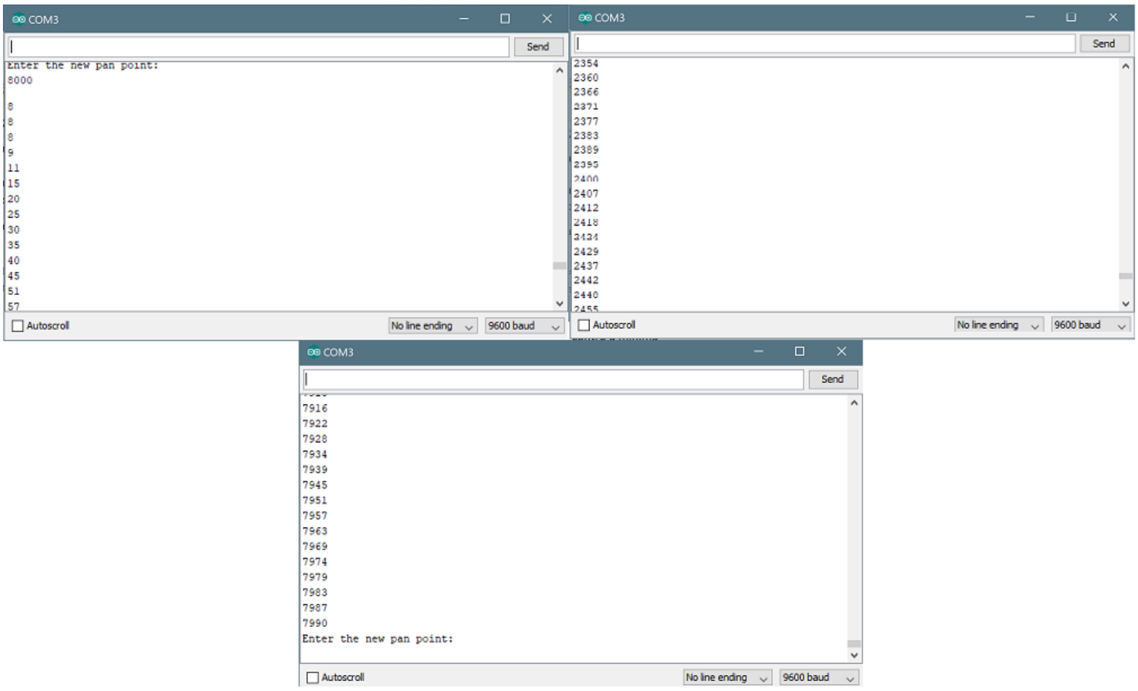


Figure 44. *Serial Terminal screen captures of the process. From top left, top right to bottom. It shows the data registered from the sensor while performing the tests.*

Figure 41 shows the readings taken from one set of measures in the terminal screen. The units used to choose the target points and limits has been in encoder pulses. The equivalencies for every servo pulse to the actual movement of the antenna in degrees will be introduced further on with the results of the servos.

For the PAN servo, will be compared the measures with the rotation of the driven wheel instead of the driver attached to the servo. This consideration is taken due to the fact that the goal of the PAN servo is to rotate the antenna around the yaw angle, which the driven wheel is in charge of. For the TILT servo the rotation is taken directly from the movement of the shaft of the servo.

7.2 Test results

There have been performed six tests in total, three for the PAN servomotor and three for the TILT servomotor.

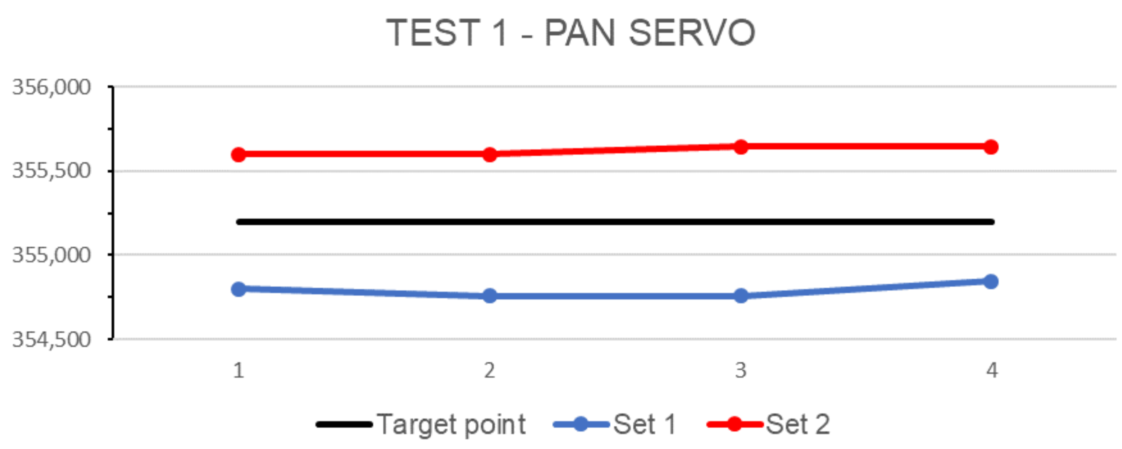
In total, there are 48 different measures, as every test contains 8 different measures. For that reason, the results are presented in different graphs.

The measurements have been grouped in two different sets for each group. Each set contain four values corresponding for the group of measurements taken when moving the servo from the same point to the target point, as it has been stated in epigraph 6.1.

7.2.1 Test 1. PAN servo

The target position set for this servo is 8000, which corresponds to a rotation of 703.297° for the driver wheel, and 355.2° for the driven wheel. This target is set to simulate the behaviour of the antenna in case the USV must do a full turn. The limits are set to 0 and 16 000, being 0° and 1406.593° respectively for the rotation of the shaft.

The results can be seen in figure 45.



Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
1	355.2°	354.79°	355.622°	0.411°	0.422°

Figure 45. *Results of test 1.*

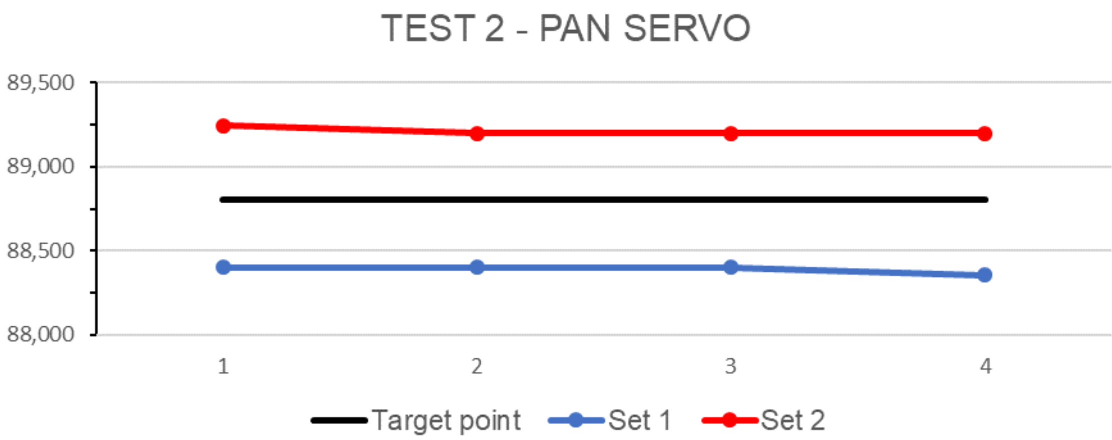
The red line represents the angle when reaching the target position from the superior limit, while the blue one represents the same but coming from the inferior limit. The black line is the target point.

The mean is calculated for both inferior and superior sets of measures. With this value it is calculated then the error showing a deviation from the target of approximately 0.4° for both cases

7.2.2 Test 2. PAN servo

In this case, a smaller rotation is tested in order to check the behaviour of the antenna for smaller variations. The target position for the shaft of the servo is set to 2000, which is in turn 175.824° for the driver wheel, and 88.8° for the driven wheel, and thus the whole structure. The limits in this case are set to 0 and 4000, which in degrees are 0° and 351.648° of shaft rotation respectively.

Figure 46 shows the results obtained in this test.



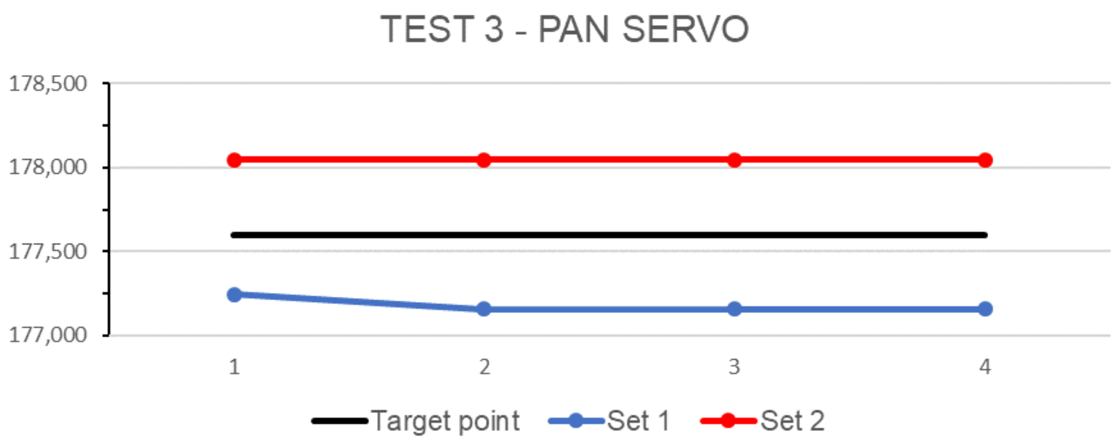
Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
2	88.8°	88.389°	89.211°	0.4°	0.411°

Figure 46. *Results for test 2*

The performance in this test is similar to the previous one, with a marginal lower deviation.

