TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

PABLO ROMERO BERNAL

MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

Master of Science Thesis

Examiner: prof. Kari T. Koskinen
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ABSTRACT

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This thesis´s aim is the design of an attitude control subsystem of an autonomous explorer submarine. This submarine has three attitude subsystems; thruster system for propulsion, ballast system for heave motion and the object of this thesis, the pendulum system for the pitch angle.

The pitch angle control is managed by varying the position of the center of gravity of the submarine relatively from the buoyancy point. To do that, the system moves the batteries of the submarine.

At the beginning of this thesis there were already some researches done about the batteries configuration and the motion system. A planetary gearbox outside the motion area of the pendulum and a stepper motor were considered to rotate the batteries and the oil container as a whole.

After considering different layouts and their interactions with the other devices inside the submarine, the planetary gearbox and the movement of the oil container have been discarded. A stepper motor, located besides the batteries and rotating with them, moves the mechanism through a gearbox based on a worm-spur gear scheme. This gearbox provides a reduction of 180:1 and self-locking behavior, which means that no energy is needed to keeping a reached pendulum position. Due to the efficiently space use, it has been possible to increase the size of the batteries to add weight to the pendulum and increase the capacity, instead of $16.000\ mAh$ now the capacity of each battery is $20.000\ mAh$.

The pendulum system is able to rotate 90° in 6.35 seconds and done simulations show that for a 20° target rotation the submarine will reach a stable equilibrium position in less than 30 seconds.

PREFACE

This Master´s thesis has been done in the department of Mechanical Engineering and Industrial Systems of Tampere University of Technology. It is part of the mechanical design for the EU-funded project Underwater Explorer for Flooded Mines (UNEXMIN).

I would like to thank first my supervisor Jussi Aaltonen and Juoko Laitinen for giving me the opportunity of joining this research group and all the advices given within this year. Moreover, I want to thank all the research staff that have made this year as an exchange student such a great and useful experience.

Tampere, 16.05.2017

Pablo Romero Bernal

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

CC license	Creative Commons license
SI system	Système international d'unités, International System of Units
TUT	Tampere University of Technology
URL	Uniform Resource Locator
A	ampere $[A]$
C	drag coefficient $[Kg/m\ s]$
D	distance between axes $[mm]$
f_1	starting pulse speed $[Hz]$
f_2	operating pulse speed $[Hz]$
FDM	Fused Deposition Modeling
g	gravity $[m^2/s]$
i	gearbox reduction
J	moment of inertia $[Kgmm^2]$
J_L	mechanism inertia $[Kgmm^2]$
J_O	rotor of motor inertia $[Kgmm^2]$
l	target rotation [°]
l_{rev}	rotation per motor revolution [°]
m	mass of the pendulum $[Kg]$
mAh	milliamps $[mAh]$
m_S	mass of the submarine $[Kg]$
n_G	gearbox efficiency
r	distance between rotational axis and the center of gravity of the pendulum $[mm]$
r_B	distance between rotational axis and the center of gravity of the batteries $[mm]$
rpm	revolutions per minute $[rad/s]$
r_S	distance between rotational axis and the center of gravity of the vehicle $[mm]$
SLS	Selective Laser Sintering
S_f	safety factor
t_0	positioning period $[s]$

t_1	acceleration/deceleration period $[s]$
T	torque produced by the pendulum system $[Nm]$
T_A	acceleration torque $[Nm]$
T_B	torque created by the batteries $[Nm]$
T_L	load torque $[Nm]$
T_M	required torque $[Nm]$
T_{Max}	maximum torque provided by the pendulum $[Nm]$
T_{min}	minimum time for a movement $[s]$
$T_{Spur\ gear}$	spur gear torque $[Nm]$
UAV	Underwater Autonomous Vehicle
δ	target position, pendulum angle $[rad]$
θ_s	stepper motor step angle [°]
φ	angle of the submarine $[rad]$
$\dot{\varphi}$	rotational velocity of the submarine $[rad/s]$
$\ddot{\varphi}$	rotational acceleration of the submarine $[rad/s^2]$

1. INTRODUCTION

Submarine vehicles are widely used nowadays, form large war or exploration water-crafts until small and unmanned robots. For exploration tasks mostly small vehicles are used, they are mainly differentiate by the way they are operated. ROVs (Remoted Operated Vehicles) are linked through a cable to a vessel where an operator conducts it, meanwhile an UAV (Underwater Autonomous Vehicle) undertakes its mission without operator intervention, when the task is done the robot come back to the pre-set location where the data is downloaded.

Such vehicles are equipped with different maneuverability systems depending on the number of freedom grades. Pumps are usually used for heave motion by taking in or pushing out water, a propulsion system like thrusters or water jets manage the surge motion and the pitch angle is based on the position of the center of gravity. The position of the center of gravity can be changed in different ways, a commonly approach is by water tanks located along the submarine, and another possibility is changing the weight distribution inside the vehicle. Large watercrafts use mainly water tanks meanwhile smaller and size limited vehicles tend to use weight distribution management systems.

This thesis relates with the design and analysis of an attitude control subsystem for an UAV. The fact that this kind of robots usually carry different measurement devices and cameras makes vital the capacity of controlling the heading of the submarine, so that such devices can be properly oriented in each situation and environment. Moreover, the non-known environment and the possible water flows make this ability vital for its maneuverability. This thesis aims the design and analysis of an attitude control subsystem that will be able to lead the pitch angle of such kind of vehicle.

The system will control the pitch of the submarine by varying the position of the center of gravity of the submarine respectively of the center of buoyancy. Due to the size and the complexity layout of the submarine, there several limitations regarding the weight, dimensions and shape of the system.

This thesis goes through the design process, requirements certification and simulation of the designed system. A simple prototype is also built to prove the operational features of the mechanism.

2. ATTITUDE CONTROL SUBSYSTEM

The object of this thesis is the design and analysis of an attitude control subsystem for an autonomous explorer submarine. Such subsystem controls the pitch angle of the submarine displacing its center of gravity respectively from its center of volume. When this position varies, it creates a restoring torque that moves the submarine towards to a new equilibrium position.

2.1 Pendulum principle

A pendulum is ideally a weight suspended through a rope so it can swing. When the weight is not at the lowest energy position, a restoring force is created that will accelerate it back to the equilibrium position. This occurs when the angle φ shown on Figure 1 differs from 0. In this application, such restoring force will move the submarine.

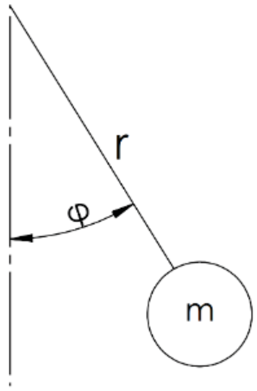


Figure 1. *Simple pendulum*

Both, buoyancy center and center of gravity of the submarine are located at the centroid of the sphere (position 0,0), as Figure 2 shows. So that, if the center of gravity of the pendulum is not at the vertical line that cross both centroid and buoyancy point, the system is not an equilibrium position ($\Sigma M_{(0,0)} \neq 0$). A restoring torque will rotate the system around the coordinates 0,0; such system behaves like a simple pendulum would.

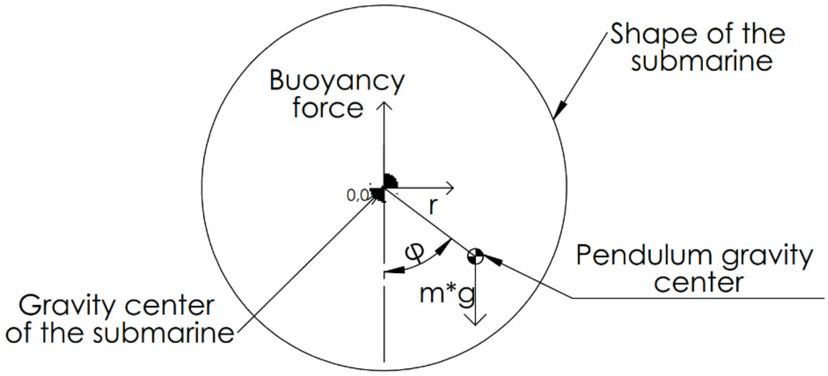


Figure 2. *Forces distribution*

An equilibrium position is a state in which the sum up of all forces is zero, so the system keep that position. This equilibrium can be stable or unstable depends on whether, after a perturbation, the system would come back towards the equilibrium position or not. When a system requires additional energy to change the current equilibrium position, it´s a stable equilibrium position. Equation (1) express the energy of the system shown on Figure 2 depending on the angle φ.

$$E = -m\ g\ r \cos\varphi \tag{1}$$

Figure 3 shows a graph of equation (1). As we can see, the system reach the minimum energy position at $= 0$, this means that the center of gravity of the pendulum is at its lowest position.

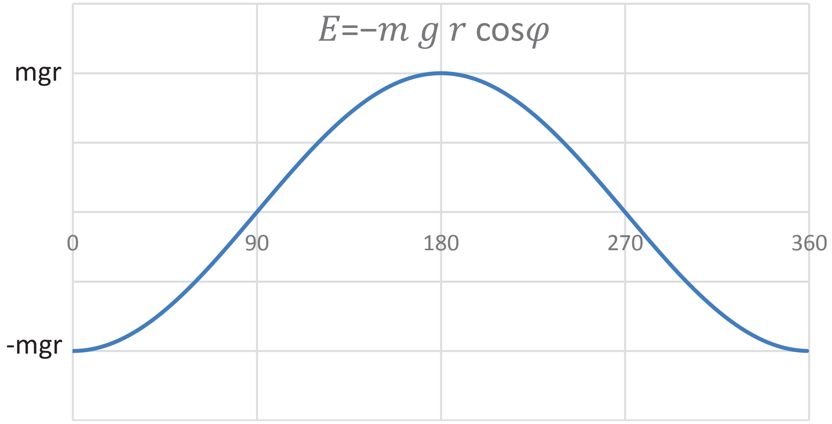


Figure 3. *Energy of the system*

2.2 Applications of pendulum control in robotics

Pendulums system have been widely investigated, from the control of its dynamic in different configuration such as single, double and triple to its applications for the balancing and motion in robots.

A main application of this technology is its use for robotics motion systems. In different configurations and designs the balance control of either simple pendulum or inverted pendulum can provide a way to achieve movement. Its application for motion system began at the end of XVII century with the invention of the monocycle. Figure 4 shows Richard's C. Hemming monocycle which was patented in 1869.

Figure 4. *Richard's C. Hemming monocycle*

Lately in 1935 Walter Nilsson upgrade the monocycle adding a heat engine and third grade of freedom aiming a completely maneuverable vehicle with a high autonomy. Figure 5 shows Walter's Nilsson monocycle.

Figure 5. *Walter's Nilsson monocycle*

This concept is nowadays still researched and future applications have been lately presented as a solution for traffic problems in crowded cities and as more efficient transport vehicle. Figure 6 shows a future vehicle presented by Bridgestone.

Figure 6. *Bridgestone's future vehicle*

Another application of pendulum control balance is to move the center of gravity in a spherical robot. This idea provides a robot that can operate on uneven surfaces and on the water propelled itself without any external force, moreover, due to its shape the robot is inherently stable. There are many potential applications for these robots like planetary exploration; spherical cheap and low-weight robots with a high maneuverability can enable long-distance mapping tasks in unknown environments [1].

Spherical robots moved by pendulum systems are also applied to reducing the cost and reliability of exploring in fields like mines mapping, security tasks or military operations. A new use for spherical robots is presented by ROSPHERE, a UPM (Universidad Politécnica de Madrid) project that provides an alternative method for crop measurement. ROSPHERE aims a low cost and less damaging way for monitoring tasks [2]. Figure 7 shows ROSPHERE´S prototype.

Figure 7. *ROSPHERE [2]*

Other applications of pendulum robotic control can be already seen as human transport vehicles. It aims a solution for transporting in crowded cities or even on irregular floors. A balance controls system moves a bi-wheeled cart to its stable equilibrium position, so that, the displacement of the user´s weight can led the motion of the vehicle. Figure 8 shows an example of robotic pendulum application for human transport.

Figure 8. *Example of pendulum control applications*

It has been also researched and development the application of an inverted pendulum control system on a robot supported by a ball. Using a ball instead of two wheels as a support allows the robots to traverse in any direction without changing its orientation [3]. Such application has a potential application as human or good transport in narrows and crowd spaces. Figure 9 shows two examples of robots that balance on a ball.

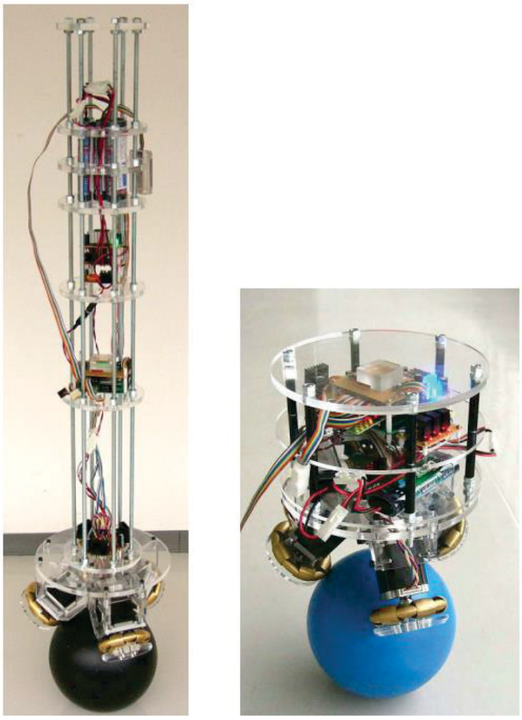


Figure 9. *Robots that balance on a ball [3]*

The available information about pendulum system uses in robotics is huge from the point of view of control, with many papers about software and hardware application and test. However, there is no so much information about mechanical design and its application as attitude control system for UAVs (Underwater Autonomous Vehicles).

2.3 Design requirements

The requirements of the pendulum system are from both behavior features and physic aspects. The requirements are from UAVs in general and from a concrete project undertook at the department of Mechanical Engineering and Industrial Systems of Tampere University of Technology. The design of the pendulum system is based on the layout of that UAV.

The behavior requirements are that the pendulum will be able to rotate 90° in less than 10 seconds and that, once it reach the target position, not additional energy will be needed.

The physic aspects are mainly due to space and weight. Since the submarine carries out exploration tasks, it equips different scientific devices that require space and add weight [4]. So that, miniaturization approach and efficient use of the space must be applied.

Due to the rotational movement of the batteries, there is space in its radius of action that cannot be used for other devices. Install the pendulum system in this space is a design requirement, so that, the rest of space can be kept free.

The weight of the submarine is a main feature. The pendulum system must be made up from as lighter parts as possible. This applies especially to the motor and gears size. In order to reduce the added weight of new parts, actual parts of the submarine can be used for the pendulum system, for instance the batteries like mass and the oil container as support.

3. PENDULUM SYSTEM CONFIGURATION

The pendulum system controls the attitude of a spherical scientific exploration submarine. Due to the space and weight submarine requirements the design aims to either use as less space as possible and add as less mass as possible. To achieve that, it uses current parts of the submarine, for instance the oil tank as support and three batteries as pendulum mass.

As Figure 10 shows, the batteries are located around the oil tank.

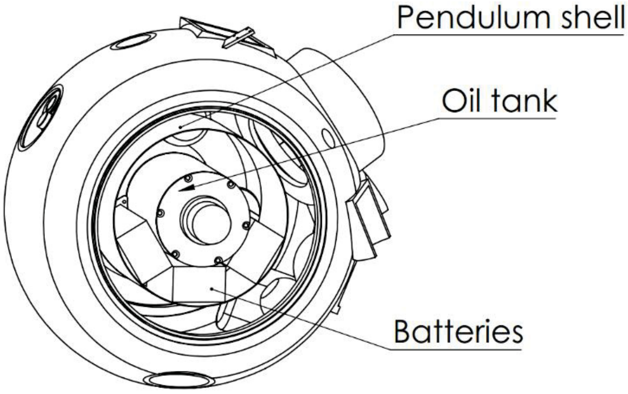


Figure 10. *Layout of the submarine*

3.1 Batteries as pendulum mass

As Figure 10 shows, the oil tank is at the middle of the submarine. This is the proper position because in this position, even though its mass varies during the ballast system operation, the center of gravity of the submarine remains at center of volume.

Three batteries of the submarine are located at around the oil tank. The pendulum uses this three batteries as pendulum mass, each battery weights 2,4 Kg so the total pendulum mass is 7,2 Kg. The mechanism of the pendulum moves the batteries around the oil tank, therefore a spherical free space is needed.

Figure 11 shows the batteries gravity position using the most suitable layout. As it shows, the distance between the center of gravity and the axis of rotation is $76{,}1\ mm$.