7.2.3 Test 3. PAN servo

The last test for the PAN servo rotation has a target position of 4000. It corresponds to 351.648° for the shaft rotation and 177.6° of the driven wheel. This value is used to simulate the behaviour of the structure in case of half turn of the boat. The limits are set to 0 and 8000, in degrees would be 0° and 703.297° for the driver wheel.



Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
3	177.6°	177.245°	178.044°	0.355°	0.444°

Figure 47. *Results for test 3*

The last test for PAN servo shows similar results as the previous tests. However, the movement from the inferior limit to the target point is slightly more accurate, while the opposite one is in this case, slightly less precise.

7.2.4 Test 4. TILT servo

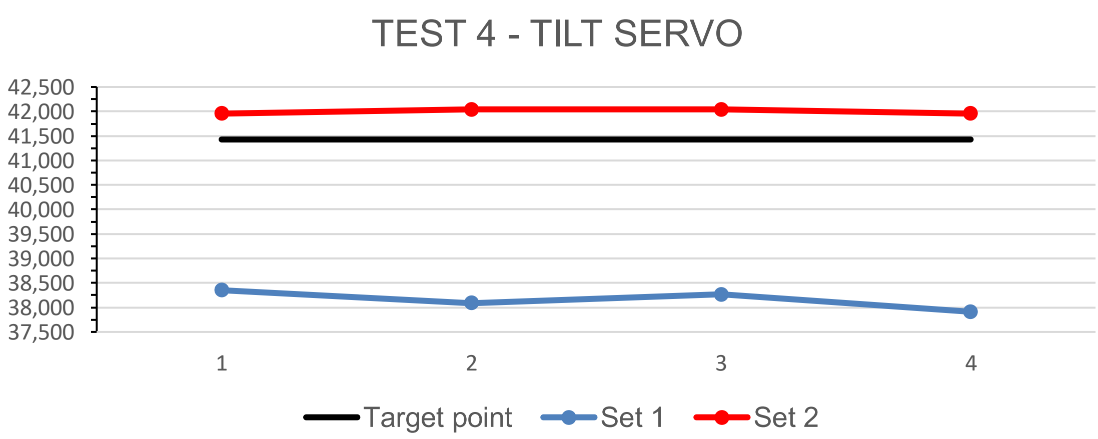
The procedure to carry out the tests on this servo is the same as the one used for the first set of tests. The only difference is that in this case, the superior and inferior limit are kept through all the testing processes.

The superior limit is 2048 and the inferior is 3072, which is 180.044° and 270.066° degrees. These values seem contradictory, as the superior limit is smaller than the inferior limit. However, this is due to the fact the servomotor default direction of rotation is counter clockwise, added to the mounting disposition of the structure, it makes that the default movement is from top to bottom.

To facilitate the comprehension of the results, a new reference system is introduced. It is located at the superior base of the structure, the one holding directly the antenna, with the rotation direction from bottom to top.

The values with this reference system are -0.066° for the inferior limit and 89.956°. These limits cover a range of 90.022° for the pitch angle of the antenna.

The target point for the first test of the TILT servomotor is 2600, which in the reference system established in the previous lines correspond to 41.429°.



Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
4	41.429°	38.154°	42.00°	3.275°	0.571°

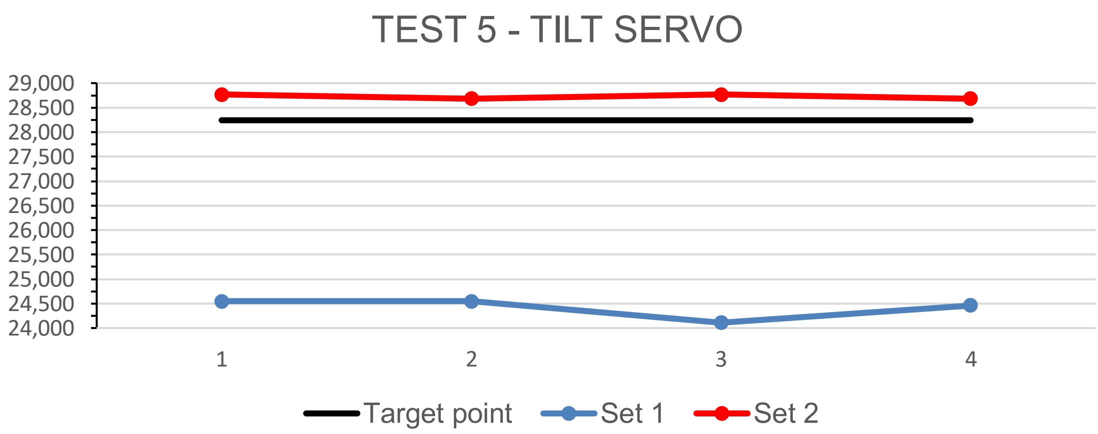
Figure 48. *Results for test 4.*

From the results it can be appreciated the large deviation when the antenna is moved from the bottom to the target position, while the second set it remains in the levels of the previous tests.

7.2.5 Test 5. TILT servo

The target point is set to 2750, which corresponds to 28.242°.

The results are shown below:



Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
5	28.242°	24.418°	28.725°	3.824°	0.484°

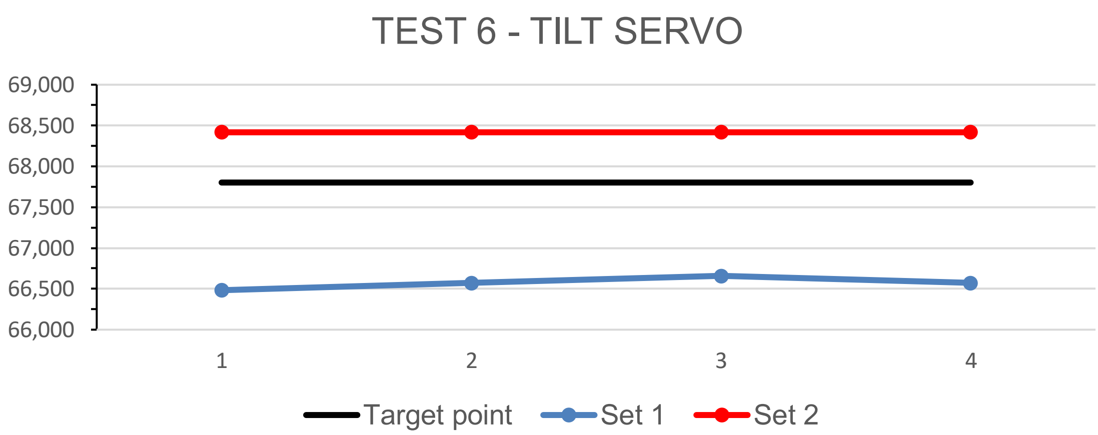
Figure 49. *Results for test 5*

In this case, the deviation when tilting the antenna from bottom to target has increased, while when moving it from to top to target the error has decreased, obtaining values similar to PAN servomotor levels.

7.2.6 Test 6. TILT servo

Last test is performed setting the target position to a higher height. The servo is set to reach 2300. It corresponds to 67.802°.

The results are showcased below.



Test	Target	Mean set 1	Mean set 2	Error Set 1	Error Set 2
6	67.802°	66.571°	68.418°	1.231°	0.615°

Figure 50. *Results for test 6*

The results for this test show and improvement in the accuracy for the inferior set compared to the previous test, while there is also a slight loss of precision when moving the antenna from the top.

8. DISCUSSION

The results obtained in the tests to assess the rotation along the yaw have been completely satisfactory, since it has been tried different movements with different amplitude and different direction of rotation, providing similar results.

The results according to the direction of the rotation follow a homogeneous pattern. In cases 1 and 2, the angular differences obtained are 0.011 ° in both cases when changing the direction of rotation. In the case of test 3, this variation is greater, being 0.089°, obtaining greater precision when rotating the antenna from the initial resting position rather than the values obtained when moving the antenna from an entire turn.

As for the amount of rotation in each test, the influence of this variable is very low, since the absolute errors of each test are very similar in all cases, being around 0.4 ° for all the tests performed.

However, the tests performed on the rotation around the pitch angle show different results. A greater disparity of results has been observed depending on the direction of rotation, and on the height of the reference.

In general, the precision obtained when turning from a lower position to a higher position is significantly lower than when the movement is made in the opposite direction. This effect can be observed in the results of tests 4, 5 and 6. When moving from bottom to top the values obtained are 3.275°, 3.824° and 1.231° respectively, while in the opposite direction the results are 0.571°, 0.484° and 0.615°.

Based on the results previously introduced, it has been observed a correlation effect between the reference point and the accuracy of the system. When rotating the antenna to a higher point, such as the case of the test 6, the dependence of the direction of rotation decreases, being of 0.616°, while using a lower point, for example test 5, the difference between of both directions is 3.34°. Using a middle point, like in test 4, the deviation observed is 2.704°, which falls between the results obtained in the other two cases studied.

A possible explanation to this phenomenon observed is that there must be a decompensation of forces in the axis of rotation, since the force resulting from the weight of the antenna is not aligned with the axis of rotation, causing an extra torque greater than the torque the servomotor can provide at working speed, causing a greater instability when rotating the pitch from the bottom rather than from the top.