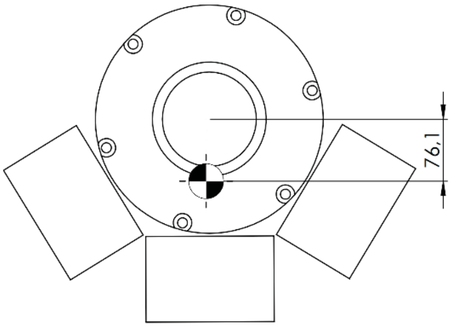


Figure 11. *Center of gravity of the batteries*

The system analogy is a simple pendulum in which the mass and radius are $7{,}2\ Kg$ and $76\ mm$ respectively. The angle φ defines the position of the pendulum as Figure 12 shows.

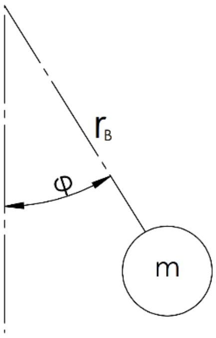


Figure 12. *Simple pendulum*

The next expression (2) defines the torque provided by the batteries as a function of φ.

$$T_B = m\, r_B\, g \sin\varphi \tag{2}$$

Where; $T_B$is the torque created by the batteries, m refers to the pendulum mass, r_B refers to the radius of rotation and g means the gravity acceleration.

The maximum torque is when the angle φ is equal to $\pm 90°$. Then, from equation (2), the maximum torque provided by the batteries is:

$$T = m\, r\, g \sin\varphi = 7{,}2\ Kg\ 76 \cdot 10^{-3} mm\ \sin 90°\ 9{,}81 \frac{m}{s^2} = \ 5{,}36\ Nm$$

3.2 Motor study and selection

An electrical motor through a gearbox moves the system. The requirements for such motor are mainly from its size and the torque and power provided. It is desired that the motor will be able to rotate the pendulum system 90° in less than 10 seconds with a power supply voltage of 24 DCV. It also must fit in the mechanism enhancing the distribution of the weight.

The system is suitable for either a standard DC or a stepper motor. The main advantages for a DC motor is the efficient and vibration-free operation. However, it has an important disadvantage. The speed of the motor is directly proportional with the load torque, and this load torque varies according to the pendulum current position, making complex the control of the system.

On the other hand, a stepper motor provides an easier behavior since the current and target position can be easily calculate through the number of steps to be undertaken. Besides, the pendulum system does not run continuously during the submarine operation time thus it makes the stepper motor suitable.

3.2.1 Stepper motor feature and selection

This section undertakes the necessary calculations for a stepper motor implementation. It follows the technical information provided by the motor supplier Oriental motor through its General Catalog [5].

The main requirement for the system is that it has to be able to rotate itself 90° in maximum 10 seconds.

The first step is to select an operating pattern. There are two basic motion profiles, start/stop operation and acceleration/deceleration operation.

Start-stop is a method of operation in which the operating pulse speed of a motor being used suddenly increases without an acceleration period, as is shown in the below Figure 13. Since rapid changes in speed are required, the acceleration torque is large.

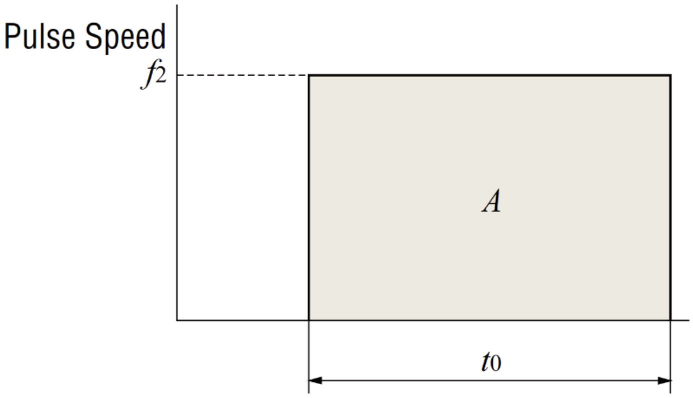


Figure 13. *Start/Stop operation [6]*

Acceleration-deceleration is method of operation in which the operating pulse gradually changes through an acceleration-deceleration period. This period takes roughly 25% of the positioning period. This pattern allows lower acceleration torque than start-stop operation, so that the necessary motor size is smaller. In Figure 14 we can appreciate the acceleration-deceleration period ($t1$) and the positioning period ($t0$).

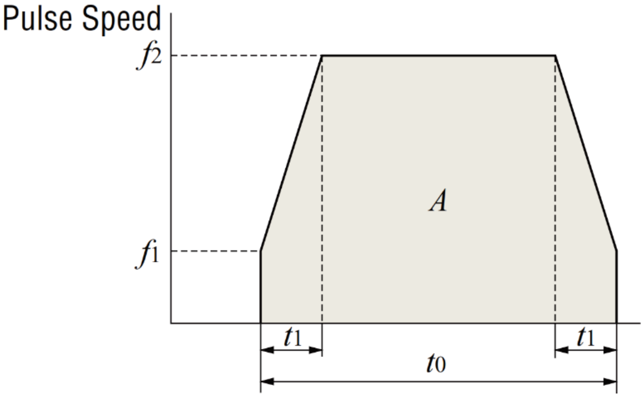


Figure 14. *Acceleration/Deceleration operation [6]*

According with the different advantages that each pattern provides, **the operation method selected is acceleration-deceleration**. Compared with start-stop method it allows smaller motor size and less stiffness structure.

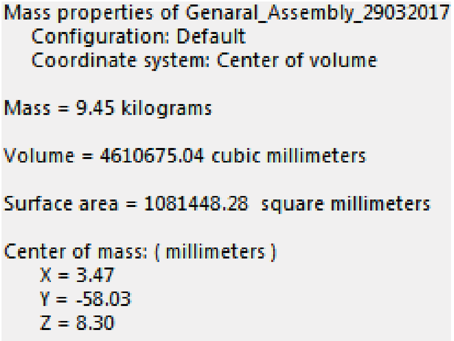
The next feature to calculate is the required torque that the motor has to provide. Following the provider's information, the required torque is determinate as follows in equation (3).

$$T_M = (T_L + T_A)\, S_f \tag{3}$$

Where load torque is calculated as (4) shows;

$$T_L = \frac{T_{Spur\ gear}}{i\, n_G} \tag{4}$$

Spur gear torque ($T_{Spur\ gear}$) is the maximum torque that the system can provide, it´s produced when the center of gravity of the system is located on the horizontal plane that cross the rotational shaft. Solidworks provides the necessary dates to calculate it as it shown in Figure 15.



```
Mass properties of Genaral_Assembly_29032017
    Configuration: Default
    Coordinate system: Center of volume

Mass = 9.45 kilograms

Volume = 4610675.04 cubic millimeters

Surface area = 1081448.28  square millimeters

Center of mass: ( millimeters )
     X = 3.47
     Y = -58.03
     Z = 8.30
```

Figure 15. *3D Solidworks model information*

$$T_{Spur\ gear} = Mass\ \ Rotational\ radio\ (Y)\ \ Gravity = 5{,}4\ Nm \tag{5}$$

Gearbox reduction (i) is 1:180 and the efficiency is 80%, so that, following the equation (4) the load torque at the motor output shaft is;

$$T_L = \frac{T_{Spur\ gear}}{i\ n_G} = \frac{5{,}4\ Nm}{180 \cdot 0{,}8} = 0{,}0375\ Nm$$

Equation (6) express the acceleration torque:

$$T_A = (J_O + J_L)\ \frac{\pi\ \theta_S}{180}\ \frac{f_2 - f_1}{t_1} \tag{6}$$

J_O is the inertia of the motor rotor, it's a provided data from the supplier.

J_L is the total inertia of the system, Solidworks calculates this date. Equation (7) calculates it taking in account the reduction of the gearbox and the inertia of the mechanism without gearbox.

$$J_L = \frac{J_{mechanism}}{i^2} = \frac{0{,}12\ kg\ m^2}{180^2} = 37 \cdot 10^{-7}\ kgm^2 \tag{7}$$

θ_S is the step angle, the motor supplier provides this date. θ_S is 1,8°.

f_2 is the operation pulse, it's calculate through the equation (8) .

$$f_2 = \frac{A - f_1\, t_1}{t_o - t_1} \tag{8}$$

The following equation (9) calculates the operating number of pulses (A), taking in account the desired movement (l), the movement due to a motor revolution (l_{rev}) and the previously mentioned step angle (θ_S).

$$A = \frac{l}{l_{rev}} \frac{360°}{\theta_S} = \frac{90°}{{}^{1}\!/_{180°}} \frac{360°}{1{,}8°} = 3240000 \tag{9}$$

Starting pulse speed (f_1) is 0 since, due to the self-locking behavior, the system doesn't need any torque to keeping a reached position.

As Figure 14 shows, for a acceleration/deceleration operation mode, the positioning period (t_o) is the total time that the systems takes to reach a target position (10 seconds in this application), and the acceleration/deceleration period (t_1) is the time within the system changes the pulse speed between f_1 and f_2. t_1 is roughly 20% of the total time t_0.

$$t_1 = 0{,}2\ t_0 = 0{,}2\ \ 10\ s = 2\ s \tag{10}$$

Then, the operation pulse f_2 is calculated through the equation (8) as follows.

$$f_2 = \frac{A - f_1\, t_1}{t_o - t_1} = \frac{3\,240\,000\ \ -0\ \ 2\ s}{10\ s - 2\ s} = 405000\ Hz$$

From equation (6) the acceleration torque T_A is;

$$T_A = (J_O + J_L)\ \frac{\pi\ \theta_S}{180}\ \frac{f_2 - f_1}{t_1}$$

$$T_A = (J_O + 37 \cdot 10^{-7}\ kg\ m^2)\ \frac{\pi\ 1{,}8°}{180}\ \frac{405000\ Hz}{2s} = (J_O + 0{,}12\ kgm^2)\ 6361 \frac{1}{s^2}$$

Then, with the equation (3) and considering a safety factor (S_f) of 2, the torque required is;

$$T_M = (T_L + T_A)\ S_f = \left(0{,}0375\ Nm + (J_O + 37 \cdot 10^{-7}\ kgm^2)\ 6361 \frac{1}{s^2}\right) 2$$

As we can see, the torque required to fulfill the system requirements depends on the inertia of the rotor. Looking the oriental motor catalogue [6], attending to PKP Series, standard type with encoder and step angle of 1,8° there are available different frame sizes. Each frame size has a different inertia of the rotor. On Table 1 we can see the different values with the torque required according to them following the equation (3) (notice that takes in account the largest version of each frame size).

Table 1. *Calculation of required torque attending different motor sizes*

Model number	Frame size $[mm]$	Rotor Inertia (J_O) $[kgm^2]$	Required torque (T_M) $[Nm]$
PKP214D	20	$2{,}9 \cdot 10^{-7}$	0,125
PKP225D	28	$18 \cdot 10^{-7}$	0,145
PKP235D	35	$50 \cdot 10^{-7}$	0,186

As Figure 16 shows, according with the charts that the supplier provides, neither PKP214D nor PKP225D provide enough torque.

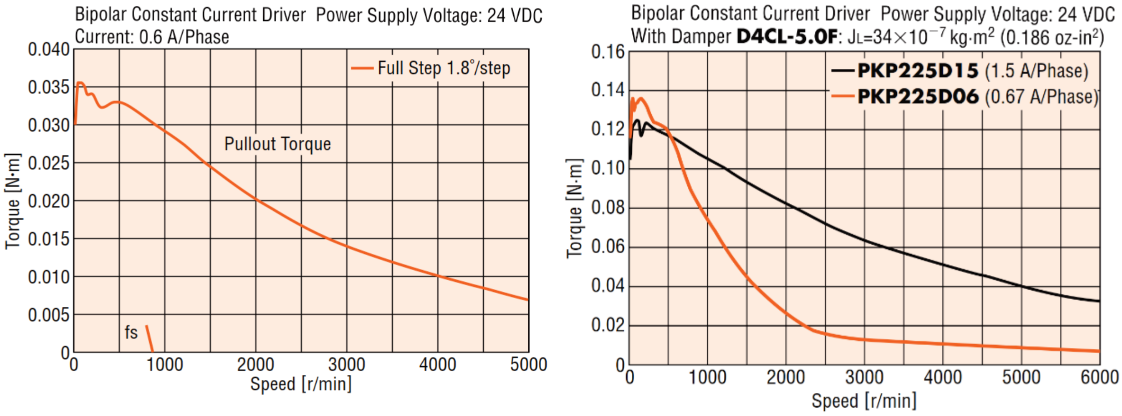


Figure 16. *Charts of models PKP214D and PKP225D [6]*

However, as we can see in Figure 17 , the model PKP235D is able to provide the required torque.

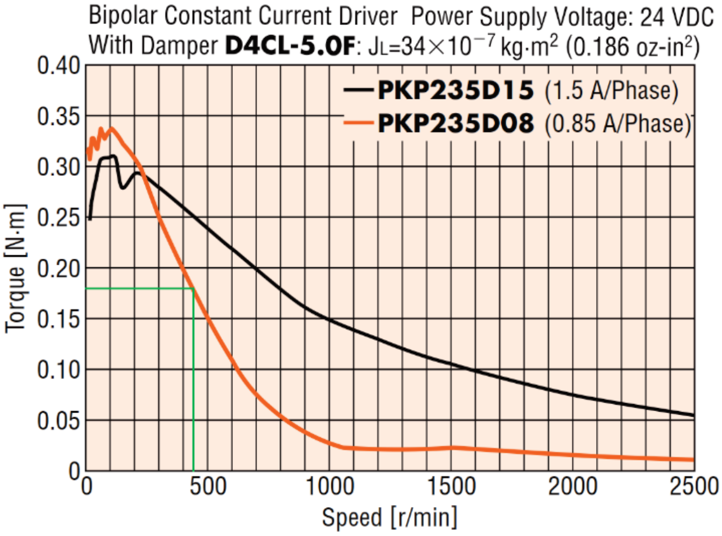


Figure 17. *Edited chart of model PKP235D [6]*

Figure 17 shows through green lines, that model PKP235D08 provides $0{,}186\ Nm$ at $425\ rpm$. The necessary rpm for a 90° rotation in 10 seconds with a reduction of 1:180 are, as equation shows, $270\ rpm$.

$$Required\ rpm = \frac{Rotation}{i\ 360\ Time\ (m)} = \frac{90}{\frac{1}{180}\ 360\ \frac{10}{60}} = 270\ rpm \tag{11}$$

This means either, the motor is able to work away from the limit, which improves the efficiency, heat production and reliability or the motor can undertake the rotation within less time than it is required. Equation (12) shows that the minimum time that takes a 90° rotation is 6,35 seconds.

$$t_{min} = \frac{\frac{Rotation}{360}\ i\ 60s}{rpm_{max}} = \frac{\frac{90}{360}\ 180\ 60}{425} = 6{,}35\ s \tag{12}$$

The selection is then the model PKP235D08. Figure 18 shows the main motor measures.

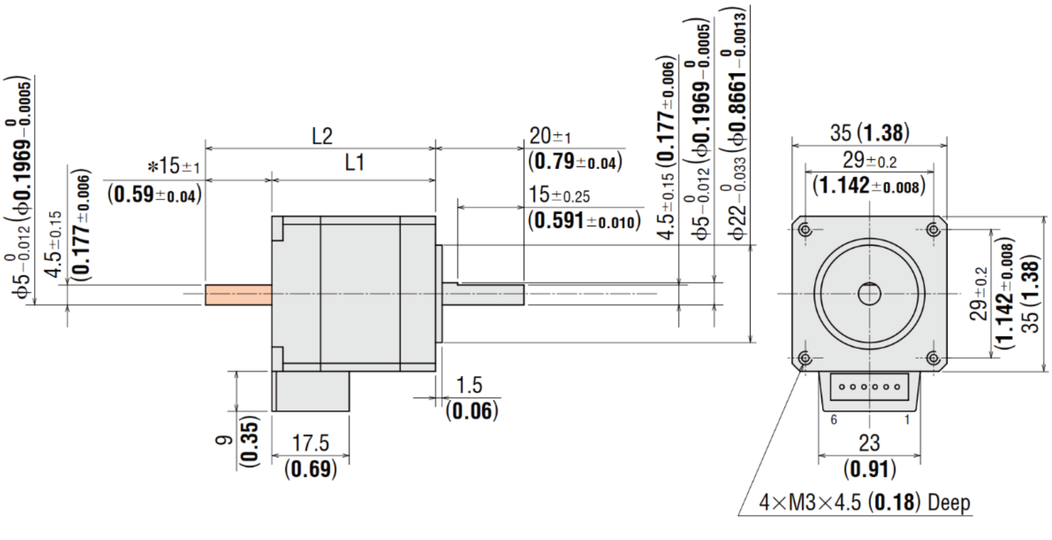


Figure 18. *Main measures of model PKP235D[6]*

3.3 Gearbox configuration study

A gearbox is a power transmission system that adapts the torque and speed provided by the driving shaft to satisfice the system's requirements. A gearbox can have a single or multiple reduction ratios and different possible configurations.

For this application the main features are:

- Great reduction to allow a smooth operation and a reasonable motor size.
- Adapted shape to the available space, see Figure 19.
- Simplicity.
- Self-locking behavior.

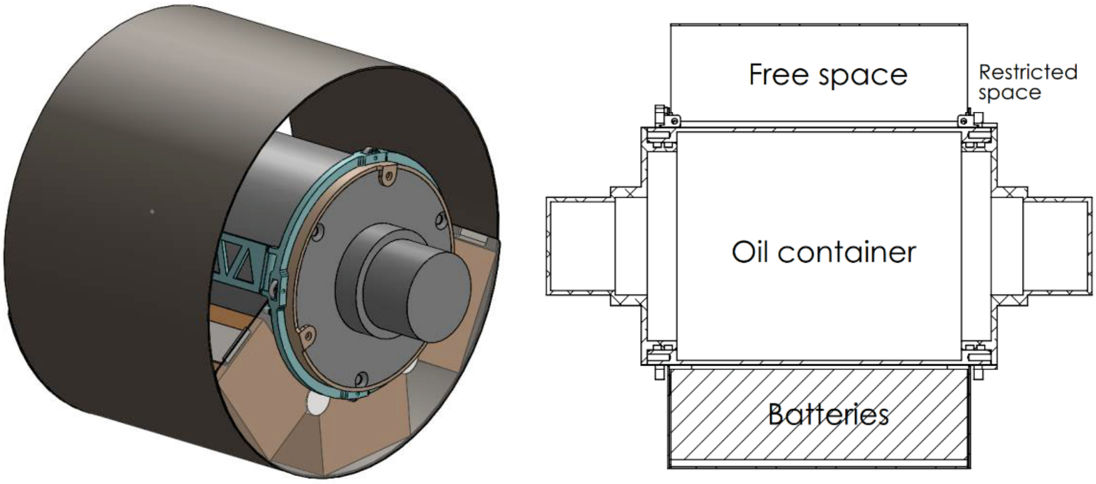


Figure 19. *Available space for the gearbox*

As Figure 19 shows, there is free space between the oil container and the shell that wraps the system. However, the space on both the left and right side is not desired to be used. Notice that such free space rotates within the pendulum itself, so that any fixed part of the gearbox must be out of this space.

3.3.1 Self-locking feature

Self-locking behavior is another requirement; this means that the gearbox must keep any pendulum position without any additional system that needs energy. A conventional gearbox has a driving shaft and a driven shaft, when the out coming torque at the driven shaft is higher than the resistant torque the system moves as the input is applied. Nevertheless, if the resistant torque overtakes the out coming torque a backdriving appears and the driven shaft becomes the driving one. This is a not desired situation.

It is possible to design a parallel self-locking gear as it is explained in the paper *Self-Locking Gears: Design and Potential Applications* [7], however this configuration does not allow a great reduction ratio since the gear size relation between driving and driven gear is proportional to the reduction ratio, in this case, at least 1:100. That would make impossible to fit the gearbox in our application. Figure 20 shows a parallel self-locking gearbox.

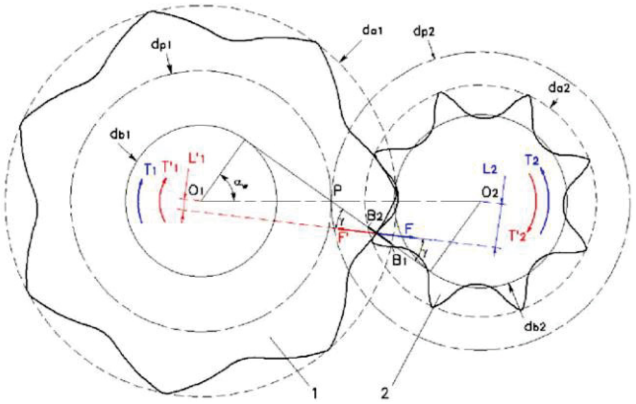


Figure 20. *Parallel self-locking gears [7]*

To achieve both, self-locking behavior and great reduction ratio, the gearbox configuration selected has a worm gear and spur gear. This configuration provides an inherent self-locking behavior [8]. Aiming a proper use of the space, an inner empty spur gear wraps the oil tank as fixed part while the worm gear rotates around it. Two bevel gears connect the motor with the worm gear, allowing locate the motor in the free space shown in Figure 19. Figure 21 shows the gears and motor layout.

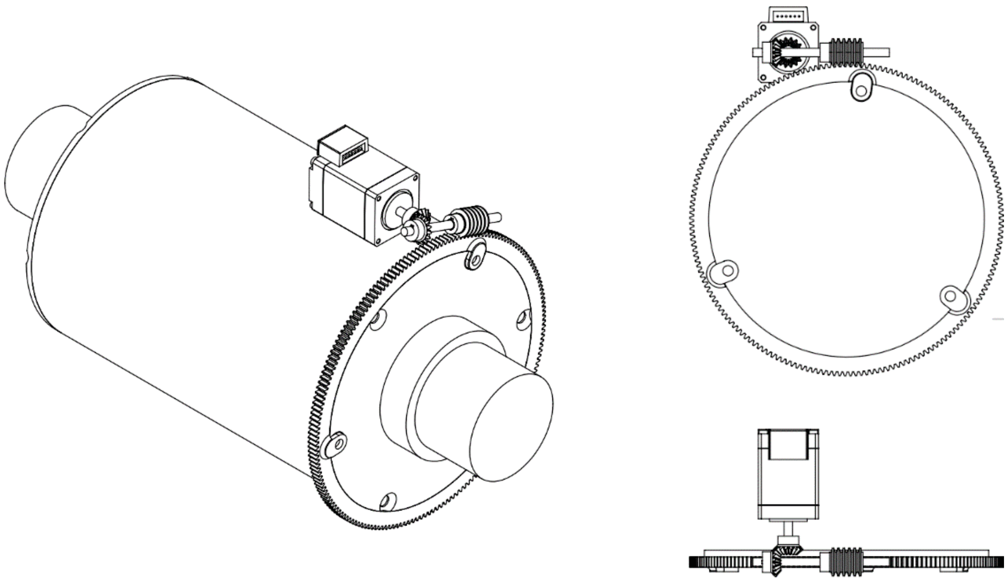


Figure 21. *Gearbox and motor layout*

3.3.2 Gearbox reduction ratio

Both spur gear and bevel gears shown previously in Figure 21 have module 1, and the pitch angle of the worm gear is 1. Then, since the nominal diameter of the spur gear is 180 mm (the oil tank diameter is 160 mm) the reduction ratio works out 1:180.

Figure 22 shows the different parts that make up the gearbox assembly. It has radial ball bearings and axial ball bearings to support the forces.

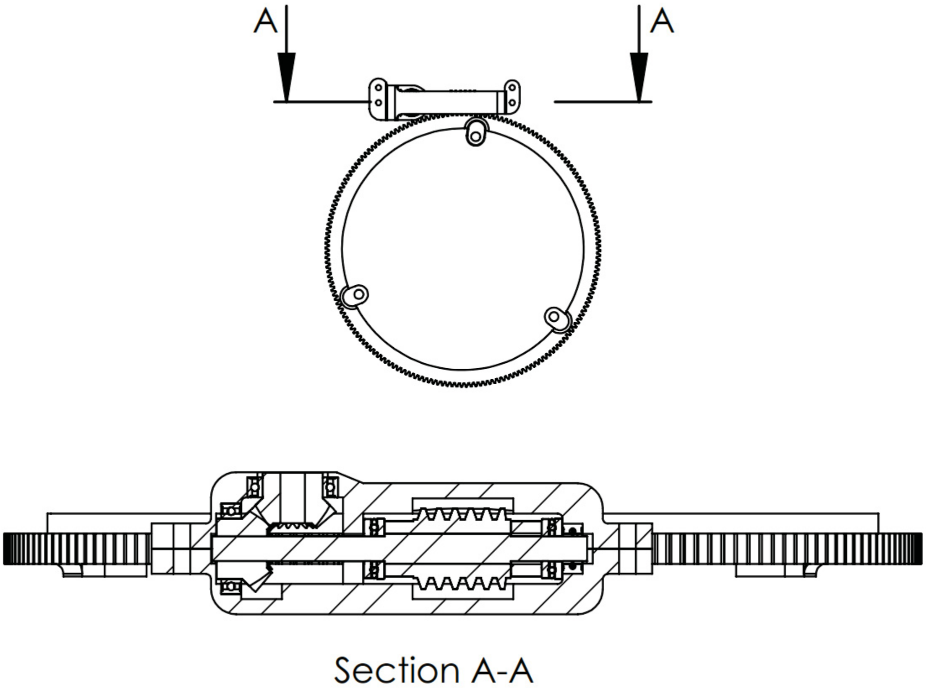


Figure 22. *Gearbox section view*

3.4 Structural design of pendulum mechanism

The structure of the pendulum is group of parts that fixes the pendulum to submarine while allows its rotation around the oil tank. It has to fulfill different design requirements regarding size, shape, weight and reliability.

3.4.1 Structural configurations studied

During the iterative design process several alternatives supports have been evaluated. Each iterative design presents an upgrade from a previously detected improvement opportunity. Such changes are also due to changes of the layout of the submarine as its development went on.

Figure 23 shows the first design approach. In this version the oil tank is moved fixed to the batteries and stepper motor. An arm that joins the shell of the submarine supports the entire whole. The need of space for the arm and the complexity of moving the oil tank container were the main reason to discard this design.

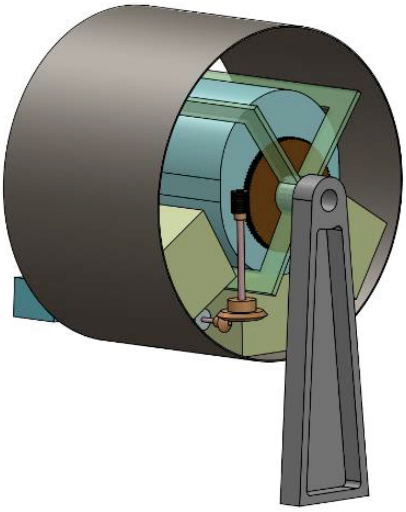


Figure 23. *First design version of the structure of the pendulum*

The next configuration studied is based on a swing sheet metal parts structure that rotates carrying the batteries around the oil tank. The advantage of this design is its thin size and the approach of moving the batteries around the oil tank instead of moving all as a whole. Figure 24 shows such sheet metal parts structure.

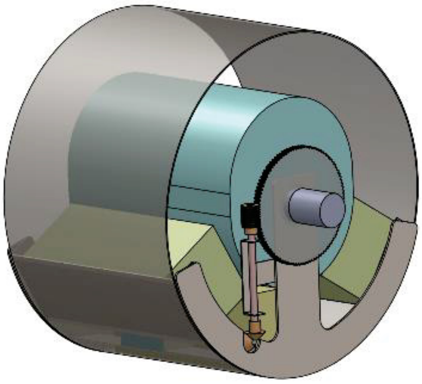


Figure 24. *Structure of the pendulum based on sheet metal parts*

Figure 25 shows an upgrade of the sheet metal parts structure previously mentioned. In this design the main parts of the mechanism are stiffener. This design fulfilled all the design requirements however, there were some disadvantages like the need of a shaft crossing the submarine to fix the pendulum and the space required at both side of the oil tank.

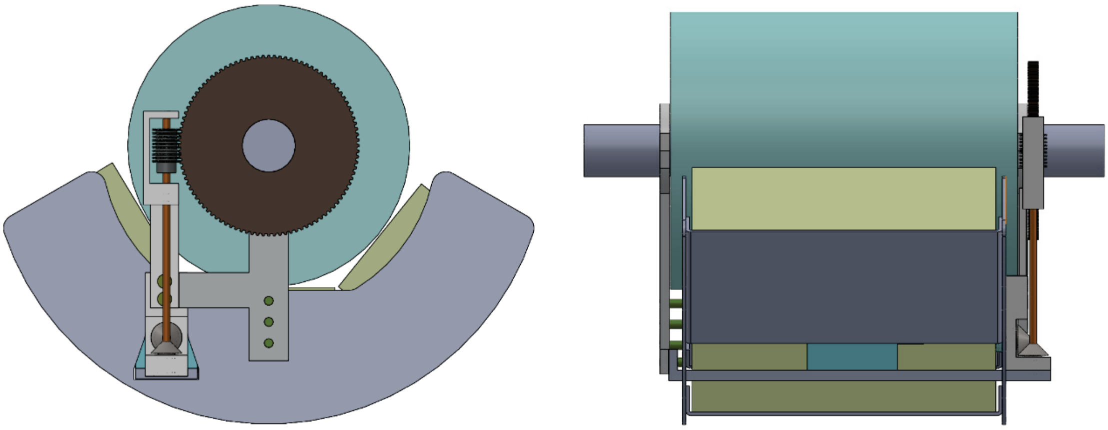


Figure 25. *Upgraded version of sheet metal based structure*

3.4.2 Structural configuration selected

The structure configuration selected uses the oil tank as single support for the whole pendulum system. The structure itself rotates around the oil tank through ball bearings using the oil tank surface as a track. In that way, all the needed parts for the structure and the motor are located inside the area previously reserved for the pendulum motion, so no extra space outside is needed. Figure 26 shows the selected structure.

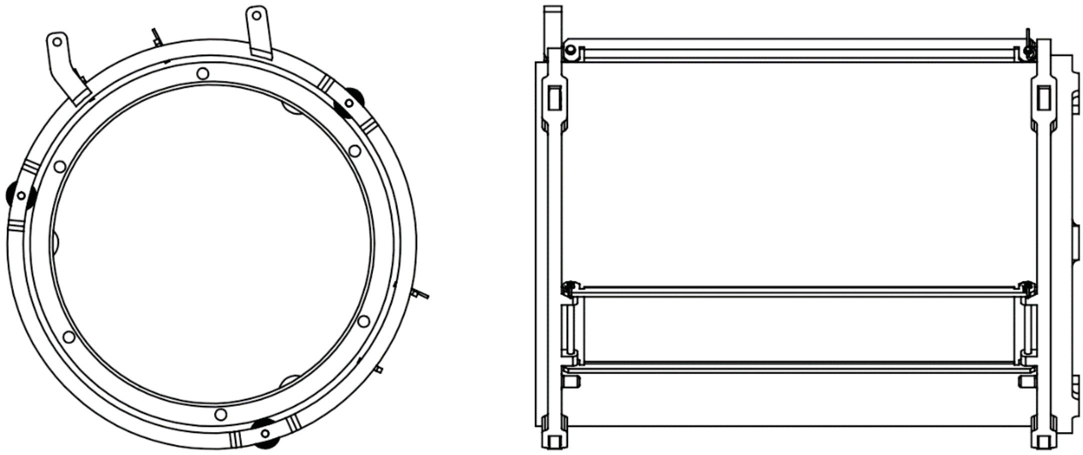


Figure 26. *Structure selected*

The selection of this structural design is made based on two advantages provided in comparison with those previously presented. The first advantage is that the structure is supported just by the oil container, so that, there is no restriction for the size of the shaft that joins the tank. Moreover, the structure can be adapted to any oil container size, either diameter or length. The second advantage is that the structure is placed entirely inside of the space reserved to the pendulum system, so there is no possible interaction with other devices. Besides, the structure is smaller than the previous versions. Figure 26 shows how the structure fits the oil container, it can also be appreciated that the structure doesn't take up any space in any side of the tank.

Figure 27 shows the assembly of the structure with the gearbox and the stepper motor. It can be seen that the ball bearings support the parts PS_01_001 and PS_01_002 and that both are fixed together through PS_01_003 and PS_01_004. The motor is joined to PS_01_003. The axial movement is restricted in both ways by the removable parts PS_01_005 and PS_01_006, these parts are fixed to the oil tank. Two screws fix the gearbox to the structure. Appendix A contains the correspondent drawings.