9. CONCLUSSIONS

The main purpose of this thesis is to design the structure of a directional antenna and its subsequent analysis. This project is part of a larger project, consisting of several independent systems interconnected with each other. The product handled in this document is a fundamental component to ensure the proper functioning of these systems.

The designed product must accomplish certain performance, accuracy and reliability requirements to ensure its proper functioning and durability.

For this, the design has started from an earlier build, modifying it and improving it to meet the objectives. For this reason, the Solidworks 2017 suite has been used, a CAD tool for engineering that facilitates the design tasks.

Solidworks presents numerous useful features for the development of the product. It allows to visualize in 3D the different solids that make up the structure as well as allowing to modify each solid separately, which provides the ability to work around a modular design. Thanks to this utility, it has been achieved a product that meets the requirements of performance and precision with the introduction of new components, such as the transmission system of the antenna pitch rotation or the new servomotors of higher quality and more precise control. Finally, the incorporation of new structural components such as additional supports, coupled with a better choice of materials and components, provide greater durability.

Along with the realization of the structure of the antenna, a control method has also been designed to govern the movement of the antenna and adapt to the needs so that it performs its function satisfactorily. The control has been made through the Arduino platform based on C++ language. Using this tool, a code has been prepared that allows to control the movement of the servomotors, and therefore, the movement of the antenna.

The main function that the directional antenna must fulfil in terms of kinematic terms is to allow rotation on two axes to follow a set reference. Therefore, a series of tests have been carried out to assess the system's capacity to maintain said reference.

The antenna allows two independent rotations, one on the yaw and another on the pitch.

The precision of the pitch rotation is overall lower than the yaw rotation. When testing the yaw rotation, the maximum deviation observed from the reference point has been 0.444°, while the pitch rotation shows a much greater deviation, being of 3,824° in the worst-case scenario.

Future research topics in this matter could focus on solving the problem described above, as well as the integration of the control code of the servomotors with the USV information system protocols, in order to control the antenna automatically, incorporating then the system into the aCOLOR project.

10. BIBLIOGRAPHY

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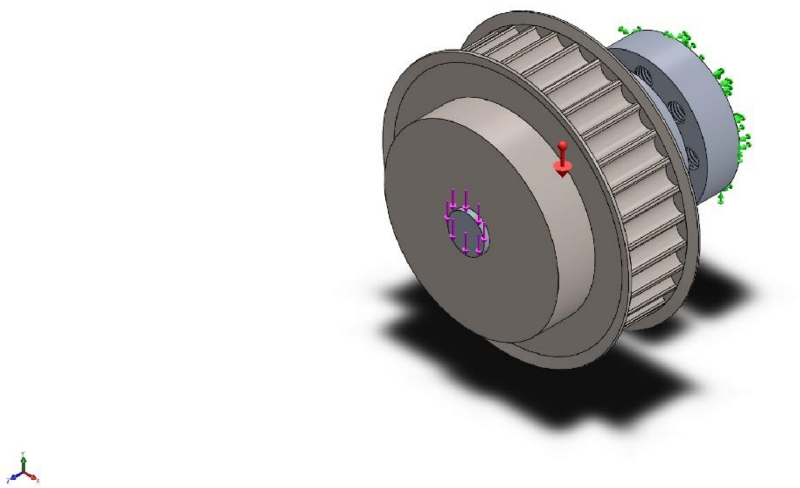
APPENDIX A. STATIC SIMULATIONS

Timing belt driven set

Table 7. *Timing belt driven set elements studied.*



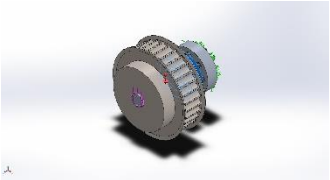
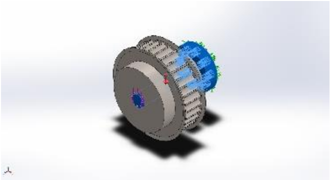
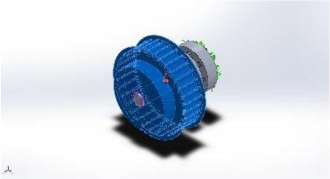
Name	Volumetric Properties
Bearing 	Mass:0.00916088 kg Volume:3.39292e-006 m^3 Density:2700 kg/m^3 Weight:0.0897767 N
Shaft 	Mass:0.0163001 kg Volume:6.15099e-006 m^3 Density:2650 kg/m^3 Weight:0.159741 N
Pulley 	Mass:0.2608 kg Volume:3.38702e-005 m^3 Density:7700 kg/m^3 Weight:2.55584 N

Table 8. *Load conditions driven set simulation.*

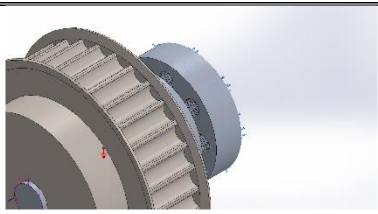
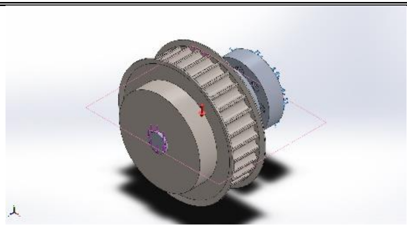
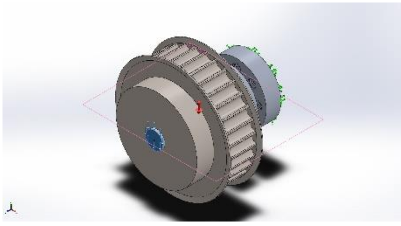
Fixture type	Fixture image	Fixture details
Fixed geometry		Restriction applied over the face in contact with the antenna
Load type	**Load Image**	**Load details**
Gravity		Reference: Top Plane Values: 0 0 -9.81 Units: m/s^2
Force		Vertical force to consider possible perturbations Values: --, --, -98.1 N

Table 9. *Mesh settings driven set simulation.*

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	2.5 mm
Tolerance	0.125 mm
Mesh Quality Plot	High
Total Nodes	75828
Total Elements	46463
Maximum Aspect Ratio	74.018
% elements with Aspect Ratio < 3	68.6
% elements with Aspect Ratio > 10	2.71
% distorted elements(Jacobian)	0

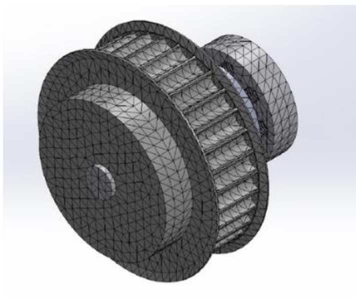


Table 10. *Results driven set simulation.*

Name	Min	Max
Von Mises stress	0.001308 MPa	44.75 MPa
Displacement	0 mm	0.07764 mm
Strain	3.955e-009	4.495e-004
Factor of Safety	7.018	4.742e+005

The tables 7,8,9 and 10 show the details of the static study for the driven components of the timing belt. The purpose of this simulation is to evaluate the possible real behaviour of the designed components in a real-world scenario.

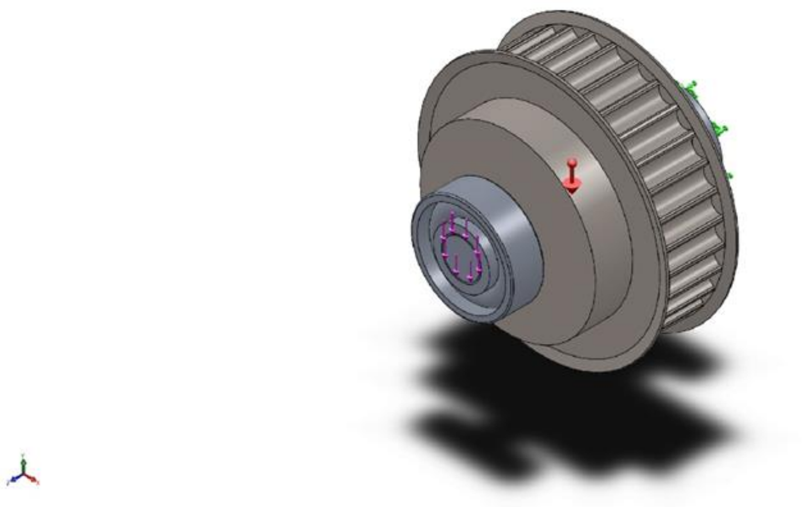
The face of the shaft directly attached to the antenna is considered as fixed geometry, as the displacements are impeded.

The loads are the weight of the components represented by the name Gravity in table 8, and a vertical force of 10 kilos approximately, to consider the loads derived from the movement of the USV and hypothetical water surges.

The results are showcased in table 10. The maximum values of stress and strain are located in the union between the shaft and the pulley. However, these values are within safe margins as the factor of safety never goes below 7.

Timing belt driver set

Table 11. *Timing belt driver set elements studied.*



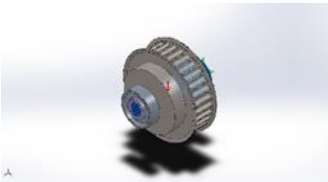
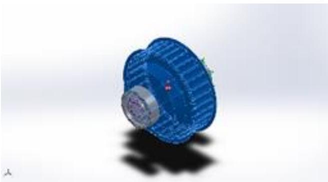
Name	Volumetric Properties
Bearing 	Mass:0.00469796 kg Volume:1.73998e-006 m^3 Density:2700 kg/m^3 Weight:0.04604 N
Shaft 	Mass:0.0113233 kg Volume:4.27296e-006 m^3 Density:2650 kg/m^3 Weight:0.110969 N
Pulley 	Mass:0.2608 kg Volume:3.38702e-005 m^3 Density:7700 kg/m^3 Weight:2.55584 N

Table 12. Load conditions driver set simulation.

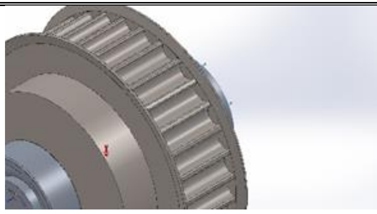
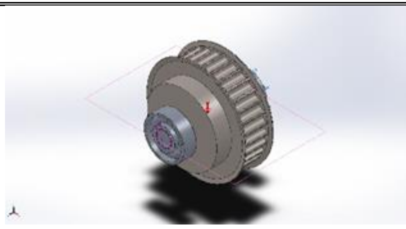
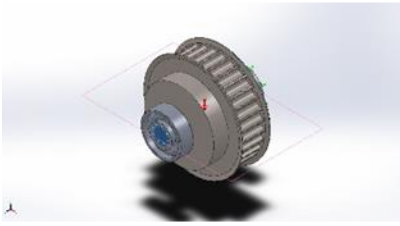
Fixture type	Fixture image	Fixture details
Fixed geometry		Restriction applied over the face in contact with the servomotor
Load type	**Load Image**	**Load details**
Gravity		Reference: Top Plane Values: 0 0 -9.81 Units: m/s^2
Force		Vertical force to consider possible perturbations Values: --, --, -98.1 N

Table 13. Mesh setting driver set simulation.

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	2.5 mm
Tolerance	0.125 mm
Mesh Quality Plot	High
Total Nodes	44175
Total Elements	27552
Maximum Aspect Ratio	36.751
% elements with Aspect Ratio < 3	75.9
% elements with Aspect Ratio > 10	1.81
% distorted elements(Jacobian)	0

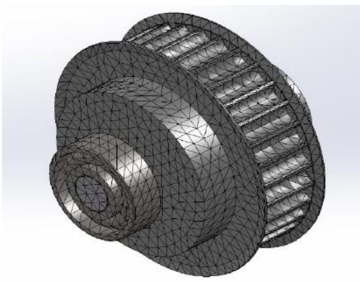


Table 14. *Results driver set simulation.*

Name	Min	Max
Von Mises stress	6.824e-004 MPa	46.81 MPa
Displacement	0 mm	0.04612 mm
Strain	1.431e-008	4.829e-004
Factor of Safety	3.211	9.092e+005

The tables 11,12,13 and 14 show the details of the static study for the driver components of the timing belt.

The face of the shaft directly attached to the servomotor is considered as fixed geometry, as the displacements are impeded.

The loads are the weight of the components represented by the name Gravity in table 12, and a vertical force of 10 kilos approximately, analogous procedure to the previous case to consider the loads derived from the movement of the USV and possible water surges.

The results are showcased in table 14. The maximum values of stress and strain are situated in the unions between the shaft and the pulley. In this case, the factor of safety is 3.211. This value is within safe values. However, simulations are based in theorical and ideal components, so the real behaviour may differ from the values obtained. To add more rigidity and safety, it is then introduced another support on the other end of the shaft, obtaining the following results.

Table 15. *Results after simulating adding an extra support.*

Name	Min	Max
Von Mises stress	1.022e-005 MPa	0.197 MPa
Displacement	0 mm	1.544e-005 mm
Strain	7.816e-011	1.363e-006
Factor of Safety	640.8	6.069e+007

The stress tensions deformations are now greatly mitigated.

APPENDIX B. REGISTRY ENTRIES

```
/** EEPROM AREA **/
#define AX_MODEL_NUMBER_L           0
#define AX_MODEL_NUMBER_H           1
#define AX_VERSION                  2
#define AX_ID                       3
#define AX_BAUD_RATE                4
#define AX_RETURN_DELAY_TIME        5
#define AX_CW_ANGLE_LIMIT_L         6
#define AX_CW_ANGLE_LIMIT_H         7
#define AX_CCW_ANGLE_LIMIT_L        8
#define AX_CCW_ANGLE_LIMIT_H        9
#define AX_SYSTEM_DATA2             10
#define AX_LIMIT_TEMPERATURE        11
#define AX_DOWN_LIMIT_VOLTAGE       12
#define AX_UP_LIMIT_VOLTAGE         13
#define AX_MAX_TORQUE_L             14
#define AX_MAX_TORQUE_H             15
#define AX_RETURN_LEVEL             16
#define AX_ALARM_LED                17
#define AX_ALARM_SHUTDOWN           18
#define AX_OPERATING_MODE           19
#define AX_DOWN_CALIBRATION_L       20
#define AX_DOWN_CALIBRATION_H       21
#define AX_UP_CALIBRATION_L         22
#define AX_UP_CALIBRATION_H         23
/** RAM AREA **/
#define AX_TORQUE_ENABLE            24
#define AX_LED                      25
#define AX_CW_COMPLIANCE_MARGIN     26
#define AX_CCW_COMPLIANCE_MARGIN    27
#define AX_CW_COMPLIANCE_SLOPE      28
#define AX_CCW_COMPLIANCE_SLOPE     29
#define AX_GOAL_POSITION_L          30
#define AX_GOAL_POSITION_H          31
#define AX_GOAL_SPEED_L             32
#define AX_GOAL_SPEED_H             33
#define AX_TORQUE_LIMIT_L           34
#define AX_TORQUE_LIMIT_H           35
#define AX_PRESENT_POSITION_L       36
#define AX_PRESENT_POSITION_H       37
#define AX_PRESENT_SPEED_L          38
#define AX_PRESENT_SPEED_H          39
#define AX_PRESENT_LOAD_L           40
#define AX_PRESENT_LOAD_H           41
#define AX_PRESENT_VOLTAGE          42
#define AX_PRESENT_TEMPERATURE      43
#define AX_REGISTERED_INSTRUCTION   44
#define AX_PAUSE_TIME               45
#define AX_MOVING                   46
```

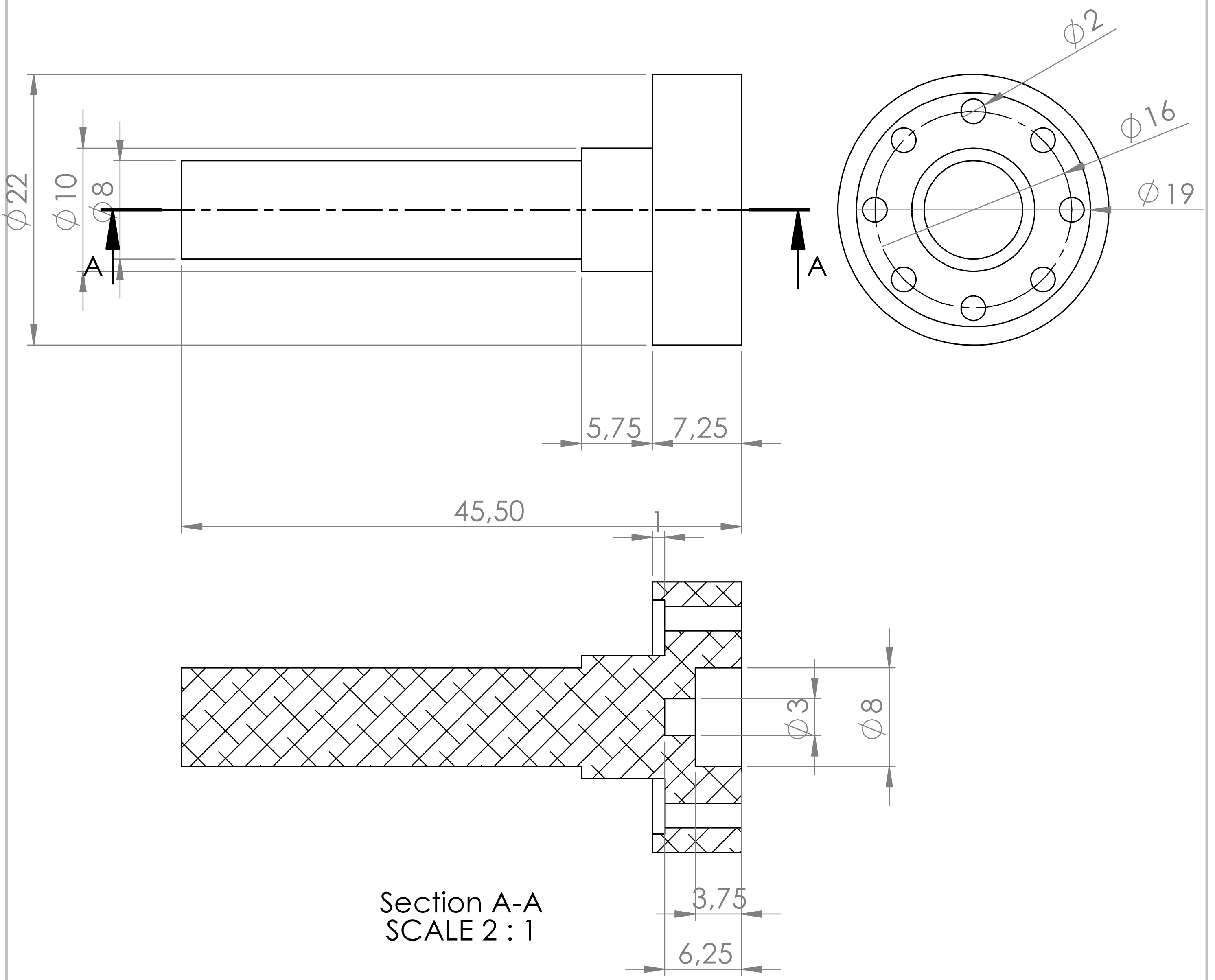
```
#define AX_LOCK                         47
#define AX_PUNCH_L                      48
#define AX_PUNCH_H                      49
```

Program 8. *Dynamixel servomotors register set*

Program 4 shows the registry for Dynamixel servomotors data sets. Those values belonging to the EEPROM area are permanently stored, while the values belonging to entries in the RAM area are reseted every time the power gets disconnected.