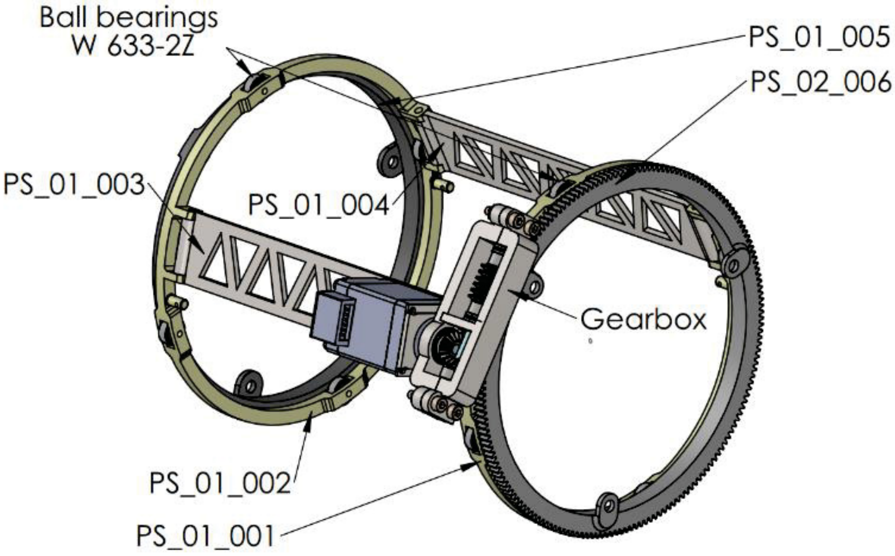


Figure 27. *Structure of the pendulum*

Figure 28 shows the space that the structure uses. As it can be seen, the gearbox is 30 mm outside of the shell and it rotates within a maximum diameter of 259 mm. The structure remains inside the safety shell.

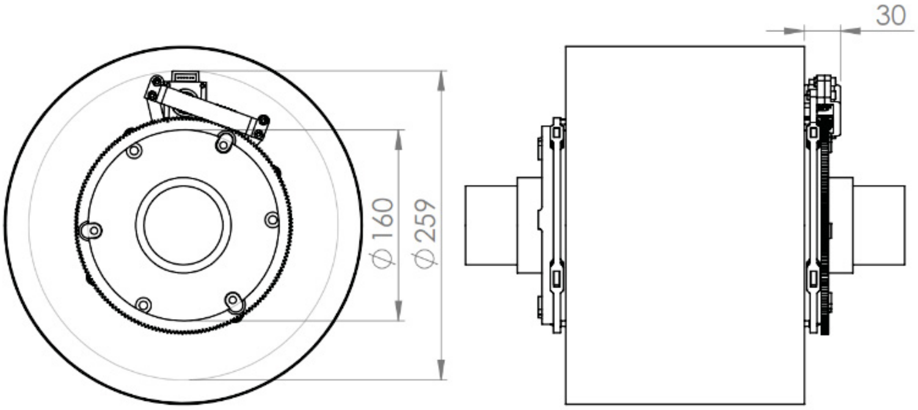


Figure 28. *Space occupied by the structure and gearbox*

A sub-structure fits together the three batteries with the main structure. This structure, as Figure 29 shows, is mainly made of sheet metal parts and 3D-printed parts. The structure allows to remove the batteries separately at any time. This design aims an easy maintenance process.

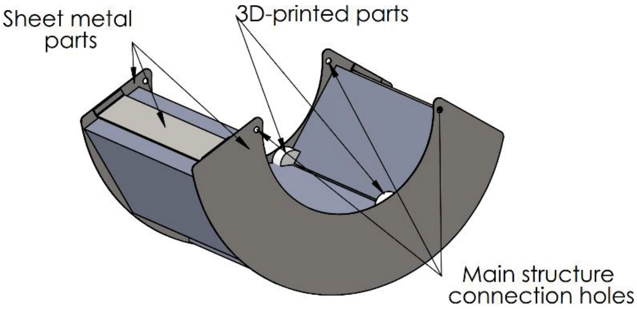


Figure 29. *Structure of the batteries*

4. PENDULUM SYSTEM SOLUTION

This section presents the results of the research. The final design is explained regarding its configuration, the efficient use of space and the features that it provides. MATLAB simulations show the expected behavior of the watercraft attending different patterns of motion.

Finally, this section provides information about the assembling process of each sub-group and the pendulum system as a whole. A 3D printed prototype is also presented.

4.1 Final design of the pendulum system

The pendulum system is a mechanism designed to vary the relative position of the center of gravity from the centroid of a spherical autonomous submarine. To undertake this, it moves three batteries around an already existent oil container. A sheet metal parts structure fixes the batteries to the main structure. The whole assembly rotates supported by eight freewheeling ball bearings, whilst the axial movement is restricted by two fixed parts at both ends. A stepper motor moves the mechanism through a gearbox that includes two bevel gears, a worm gear and a spur gear, which provide a reduction of 1:180 and self-locking behavior. Figure 30 shows such pendulum system and a detail view of the gearbox.

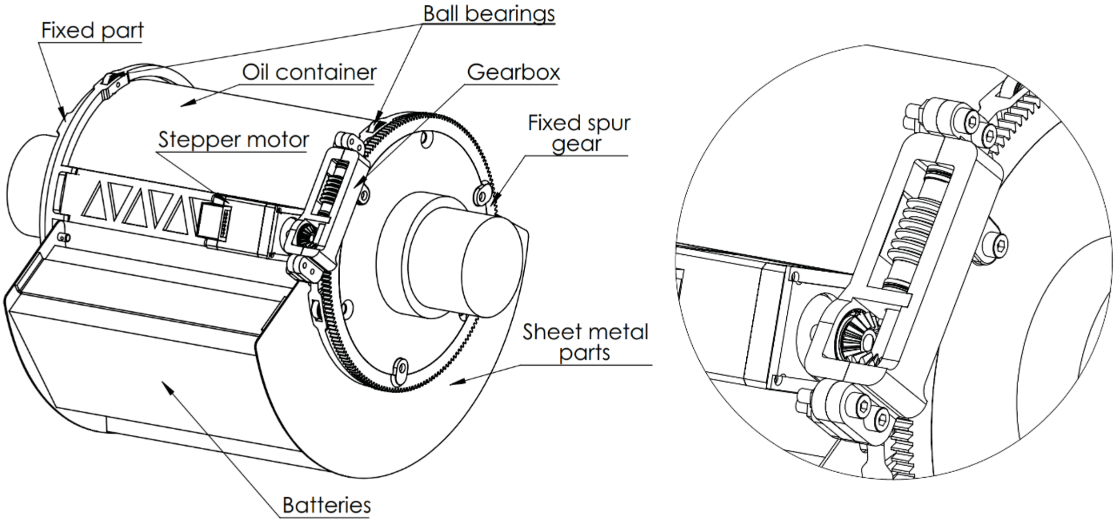


Figure 30. *Pendulum system*

Figure 31 shows the main dimensions of the pendulum. The shown dimensions refers to the space that the pendulum system takes while it is rotating. As it can be seen, besides the space took by the rotation of the batteries, the mechanism takes up $29\,mm$ on the right side and $16\,mm$ on the left.

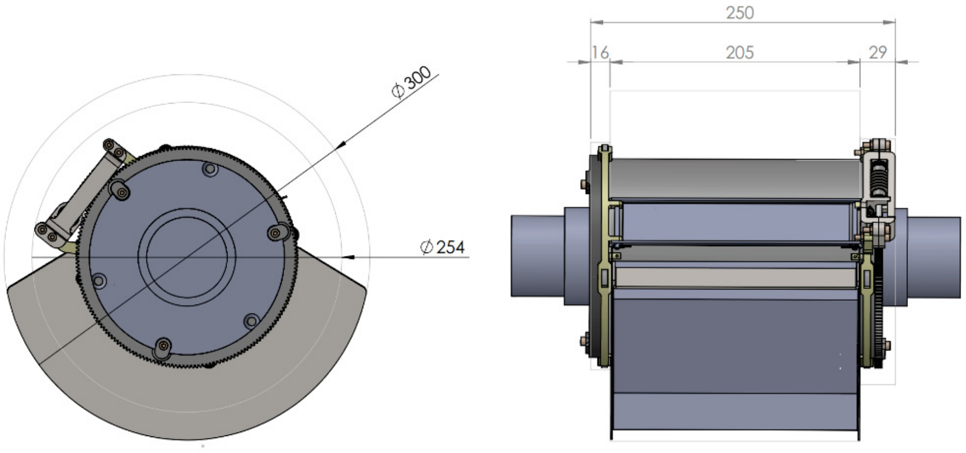
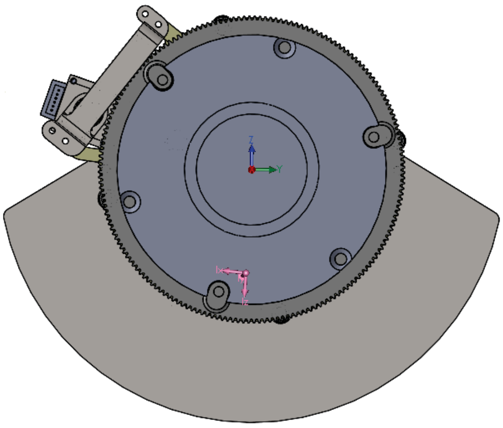


Figure 31. *Main dimensions of pendulum system*

4.2 Features reached of the pendulum system

The whole assembly weights $9{,}2\,Kg$, in which the batteries work out $7{,}2\,Kg$. So that, since the batteries are already components of the submarine, the pendulum adds $2\,Kg$ to the submarine.

Figure 32 shows the position of the center of gravity using the centroid of the submarine as reference coordinate system.



	Center of gravity (m)
x	0,005
y	0,003
z	-0,0613

Figure 32. *Center of mass location*

The distance r on the plane zx, between the rotational axil (centroid) and the center of gravity is calculate in the expression (13).

$$r = \sqrt{0{,}003^2 + (-0{,}0613)^2} = 0{,}0614\, m \tag{13}$$

The torque created by the pendulum is expressed by the next equation (14).

$$T = m\, r\, g\ \sin\varphi \tag{14}$$

Then, the maximum torque ($\varphi = 90°$) is;

$$T_{Max}\ = 9{,}2\, Kg\ 0{,}0614\, m\ 9{,}81 \frac{m}{s^2}\ \sin 90° = 5{,}5\, Nm$$

Table 2 sums up the main features of the pendulum.

Table 2. *Main features of the pendulum system*

Weight	$9{,}2\, Kg$
Weight without batteries	$2\, Kg$
Maximum torque	$5{,}5\, Nm$
Time to rotate 90° (from equation (12))	$6{,}35\, s$

4.3 Simulation of the pitch angle control

The equation of motion of the submarine is expressed as equation (15) shows:

$$\ddot{\varphi} = -\dot{\varphi}\,\frac{C}{J} - \frac{m\, r\, g}{J}\ \sin(\varphi + \delta) \tag{15}$$

Where; φ is the angular position of the submarine, $\dot{\varphi}$ is the angular velocity of the submarine, $\ddot{\varphi}$ is the angular acceleration of the submarine, C is the drag coefficient of the submarine, J is the moment of inertia of the submarine, r is the distance between centroid and center of gravity of the pendulum, m is the mass of the pendulum and δ is the target position.

Figure 33 shows the position of the UAV and the target position, which means the angle between the submarine and the pendulum system.

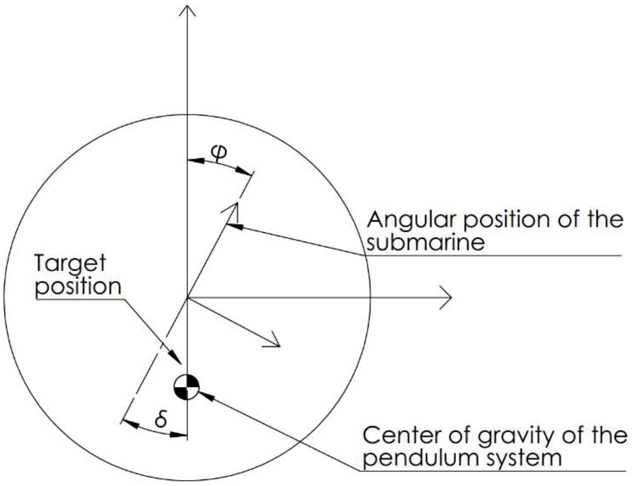


Figure 33. *UAV variables*

The drag coefficient for the latest shape version of the submarine has not been yet calculated. For a perfect sphere this data is in the order of $10^{-4}\ Kg/m\ s$ [4] but this is far from the real coefficient for a real sphere with several devices outside. In contrast to the thrusters system, the higher the drag coefficient the better for the stabilizing behavior.

Figure 34 shows a Simulink block diagram of equation (15). In this case, the model simulates a situation in which the UAV is released in the water with the pendulum system at a neutral position, so the system is stable, and after 5 seconds the pendulum system rotates to the target position. Then, the restoring torque moves the vehicle towards the new equilibrium position. This simulation approximates the reality when, being the submarine in a stable position, the pendulum system is set to rotate as fast as possible. Taking in account that the pendulum system is able to rotate 90° in 6.35s, it takes around 1.4s to rotate 20°. This simulation takes that time as $0s$, that is the step response.

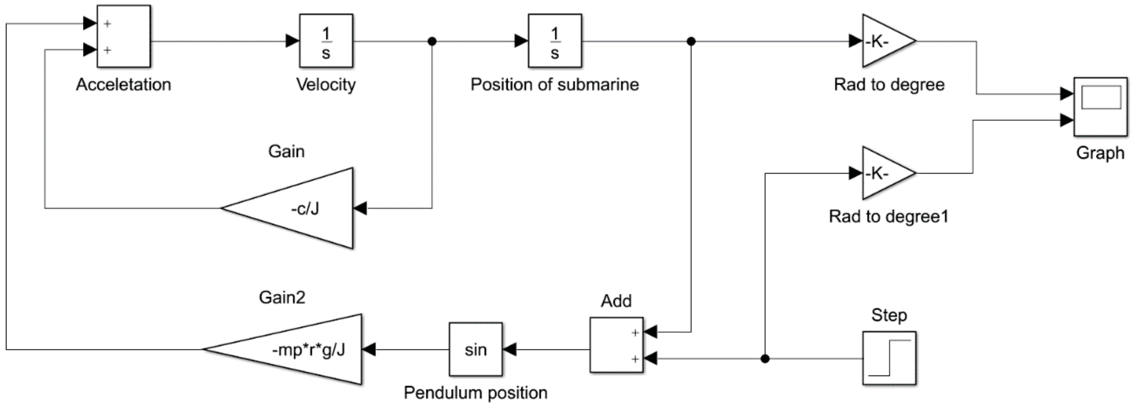


Figure 34. *Simulink block diagram of equation (15)*

Figure 35 shows the behavior of the submarine when the target position is $\varphi = \pi/9$ and the theoretic perfect drag coefficient is used. Blue line represent the position of the submarine meanwhile the red one express the position of the pendulum.

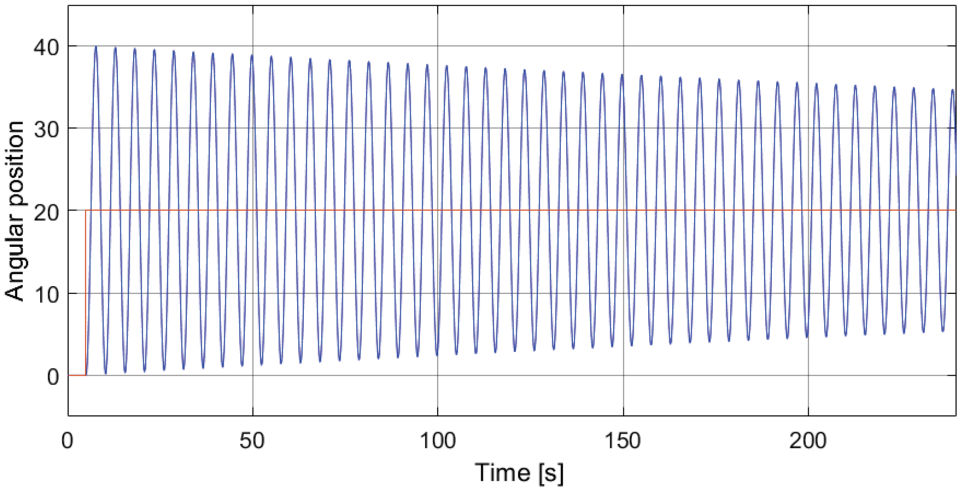


Figure 35. *Step response, ideal drag coefficient*

As we can see in Figure 35, the oscillations of the submarine does not seem realistic. This is because the drag coefficient used does not represent the real shape and roughness of the submarine. As we can see in Figure 36, using a more realistic drag coefficient (in the order of 0.5 $Kg/m\ s$) the vehicle simulation seems to behave properly.