APPENDIX C. DRAWINGS

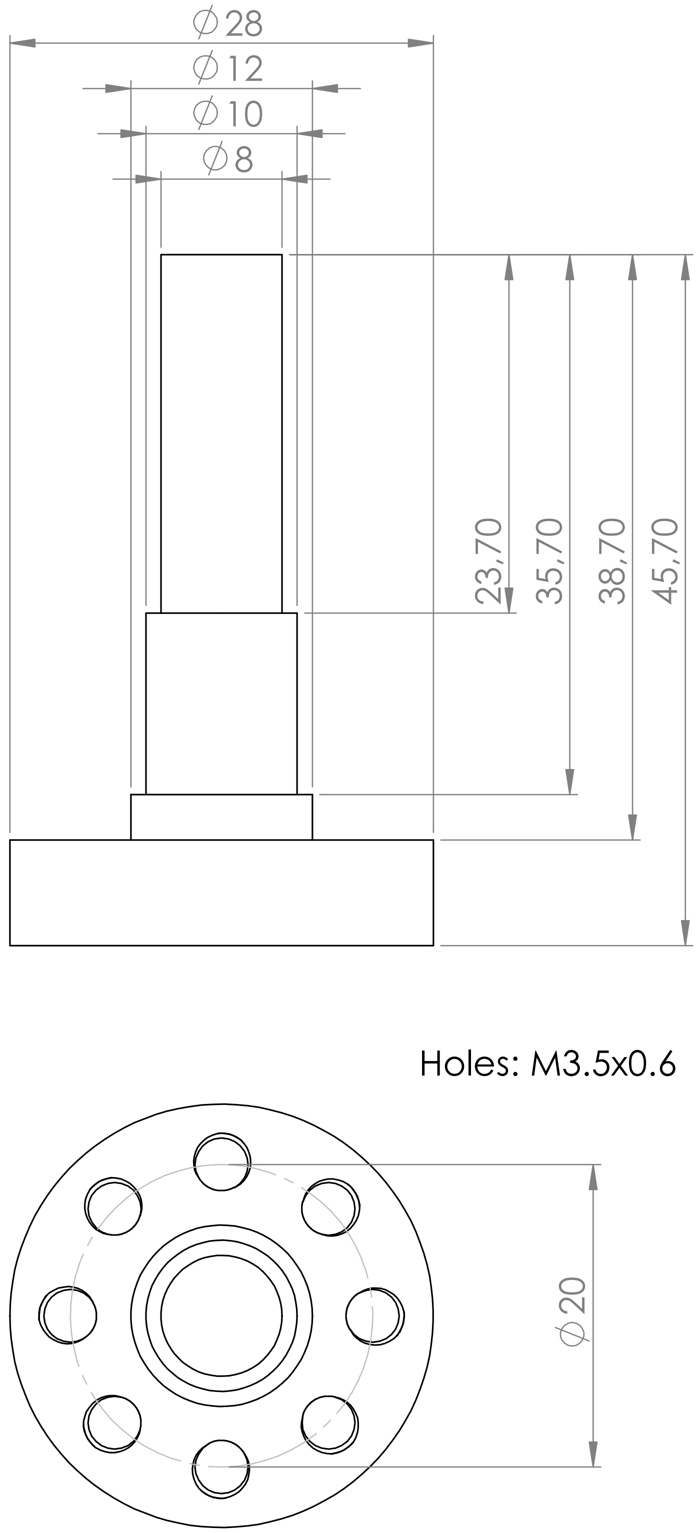
REV.	DESCRIPTION	DATE	APPROVED



Section A-A
SCALE 2 : 1

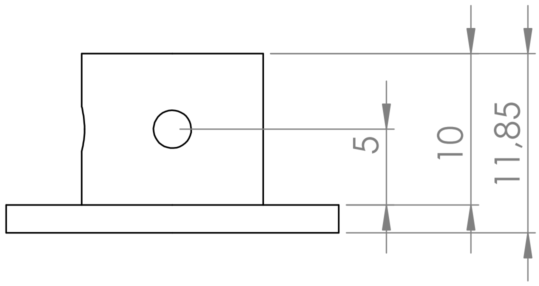
TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A4
	FINISH:		TITLE: Shaft - Pitch servomotor	
SCALE:2:1	MAKE OR BUY: Make			
DRAWN BY	DATE	MATERIAL: Aluminium Alloy	DWG NO. ACO-P-01013-B	REVISION
CMA	02/04/2019			
DO NOT SCALE DRAWING		WEIGHT: 11.54	REPLACES: / REPLACED BY:	SHEET 1 OF 1

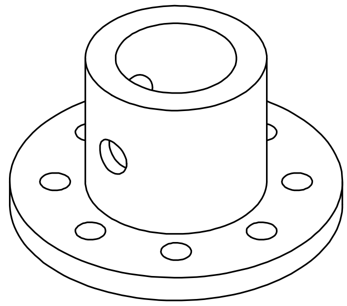
REV.	DESCRIPTION	DATE	APPROVED

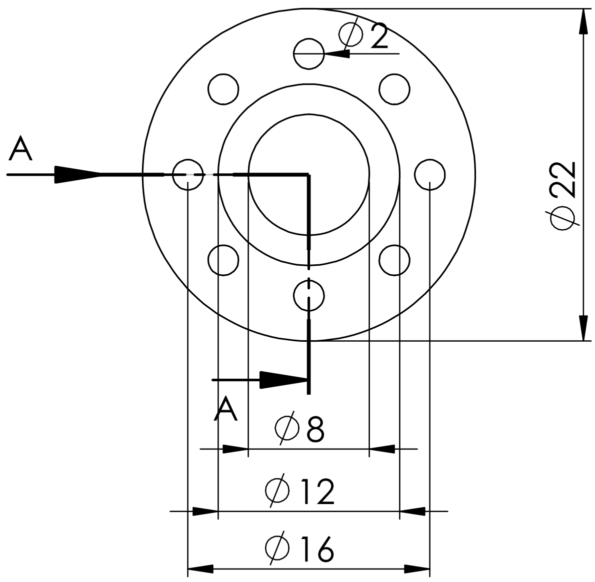


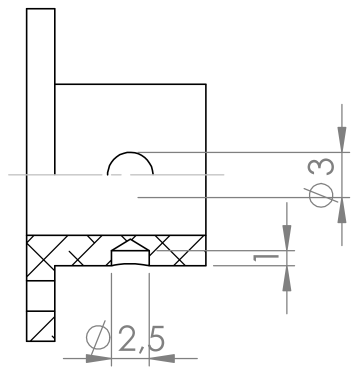
TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A4
	FINISH:		TITLE: Shaft 2 - Pitch servomotor	
SCALE:2:1	MAKE OR BUY: Make			
DRAWN BY: CMA	DATE: 04/02/2019	MATERIAL: Aluminium Alloy	DWG NO. ACO-P-01003-B	REVISION
DO NOT SCALE DRAWING		WEIGHT: 16.61	REPLACES: / REPLACED BY:	SHEET 1 OF 1

REV.	DESCRIPTION	DATE	APPROVED





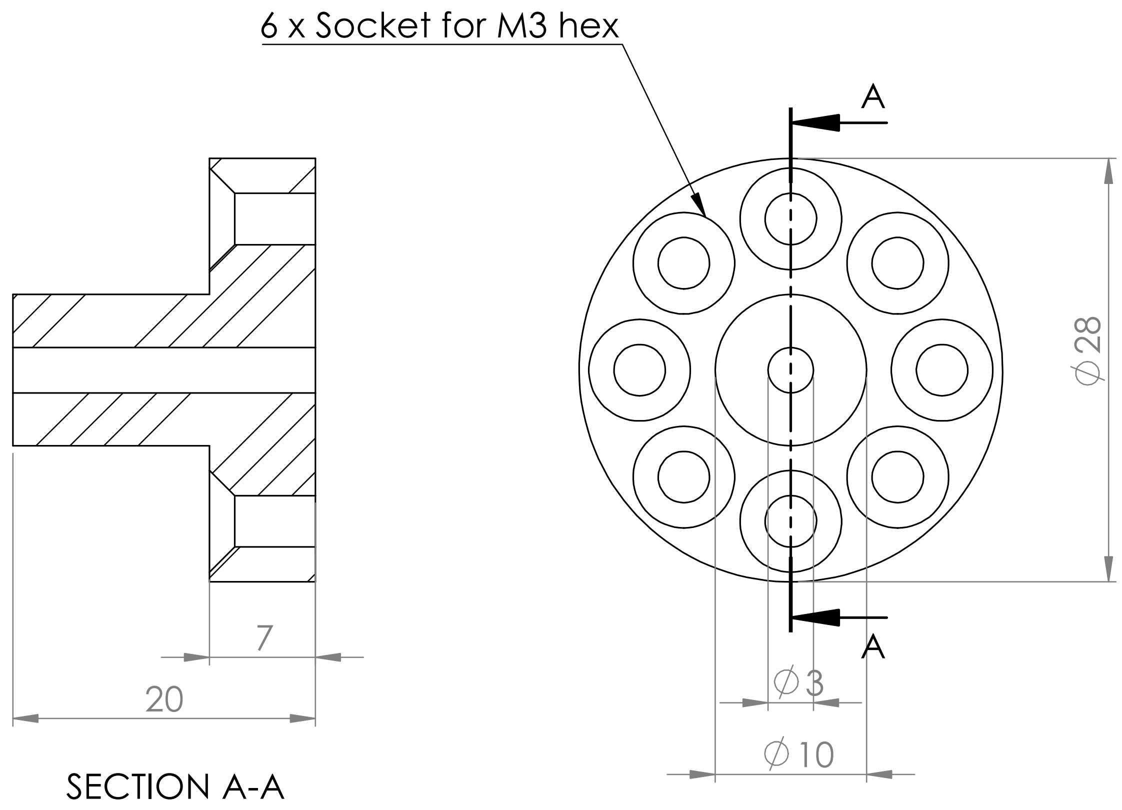




SECTION A-A

TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A4
	FINISH:		TITLE: Shaft - Yaw servomotor	
SCALE:2:1	MAKE OR BUY: Make			
DRAWN BY: CMA	DATE: 02/04/2019	MATERIAL: Aluminium Alloy	DWG NO. ACO-P-01006-B	REVISION
DO NOT SCALE DRAWING		WEIGHT: 3.16	REPLACES: / REPLACED BY:	SHEET 1 OF 1

REV.	DESCRIPTION	DATE	APPROVED



TOLERANCES UNLESS OTHERWISE SPECIFIED

MACHINING: ISO 2768-m
FLAME CUTTING: ISO 9013-IA
WELDING: EN ISO 13920-BF
WELD CLASS: EN 25817-C
SHEETMETAL: DIN 6930-m

DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED

DEBUR AND BREAK SHARP EDGES

SURFACE FINISH:

aColor

A4

FINISH:

TITLE: Dragged shaft

SCALE:2:1

MAKE OR BUY: Make

DRAWN BY	DATE
CMA	08/04/2019

MATERIAL: PLA

DWG NO. ACO-P-01010-B

REVISION

DO NOT SCALE DRAWING

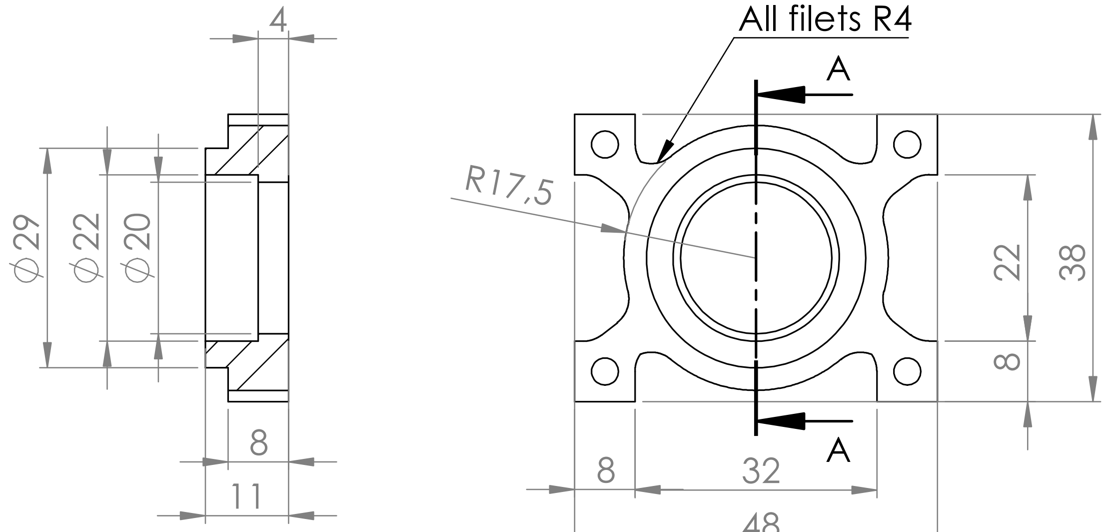
WEIGHT: 4.62

REPLACES:

REPLACED BY:

SHEET 1 OF 1

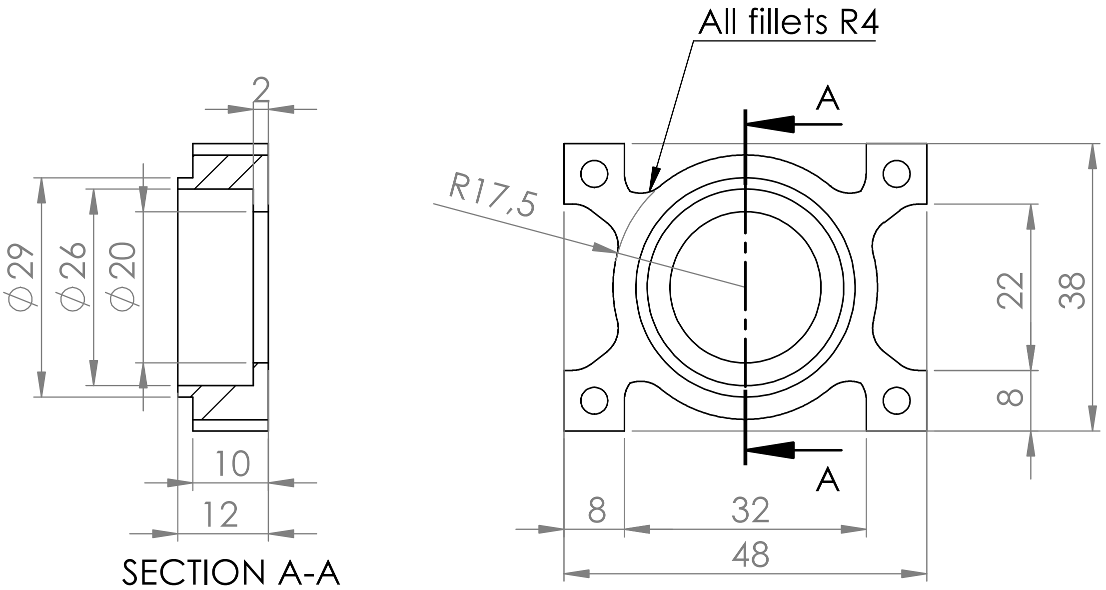
REV.	DESCRIPTION	DATE	APPROVED



SECTION A-A

TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A4
	FINISH:		TITLE: Bearing housing	
SCALE:1:1	MAKE OR BUY: Make			
DRAWN BY	DATE	MATERIAL: PLA	DWG NO. ACO-P-01019-B	REVISION
CMA	05/04/2019			
DO NOT SCALE DRAWING		WEIGHT: 8.39	REPLACES:	REPLACED BY:	SHEET 1 OF 1

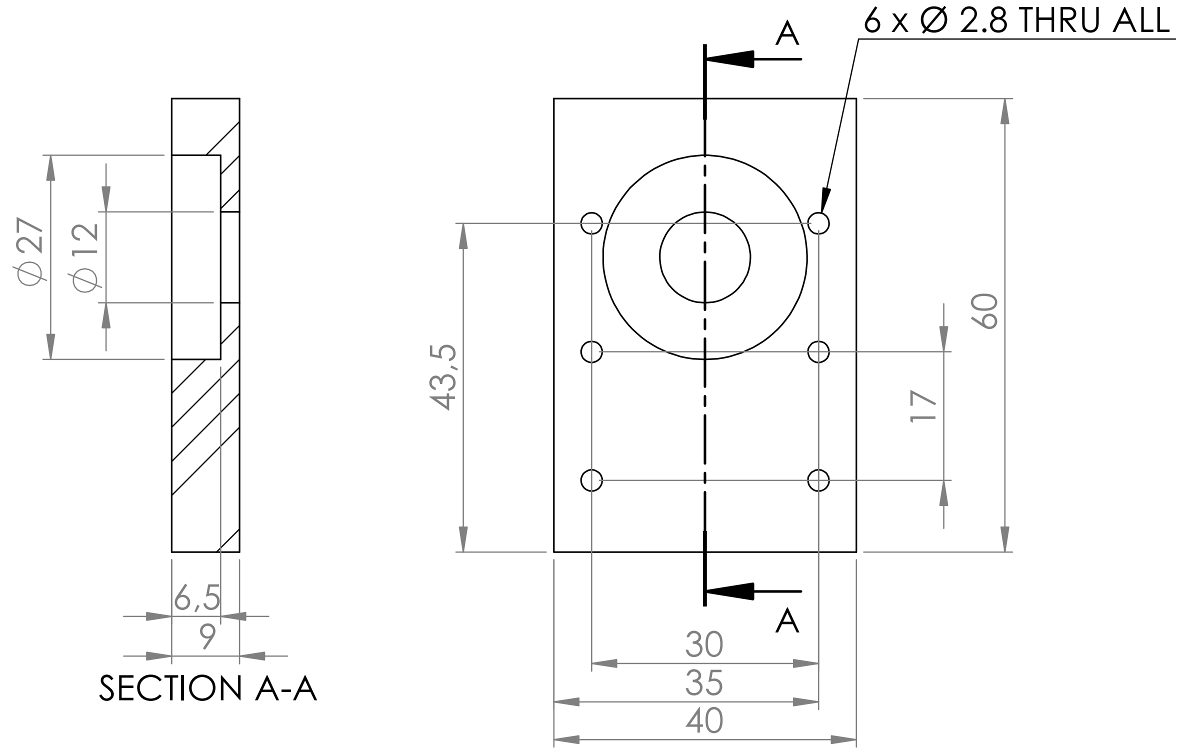
REV.	DESCRIPTION	DATE	APPROVED



SECTION A-A

TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor — A4
	FINISH:		TITLE: Bearing housing 2
SCALE:1:1	MAKE OR BUY: Make		
DRAWN BY: CMA	DATE: 05/04/2019	MATERIAL: PLA	DWG NO. ACO-P-01002 — REVISION
DO NOT SCALE DRAWING		WEIGHT: 8.25	REPLACES: — REPLACED BY: — SHEET 1 OF 1