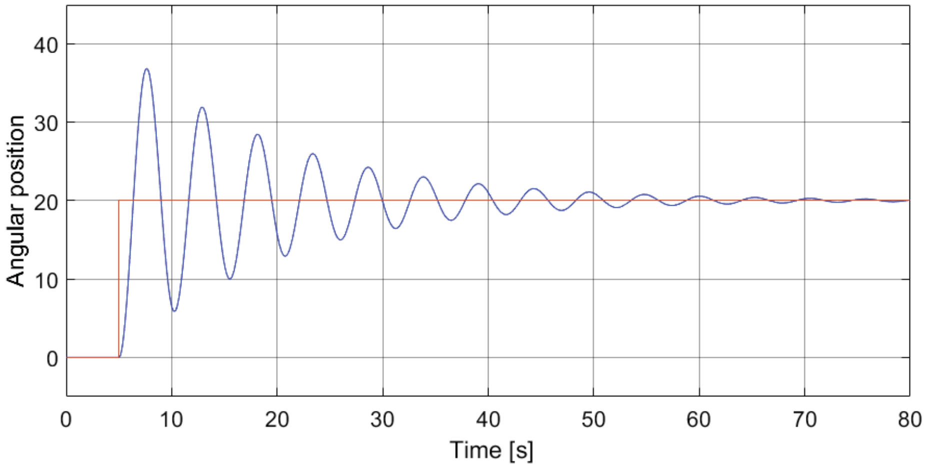


Figure 36. *Step response, real drag coefficient*

As we can appreciate, it takes around 60 seconds to reach a reasonable stability at the new equilibrium position. The oscillations of the system can be decreased varying the way the pendulum rotates. Instead of reaching the target position immediately, it´s possible to move towards that position linearly. In Figure 37 we can see a Simulink block diagram that simulates that system.

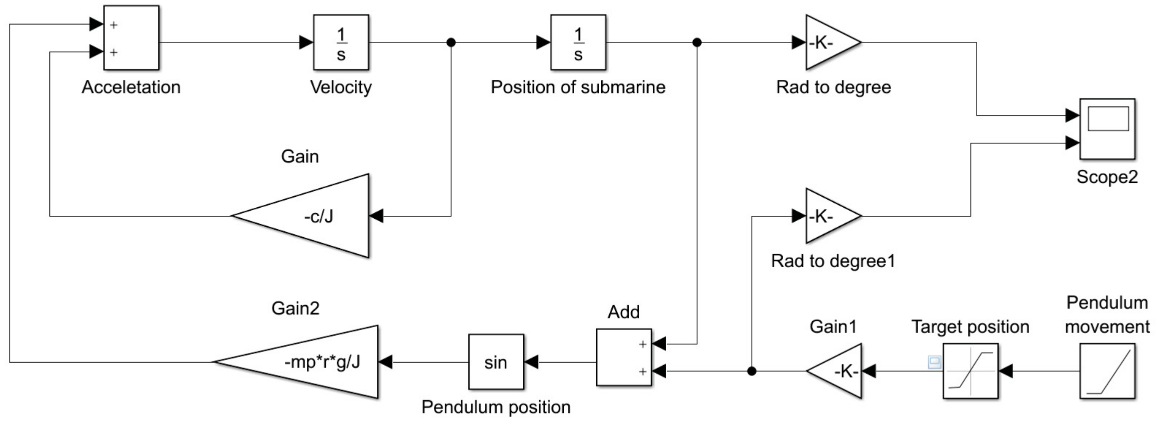
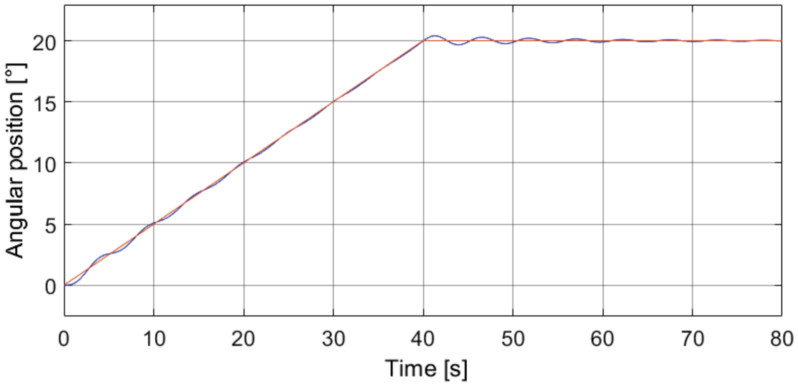


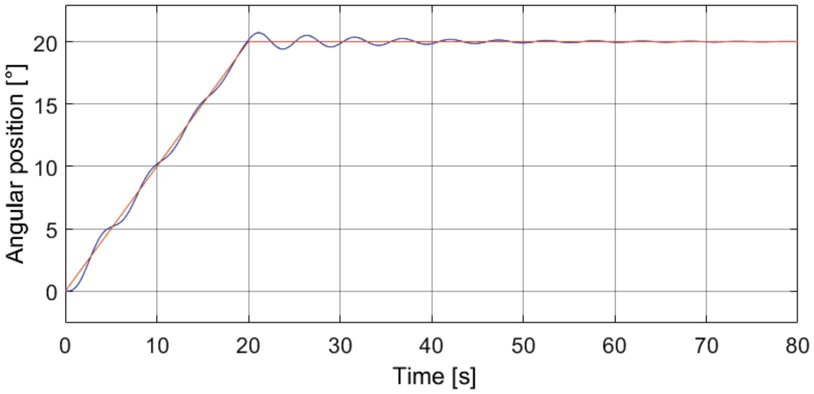
Figure 37. *Simulink block diagram of a linear pendulum movement*

The diagram shown in Figure 37 simulates a situation in which at the beginning both, target position and pendulum angle are 0. Then the pendulum begins to rotate towards the target position linearly.

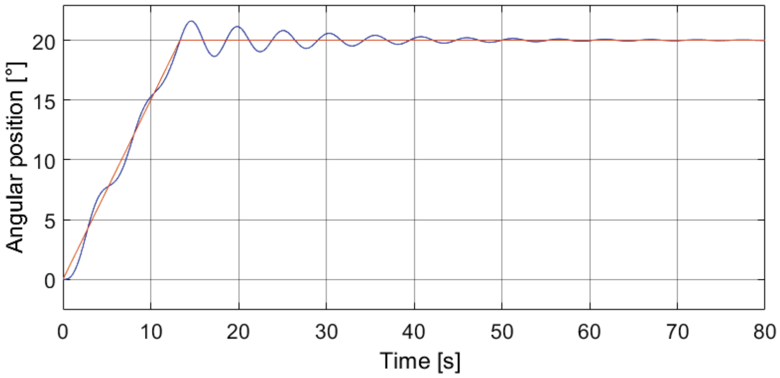
Figure 38 shows the case in which the pendulum position varies linearly up to 20°. From up to down; 0.5, 1, 1.5, 2 degrees a second. Blue line shows the position of the submarine and red line the position of the pendulum.



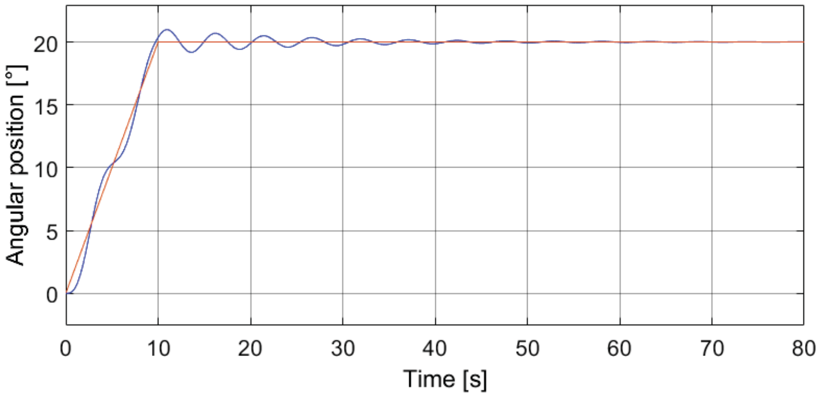
a) 0.5 degrees per second



b) 1 degrees per second



c) 1.5 degrees per second



d) 2 degrees per second

Figure 38. *UAV behavior when the pendulum moves linearly*

As we can appreciate, the motion of the system improves moving linearly instead of reaching the maximum speed immediately. As we can see in Figure 38 moving at 0.5 degrees a second the oscillations are smaller than moving at 2 degrees a second, but the time that takes to reach the target position is longer. As it can be seen, moving at 2 degrees a second, it reaches a stable position in approximately 30 seconds.

It is remarkable that the features of the motor improve when the speed is not the main requirement. Moving slower the efficiency of the motor is higher and both motor and worm gear generate less heat.

It would be also possible to use a PID control to reduce the oscillations, however such research is out of this thesis´s reach.

4.4 Pendulum mechanism equipment

The pendulum system is joined to the submarine just through the ballast system tank. So that, it´s possible to assemble the pendulum system to this container outside the submarine and install the entire whole at once. However, it is also possible to assemble and disassemble the system without removing the ballast system installed. This section explains the process to be undertaken to do so.

Three main groups of parts make up the pendulum system; structure, gearbox and battery set. Each group is designed to be assembled separately before joining the general system. The battery set allows moreover, extracting the batteries at any moment. Figure 39 Shows a exploded view of the pendulum system.

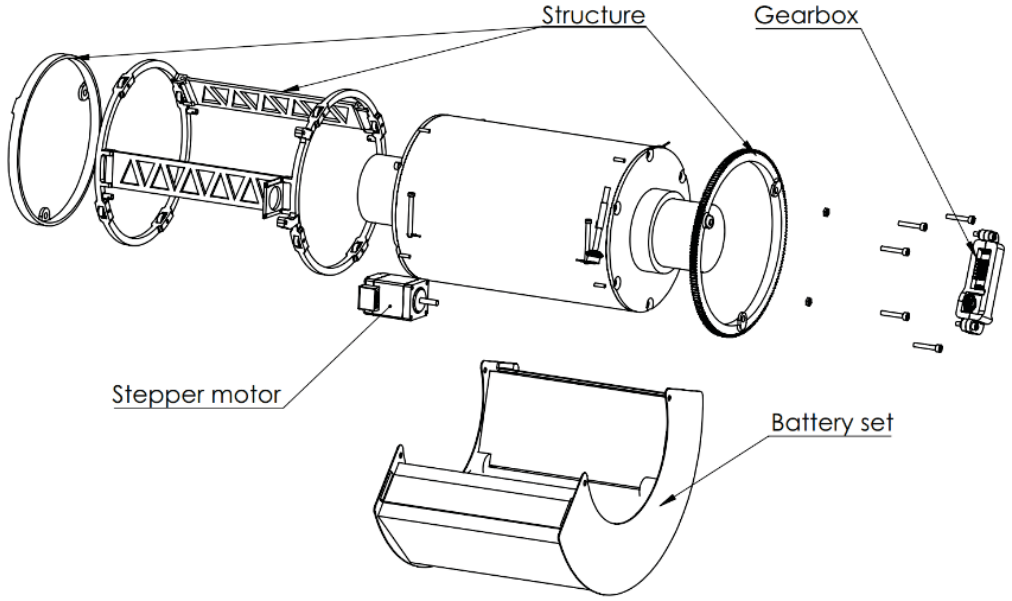


Figure 39. *Exploded view of pendulum system*

4.4.1 Gearbox group

The gearbox has 15 parts besides screws and nuts. Three of these parts are 3D printed, two are made by lathing and the rest are standard ball bearings and keys. Figure 40 shows an exploded view of the gearbox.

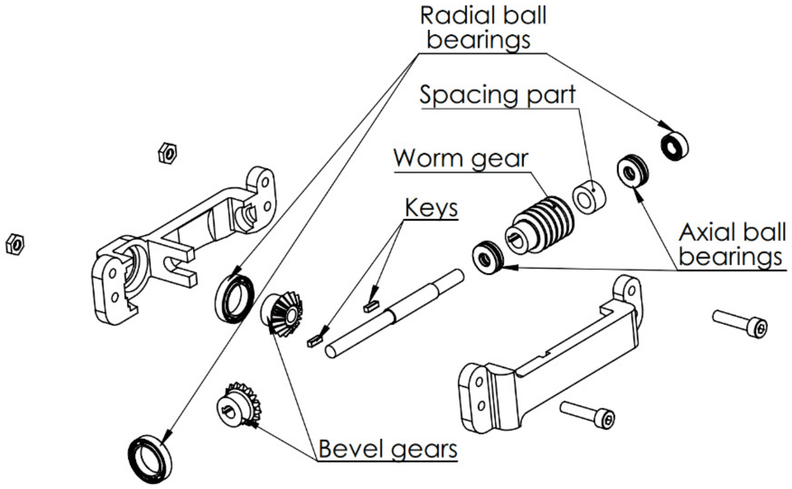


Figure 40. *Gearbox exploded view*

Some consideration have to be taken in account. Attending to the supplier datasheet [9], using the bevel gears reference A1016M16-1, the distance between their axes is 15 mm. And as equation (16) express the distance between the axis of the worm gear and the spur gear is 97 mm. Worm gear reference 351000 from Mekanex catalogue [10].

$$D_{Spur-Worm} = \frac{D_{spur} + D_{worm}}{2} = \frac{180 + 14}{2} = 97\ mm \tag{16}$$

Figure 41 shows the distance both between the bevel gears and between spur and worm gear.

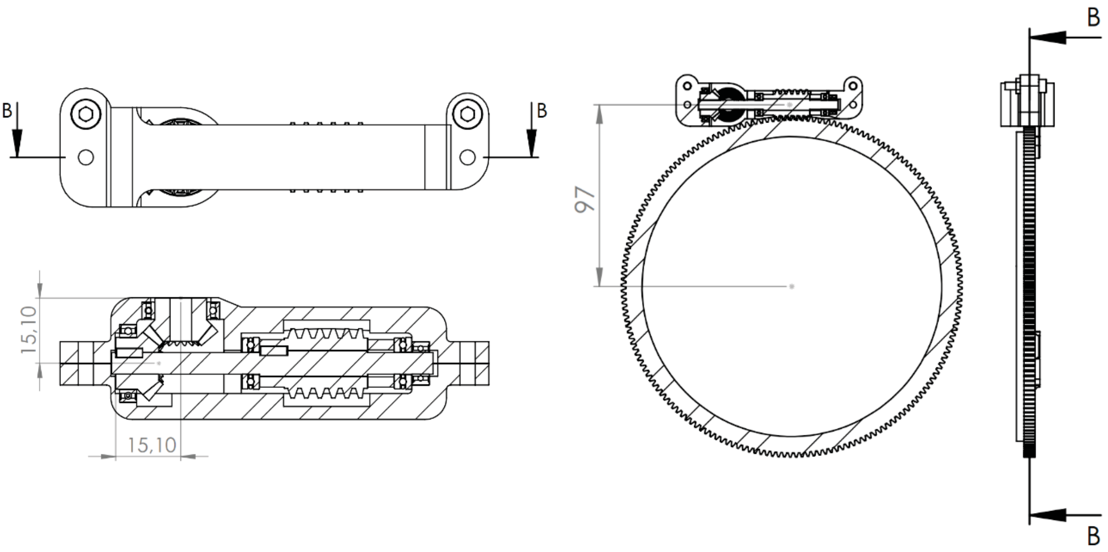


Figure 41. *Section view of the gearbox*

4.4.2 Structure group

The structure is the group of parts that fix the pendulum to the robot whilst allow its rotation. The gearbox, battery set and motor are fixed to the structure. The structure is fixed to the ends of the oil container and rotates around the oil container surface supported by 8 ball bearings. The spur gear works both as a gear and as structural part.

Due to the non-standard shape, it is cheaper to build some parts by 3D printing in metal that any other method. These parts are PS_01_001, PS_01_002 and PS_02_006. Figure 42 shows a exploded view of the structure.

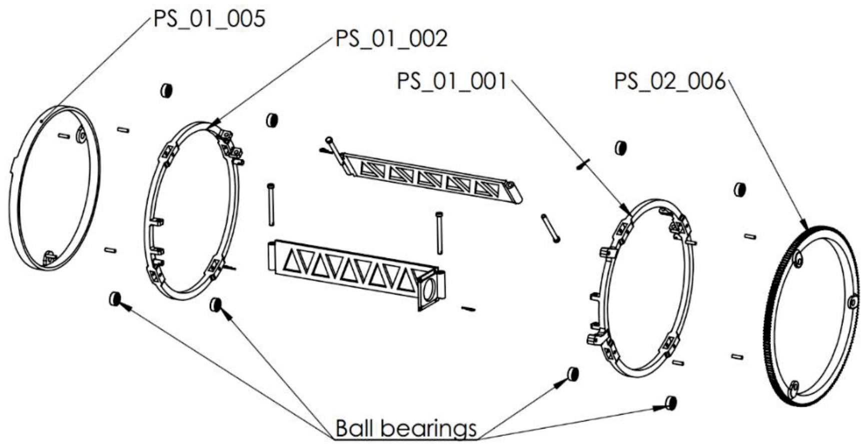


Figure 42. *Exploded view of the structure*

4.4.3 Battery set

The layout of the battery set is aiming to getting the center of gravity at the lowest possible position. It joins the structure through the parts PS_01_001 and PS_01_002, and can be assembled and disassembled at any time. Its structure is based in sheet metal parts.

Figure 43 shows the battery set and a detail view of the union between the battery set and the main structure. As it can be seen, it equips a rapid removal system.

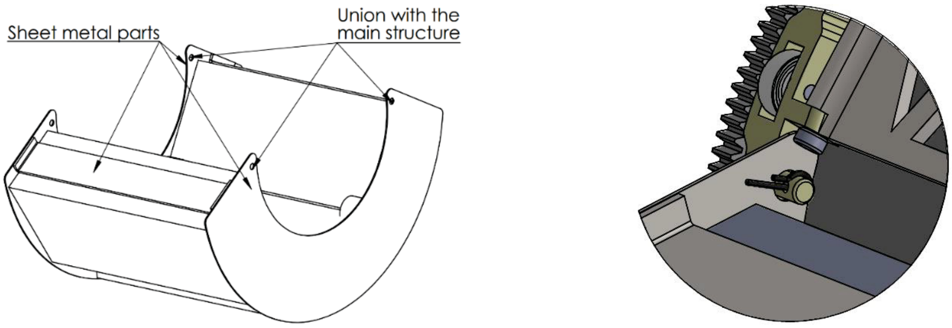


Figure 43. *Battery set*

4.5 3D- printed prototype

In order to test the design and prove its working features a prototype has been built. This is make up from 3D parts and standard parts. The use of a prototype allows to prove the assembly process and the identification of possible upgrades whilst checks the absence of design mistakes.

The technology used is mainly FDM (Fused Deposition Modeling) for structural parts and SLS (Selective Laser Sintering) for smaller and more detailed ones.

Figure 44 shows the different parts that make up the gearbox.

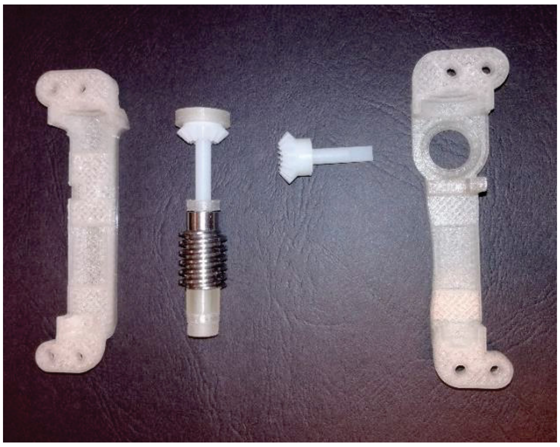


Figure 44. *3D printed parts*

The smaller and more accurate parts are built by SLS. Printing parts by SLS is more expensive than by FDF and it takes longer, but the result is more accurate. Figure 45 shows the main shaft of the gearbox, a bevel gear and the key that fixes them printed using SLS technology. It is also show a detail view of the union between the shaft and bevel gear through the key.

a) Exploded view

b) Detail view

Figure 45. *SLS printed parts*

The main parts of the system have also been printed. It is the structural part in which the gearbox is fixed and the spur gear that completes the train power system. Figure 46 shows such parts and the assembly of the gearbox.

Figure 46. *3D printed parts*

The prototype has proved the stiffness of the design and its ease assembling process. The analysis of the assembly points out the possibility of fixing the motor directly to the gearbox as a way to reduce the complexity of the system, however it would imply the need to release its wires any time the gearbox is extracted. This improvement opportunity must be studied further.

5. CONCLUSIONS

This thesis studies the mechanical design and analysis of an attitude control subsystem for an autonomous explorer submarine that will lead the pitch angle of an UAV. This system is able to vary the position of the center of gravity of a submarine respect of its center of buoyancy, so that the robot goes itself to the new equilibrium position. This attitude subsystem allows the control of the pitch angle at any moment and can be used along with any other attitude system to lead the movement of such vehicles.

The design has been undertaken through the CAD (Computer Aided Design) software SOLIDWORKS. All the parts that make up the system have been either modelled or got from its supplier, moreover the real 3D model of an existent UAV is used at every stage of design adding new requirements. The system is designed in such way, that its performance does not interfere with any other device while it uses some parts of the vehicle as own parts, for instance the oil container and the batteries.

MATLAB is used to simulate the behavior of the submarine and the pendulum system. This simulation uses accurate data from SOLIDWORKS and the specifications of the submarine used as based. However, the drag coefficient for rotation of the submarine is not available yet due to last changes in the shape of the submarine. A further research would be a study of such drag coefficient and add it to the simulations to improve its results. The obtained results show that the presented system is able to lead the pitch angle within the required time.

A prototype is built to check the main features of the system and ensure an iterative design process. The assembly process of the system has been also tested using this mock-up. The technology used has been mainly FDM (Fused Deposition Modeling) and SLS (Selective Laser Sintering).

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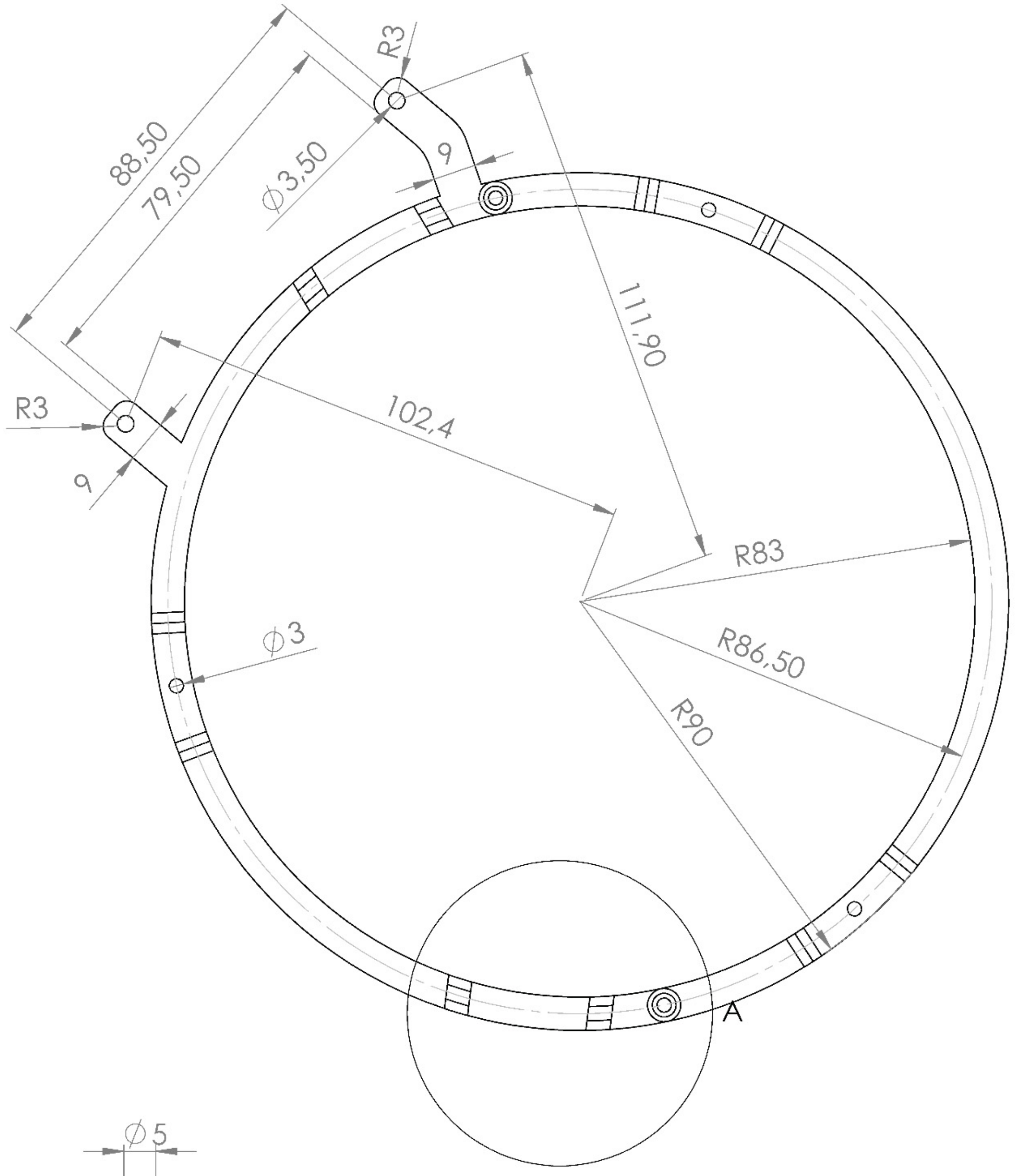
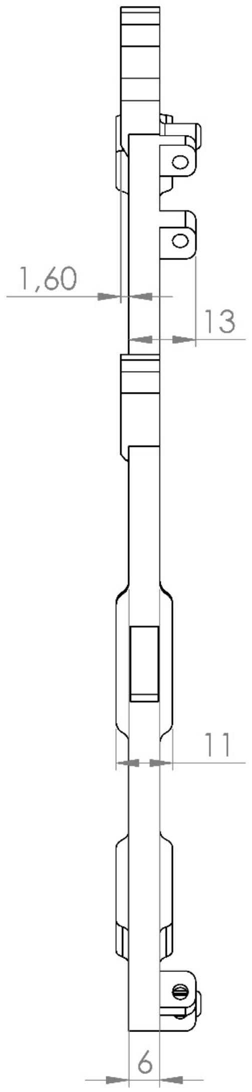
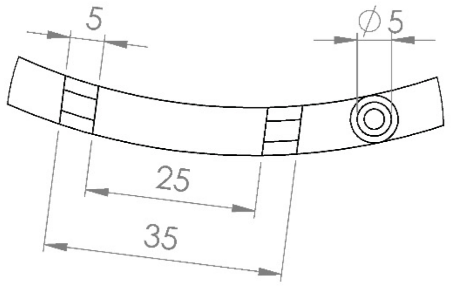
APPENDIX A: DRAWINGS







DETAIL A
SCALE 1 : 1

TAMPEREEN TEKNILLINEN YLIOPISTO
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	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

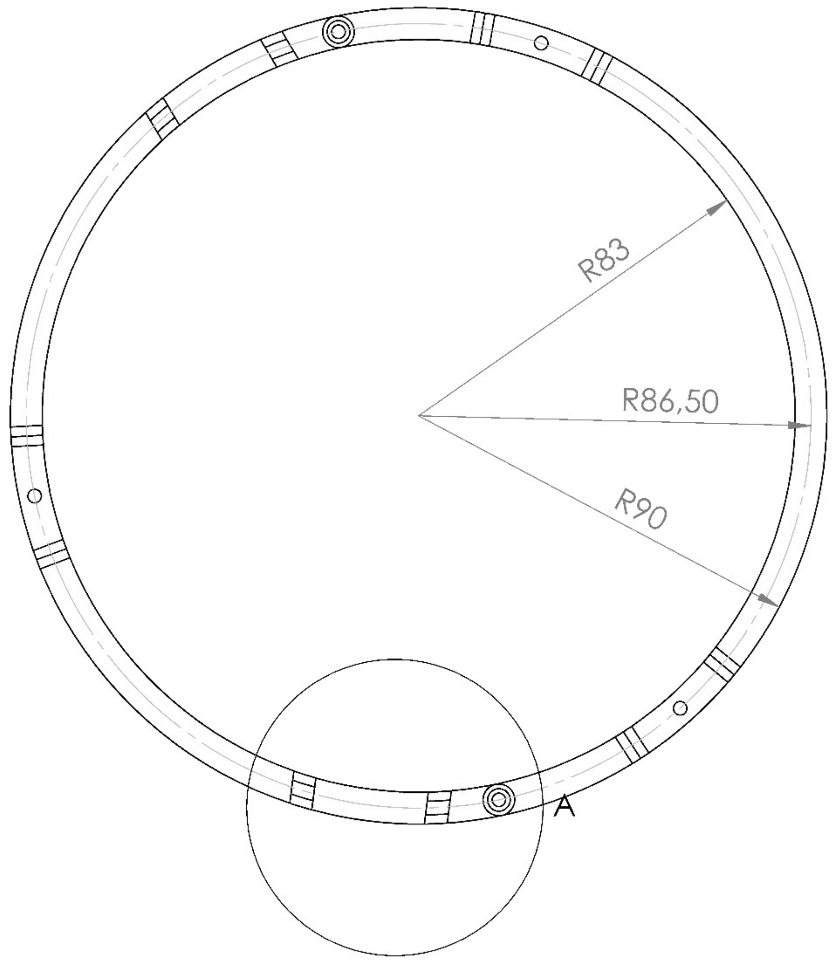
SIZE: A3
SHEET 1 OF 1
SCALE 2:3

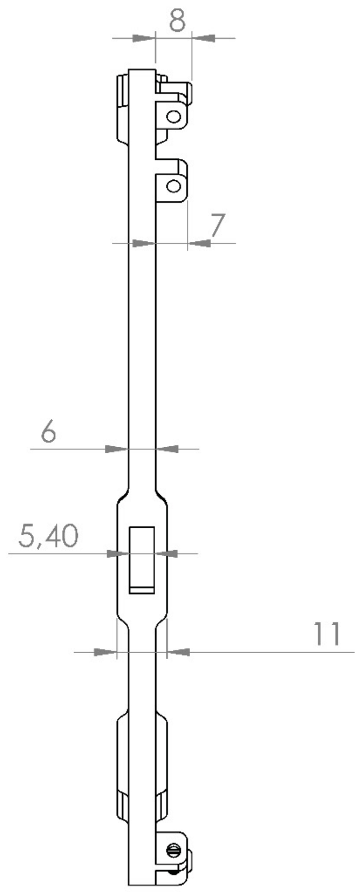
REVISION

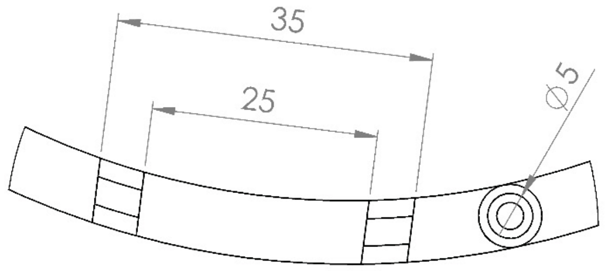
MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

DWG NO. PS_01_001

MATERIAL:







DETAIL A
SCALE 4 : 3

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TAMPERE UNIVERSITY OF TECHNOLOGY

REVISION

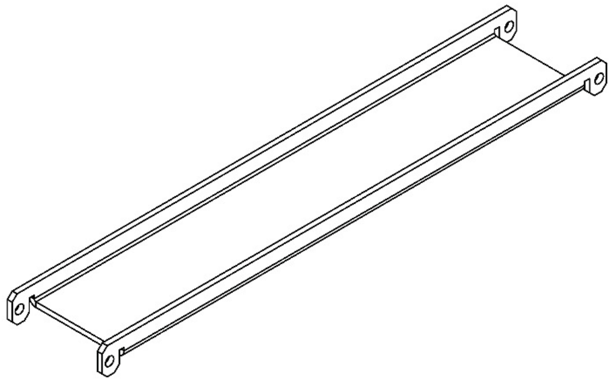
MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

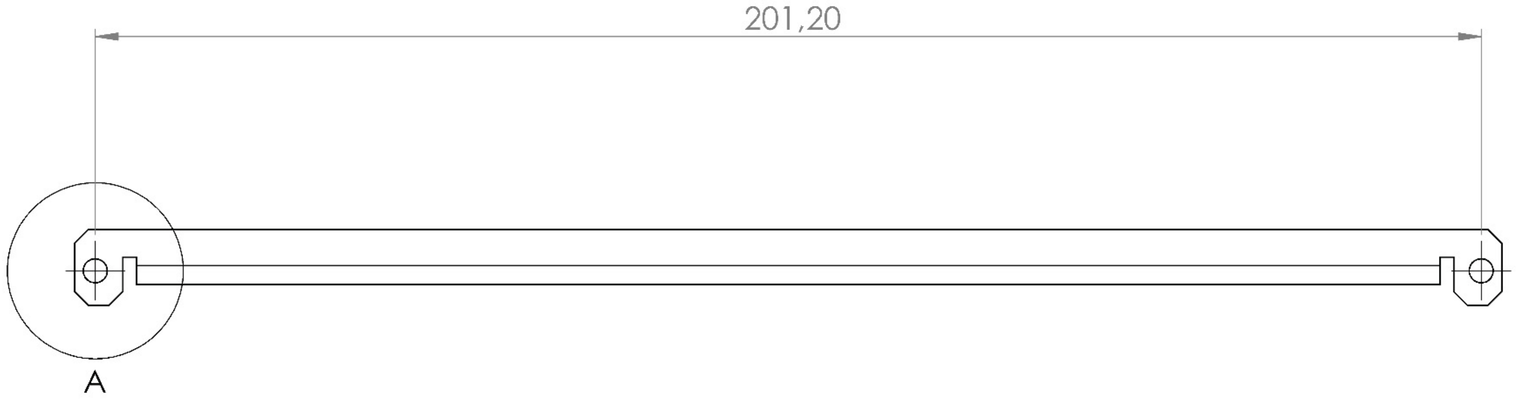
	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