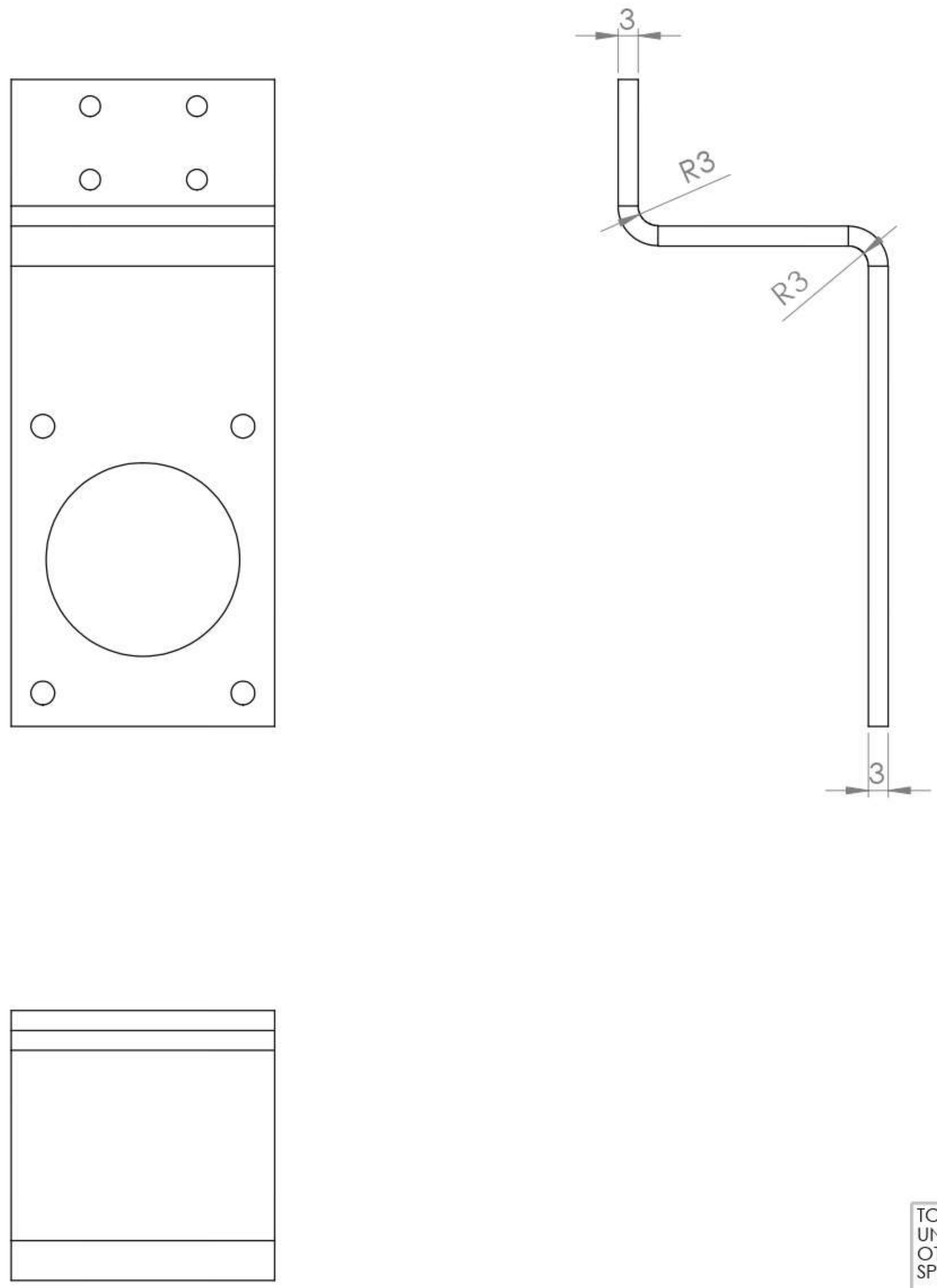
REV.	DESCRIPTION	DATE	APPROVED

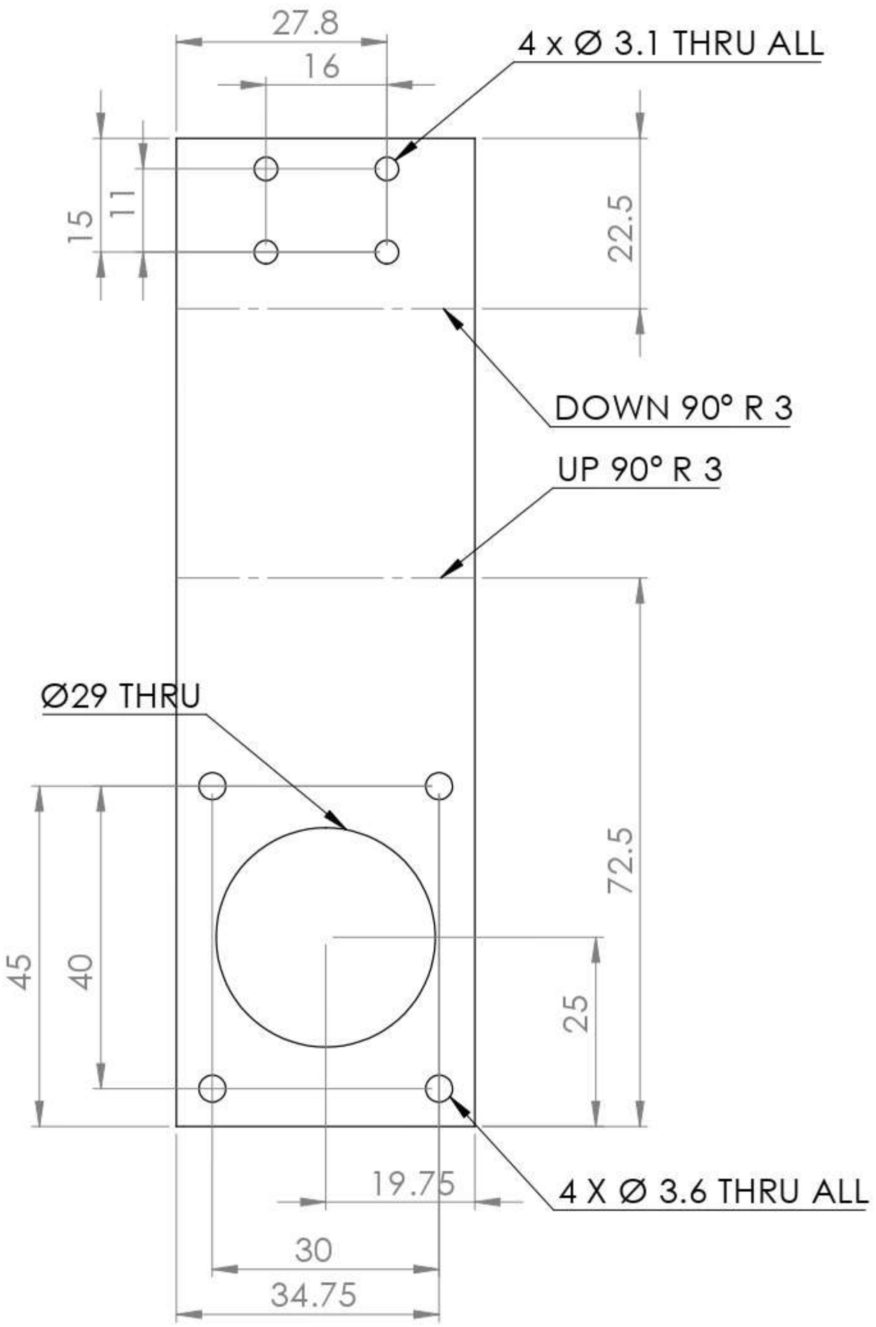


SECTION A-A

TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: FLAME CUTTING: WELDING: WELD CLASS: SHEETMETAL:	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A4
	FINISH:		TITLE: SUPPORT HOLDER	
SCALE:1:1	MAKE OR BUY: Make			
DRAWN BY CMA	DATE 04/08/2019	MATERIAL: PLA	DWG NO. ACO-P-01014-B	REVISION
DO NOT SCALE DRAWING	WEIGHT: 17.61	REPLACES:	REPLACED BY:	SHEET 1 OF 1

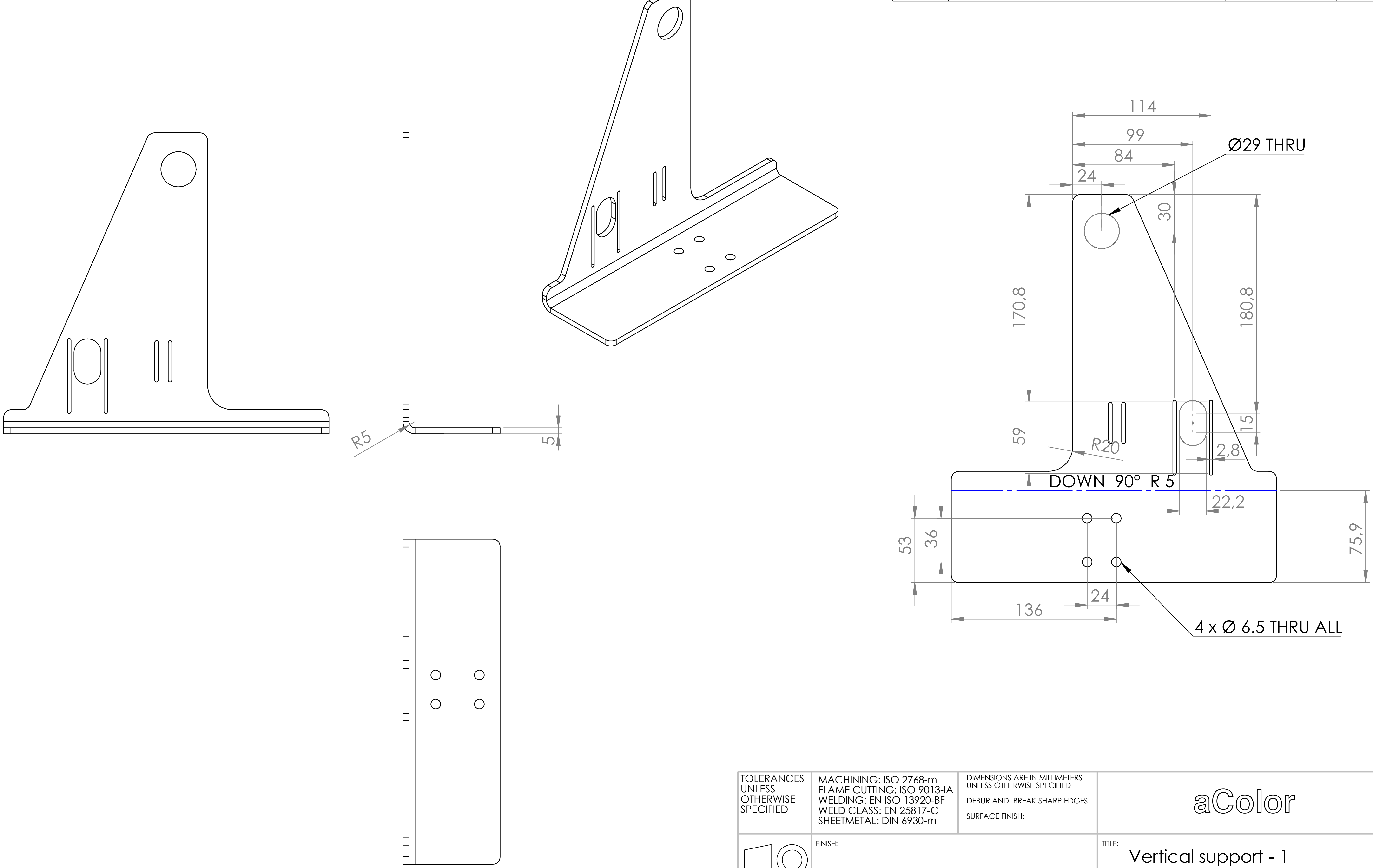
REV.	DESCRIPTION	DATE	APPROVED





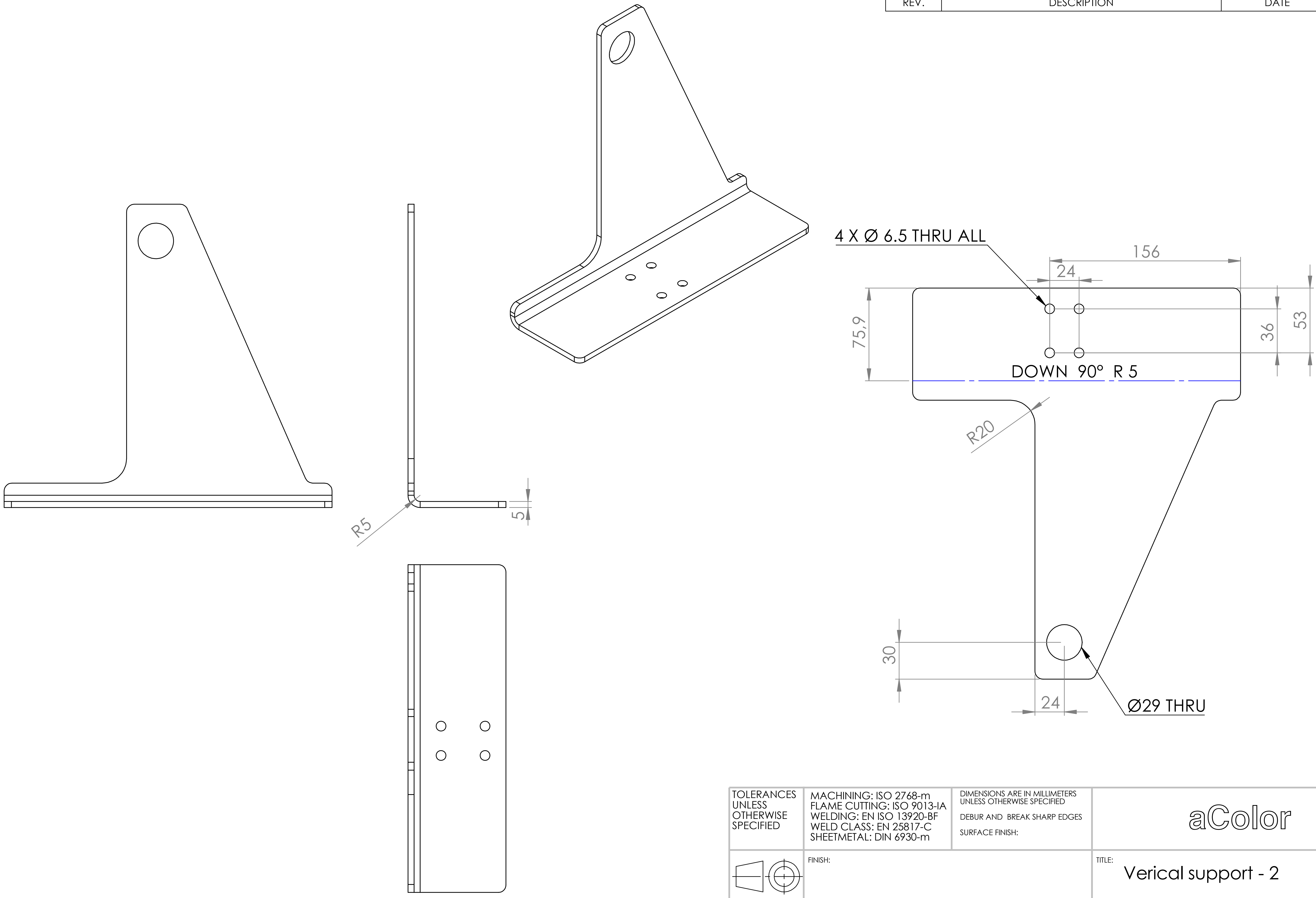
TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A3
	FINISH:		TITLE: Support for shaft	
SCALE:1:1	MAKE OR BUY: Buy			
DRAWN BY CMA	DATE 2019-04-08	MATERIAL: Material <not specified>	DWG NO. ACO-P-01017-B	REVISION
DO NOT SCALE DRAWING		WEIGHT: 13.29	REPLACES: / REPLACED BY:	SHEET 1 OF 1

REV.	DESCRIPTION	DATE	APPROVED



TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A3
	FINISH:		TITLE: Vertical support - 1	
SCALE:1:3	MAKE OR BUY: Buy			
DRAWN BY CMA	DATE 04/02/2019	MATERIAL: Material <not specified>	DWG NO. ACO-P-01008-B	REVISION
DO NOT SCALE DRAWING		WEIGHT: 224.27	REPLACES: / REPLACED BY:	SHEET 1 OF 1

REV.	DESCRIPTION	DATE	APPROVED



TOLERANCES UNLESS OTHERWISE SPECIFIED	MACHINING: ISO 2768-m FLAME CUTTING: ISO 9013-IA WELDING: EN ISO 13920-BF WELD CLASS: EN 25817-C SHEETMETAL: DIN 6930-m	DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED DEBUR AND BREAK SHARP EDGES SURFACE FINISH:	aColor	A3
	FINISH:		TITLE: Verical support - 2	
SCALE:1:3	MAKE OR BUY: Buy			
DRAWN BY CMA	DATE 04/08/2019	MATERIAL: Material <not specified>	DWG NO. ACO-P-01009-B	REVISION
DO NOT SCALE DRAWING		WEIGHT: 224.27	REPLACES: / REPLACED BY:	SHEET 1 OF 1