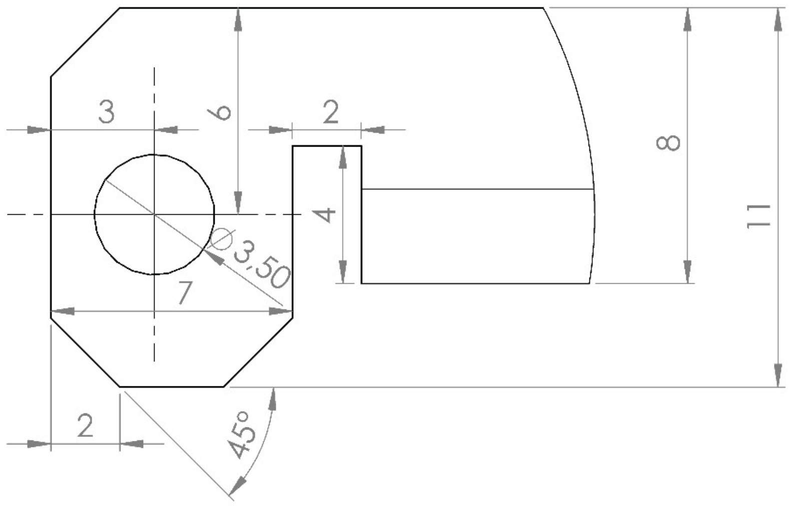
DWG NO. PS_01_002

SIZE: A3 | SHEET 1 OF 1 | SCALE 2:3

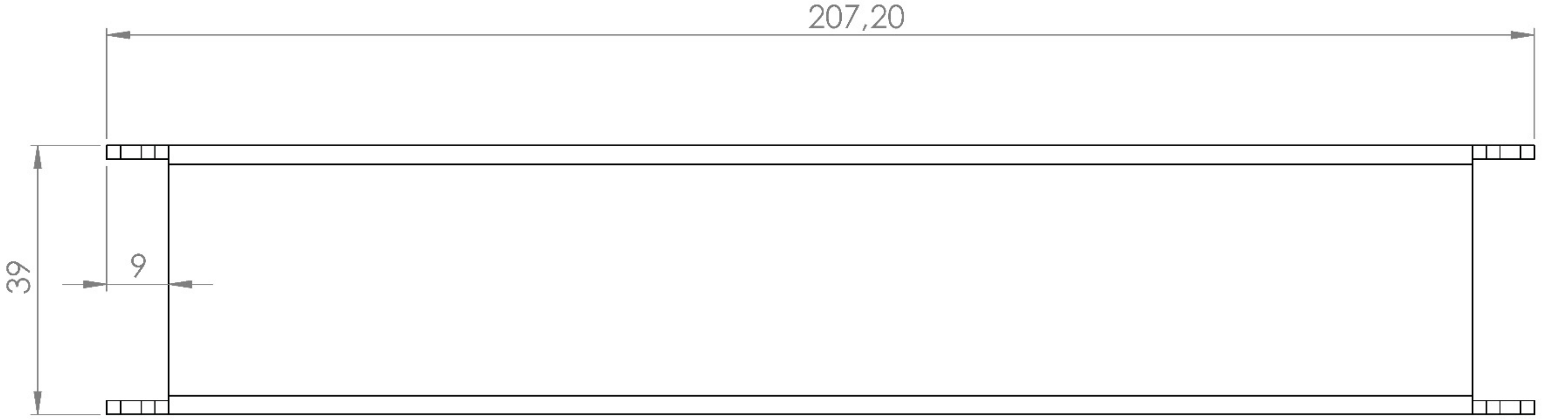
MATERIAL:





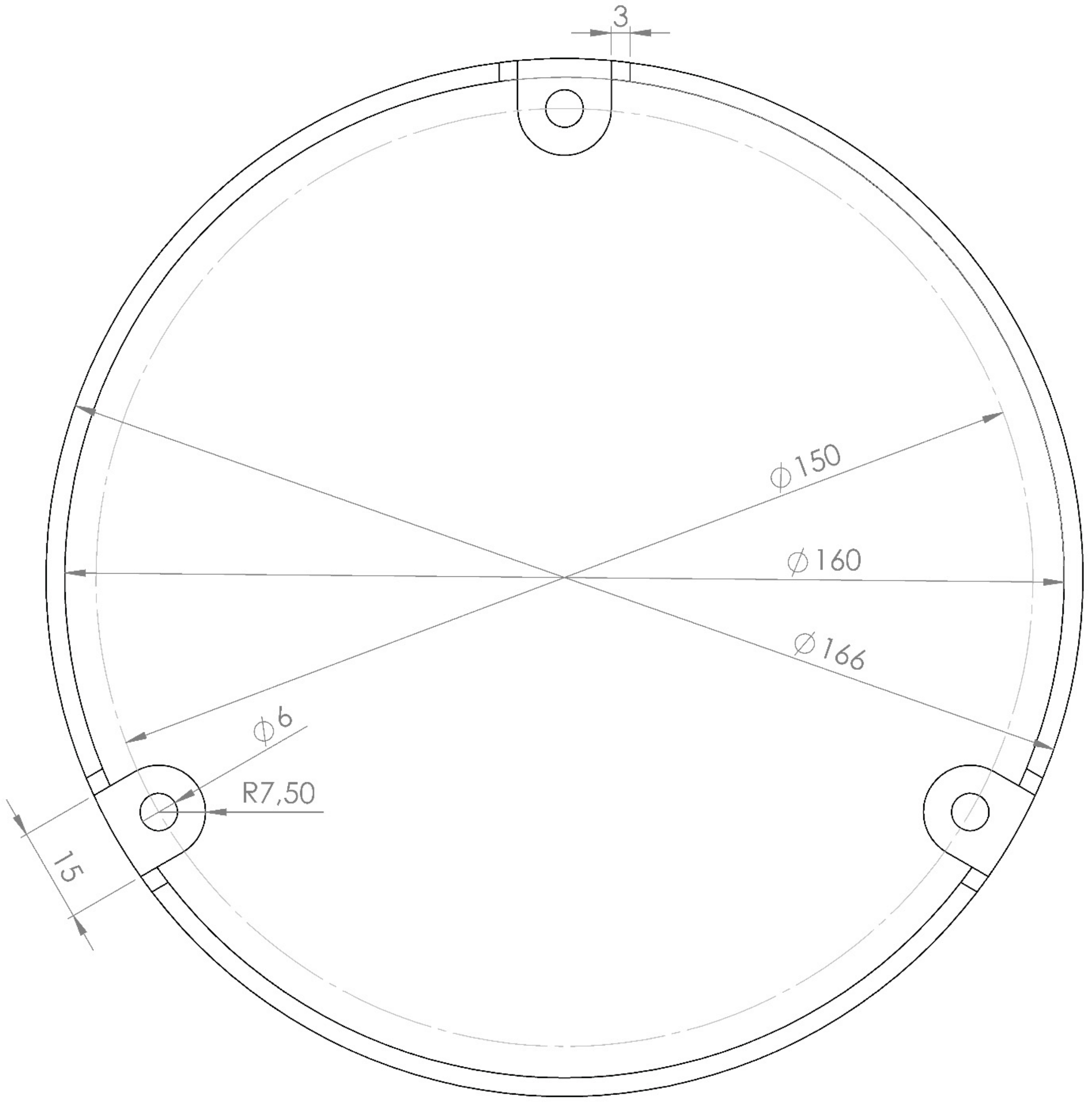


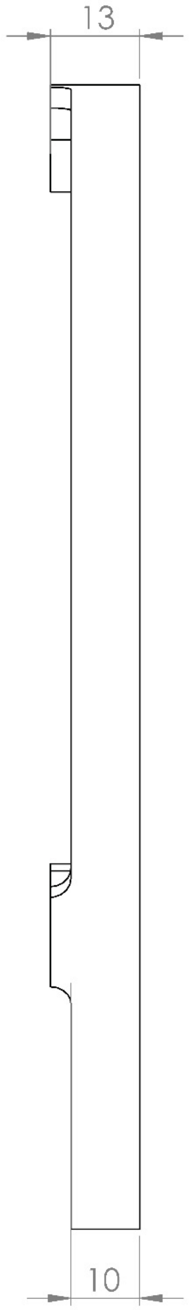
DETAIL A
SCALE 5 : 1



PS_01_004

TAMPEREEN TEKNILLINEN YLIOPISTO **TAMPERE UNIVERSITY OF TECHNOLOGY**			REVISION	
	NAME	DATE	MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE	
DESIGNED	PABLO ROMERO BERNAL	10.02.2017	DWG NO.	PS_01_004
DRAWN	PABLO ROMERO BERNAL	14.05.2017		
CHECKED				
SIZE: A3	SHEET 1 OF 1	SCALE 1:1	MATERIAL:	





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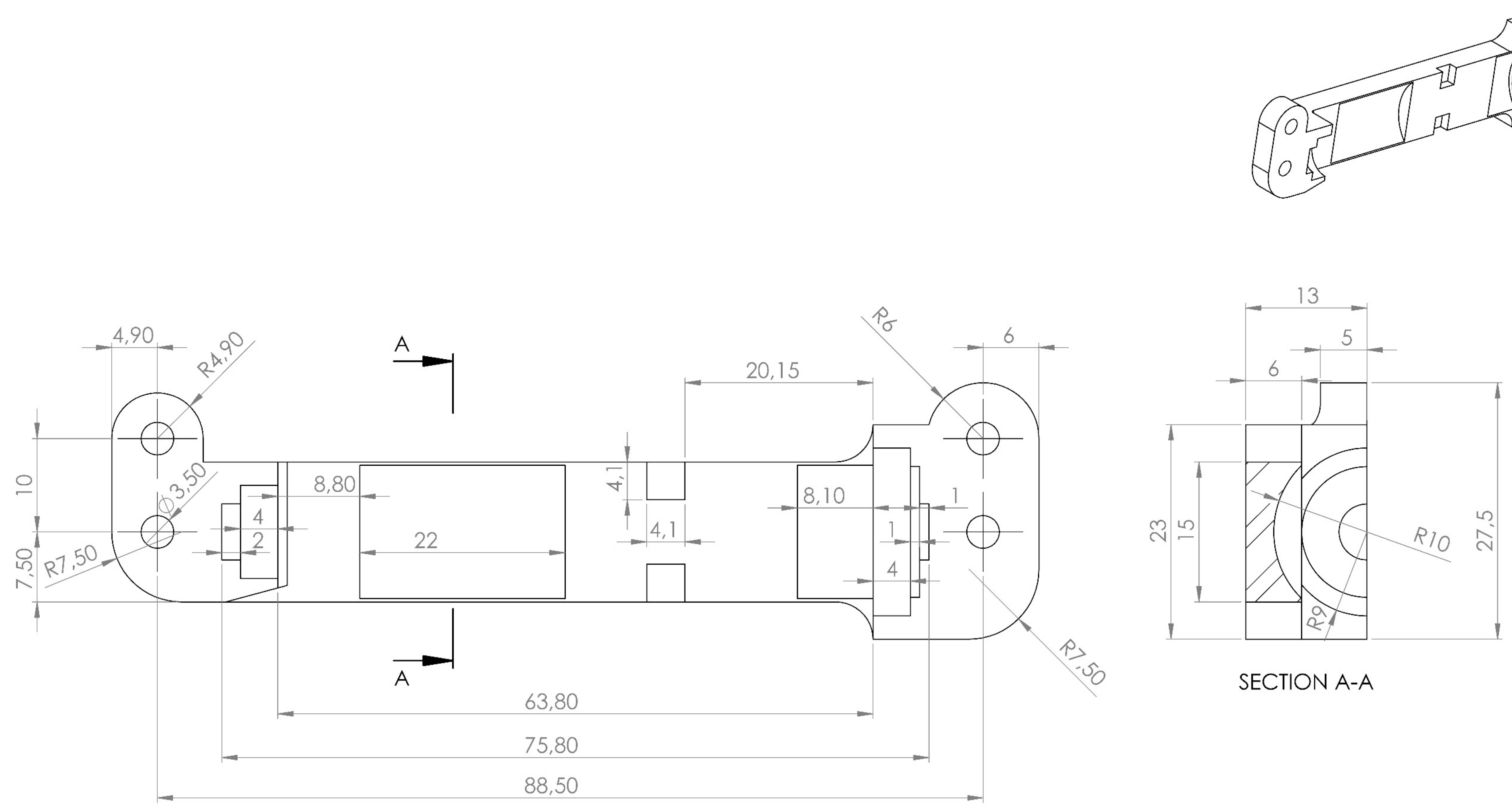
	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		
SIZE: A3	SHEET 1 OF 1	SCALE 1:1

REVISION

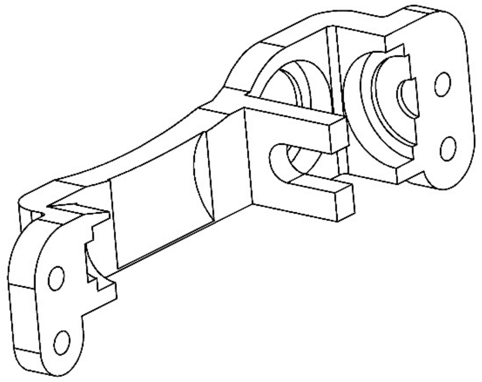
MECHANICAL DESIGN AND ANALYSIS
OF AN ATTITUDE CONTROL
SUBSYSTEM FOR PITCH ANGLE OF AN
AUTONOMOUS EXPLORER SUBMARINE

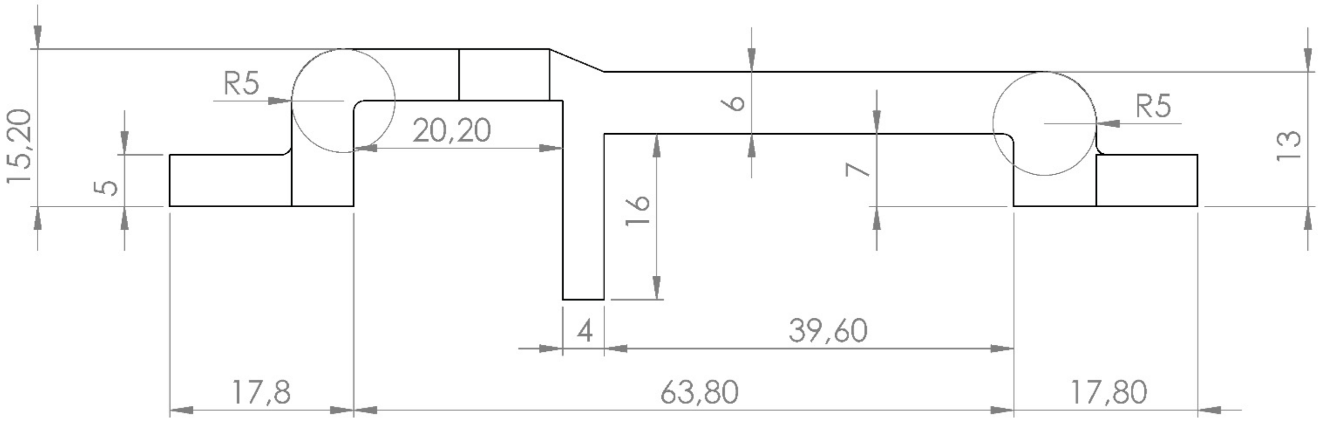
DWG NO. PS_01_005

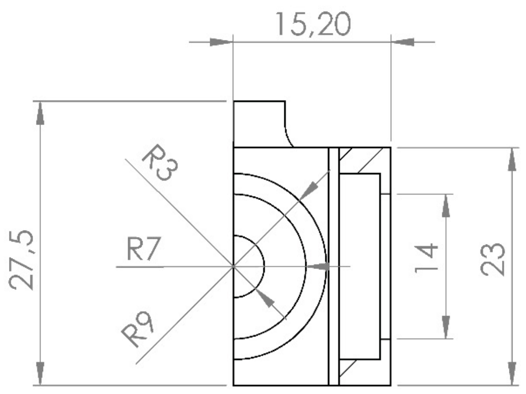
MATERIAL:



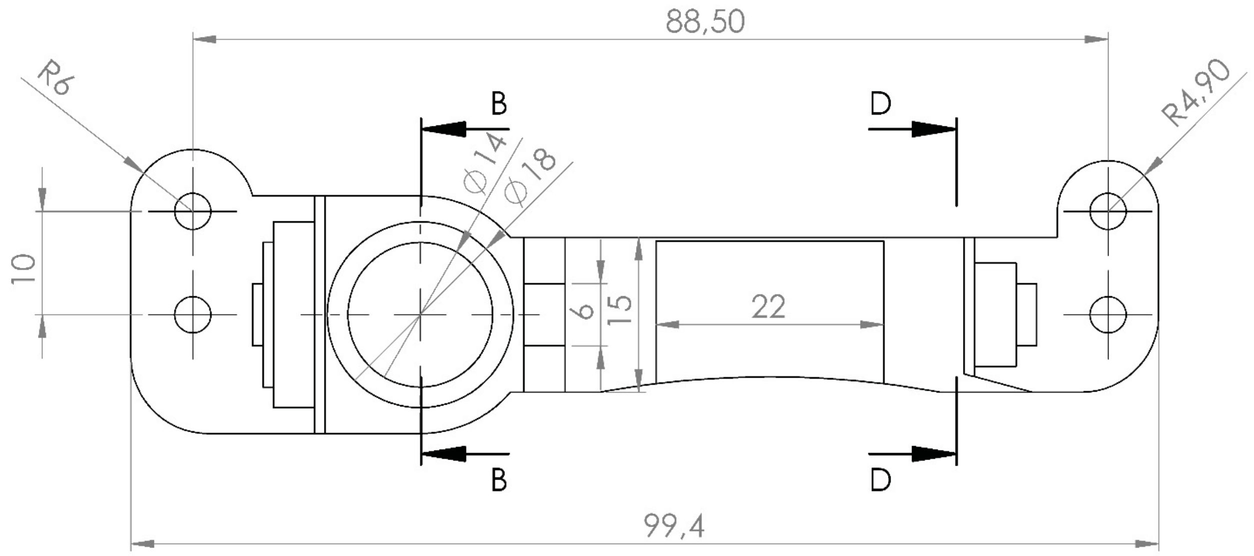
TAMPEREEN TEKNILLINEN YLIOPISTO **TAMPERE UNIVERSITY OF TECHNOLOGY**			REVISION
	NAME	DATE	MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017	
DRAWN	PABLO ROMERO BERNAL	14.05.2017	DWG NO. PS_02_001
CHECKED			
SIZE: A3	SHEET 1 OF 1	SCALE 2:1	MATERIAL:

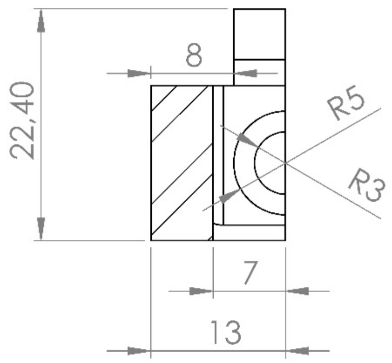






SECTION B-B





SECTION D-D

TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

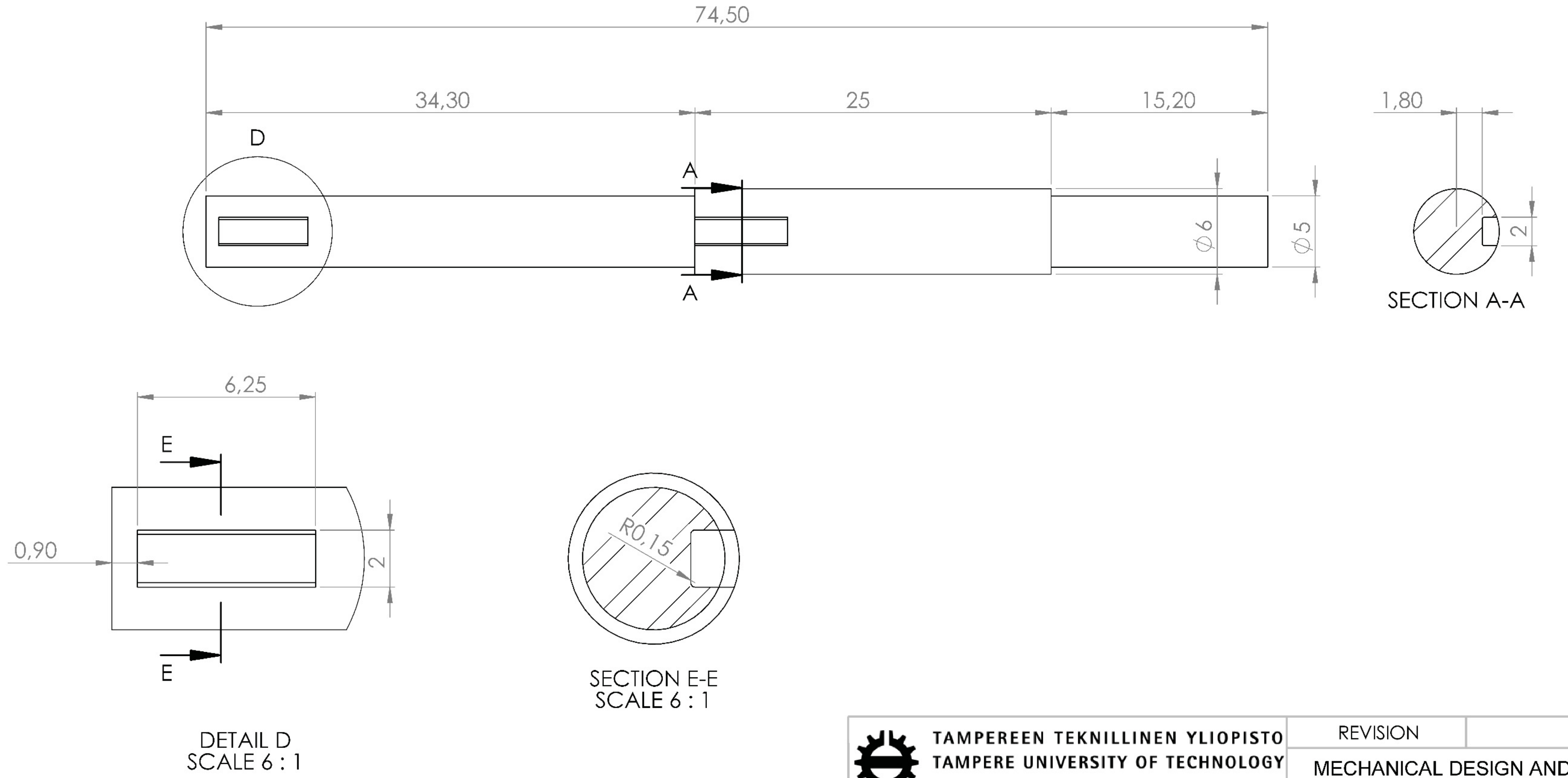
SIZE: A3	SHEET 1 OF 1	SCALE	3:2

REVISION

MECHANICAL DESIGN AND ANALYSIS
OF AN ATTITUDE CONTROL
SUBSYSTEM FOR PITCH ANGLE OF AN
AUTONOMOUS EXPLORER SUBMARINE

DWG NO. PS_02_002

MATERIAL:



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TAMPERE UNIVERSITY OF TECHNOLOGY

REVISION

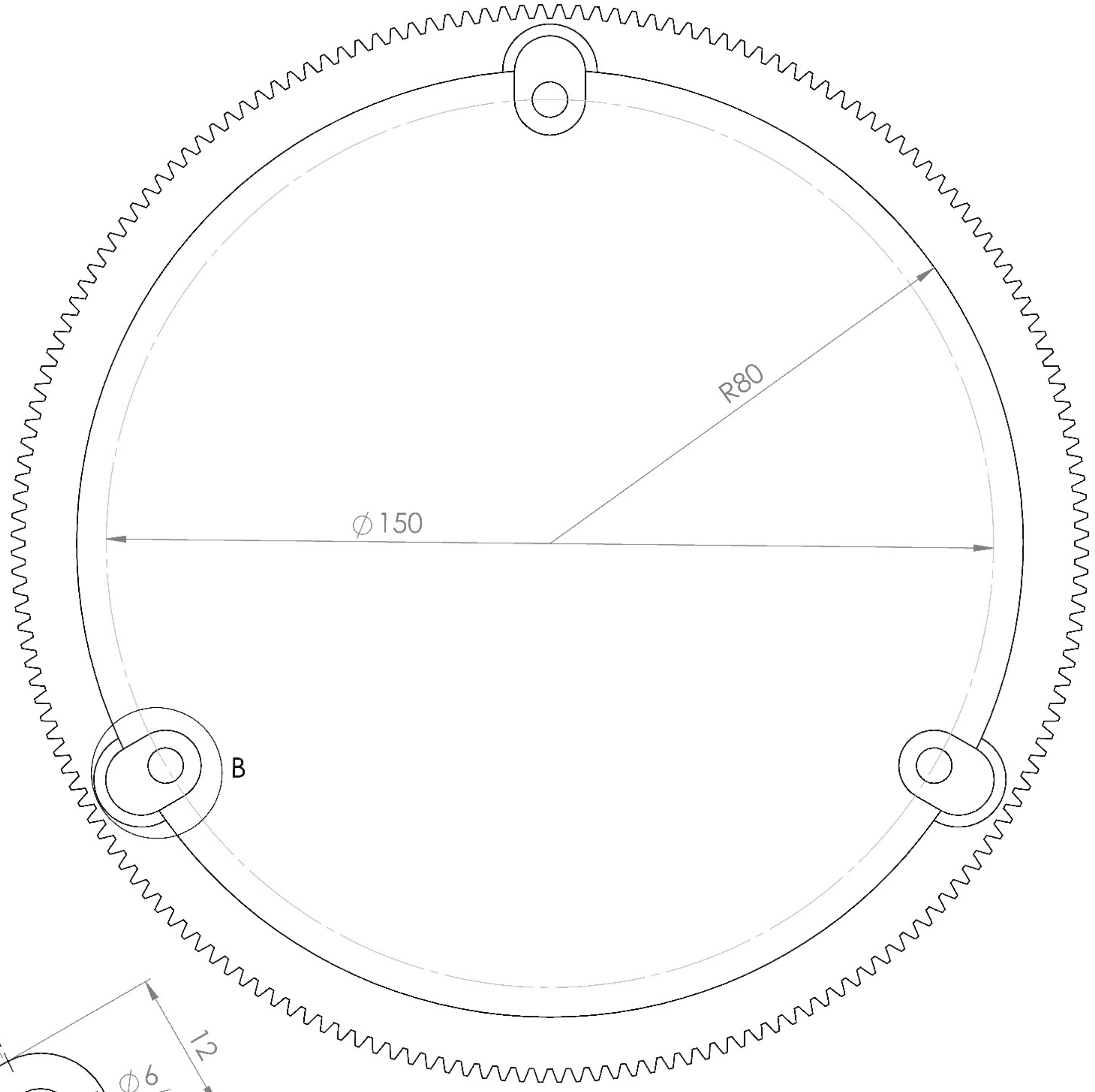
MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

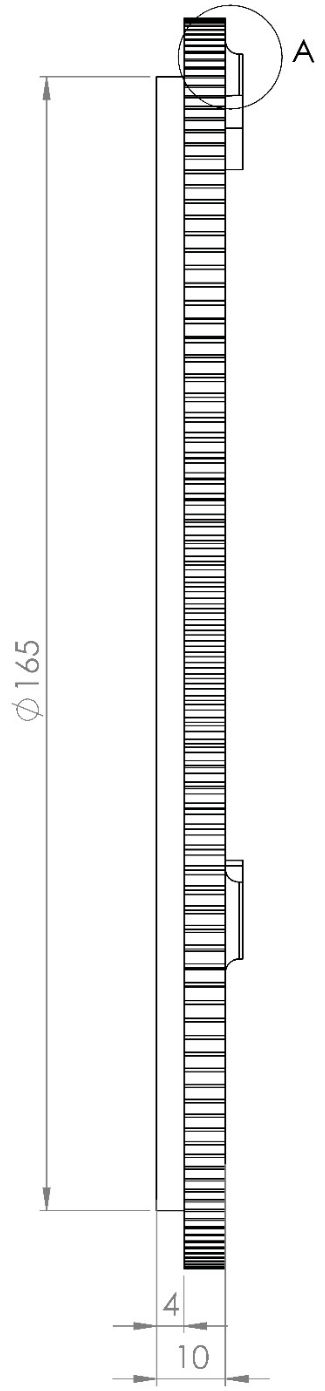
	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

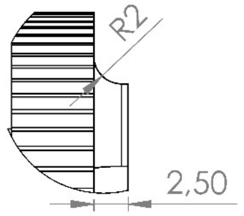
DWG NO. PS_02_003

SIZE: A3 | SHEET 1 OF 1 | SCALE 3:1

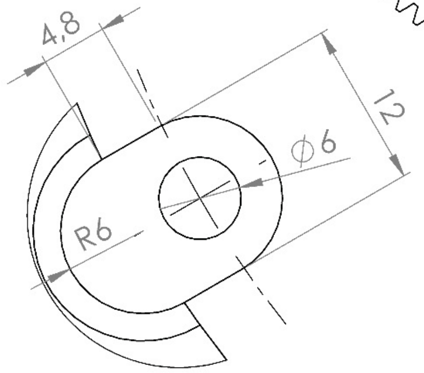
MATERIAL:







DETAIL A
SCALE 2 : 1



DETAIL B
SCALE 2 : 1

Spur gear dimensions:

- Module: 1
- N. Teeth: 180
- Nom. Diameter: 180 mm

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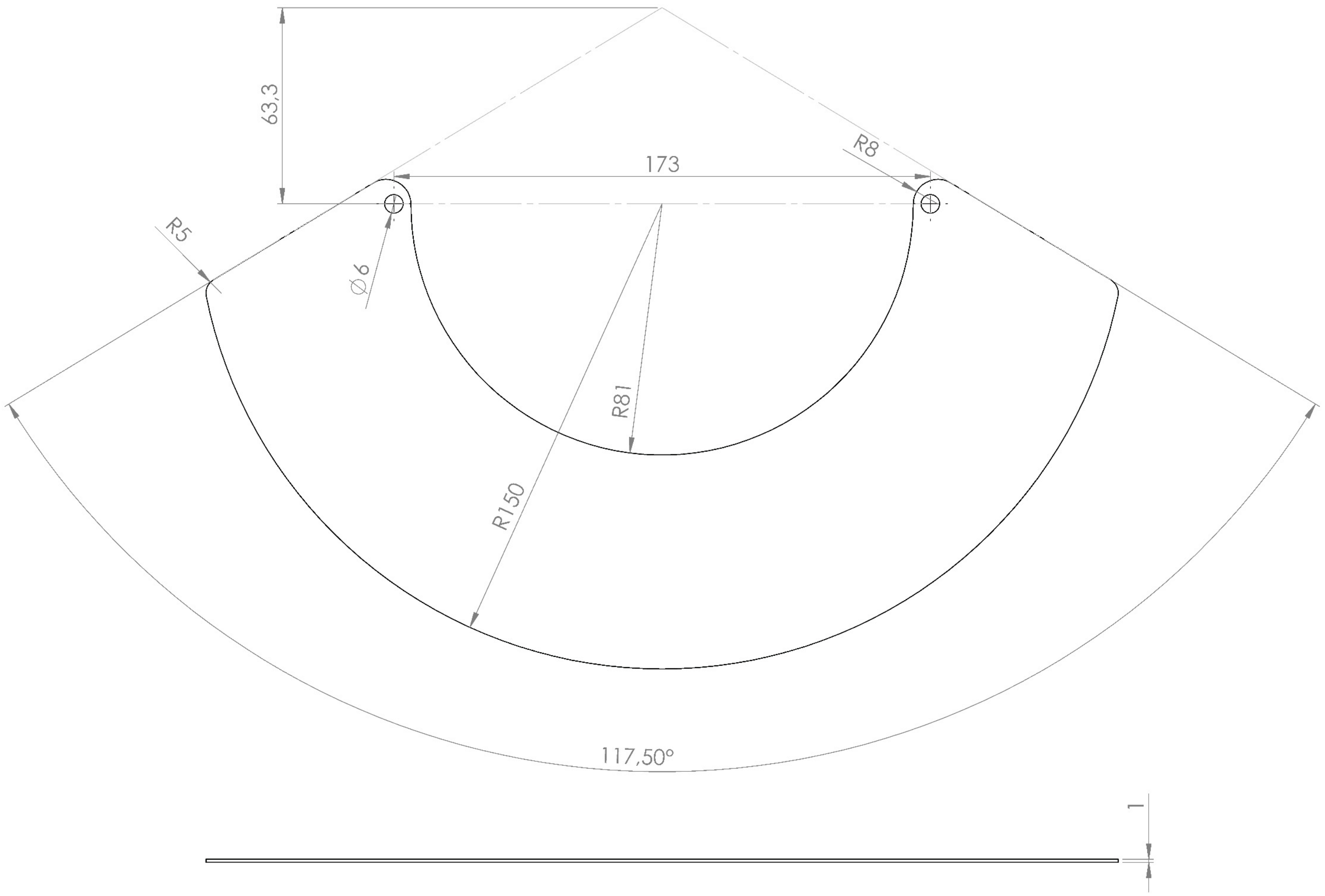
REVISION

MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

DWG NO. PS_02_006

SIZE: A3	SHEET 1 OF 1	SCALE	1:1	MATERIAL:



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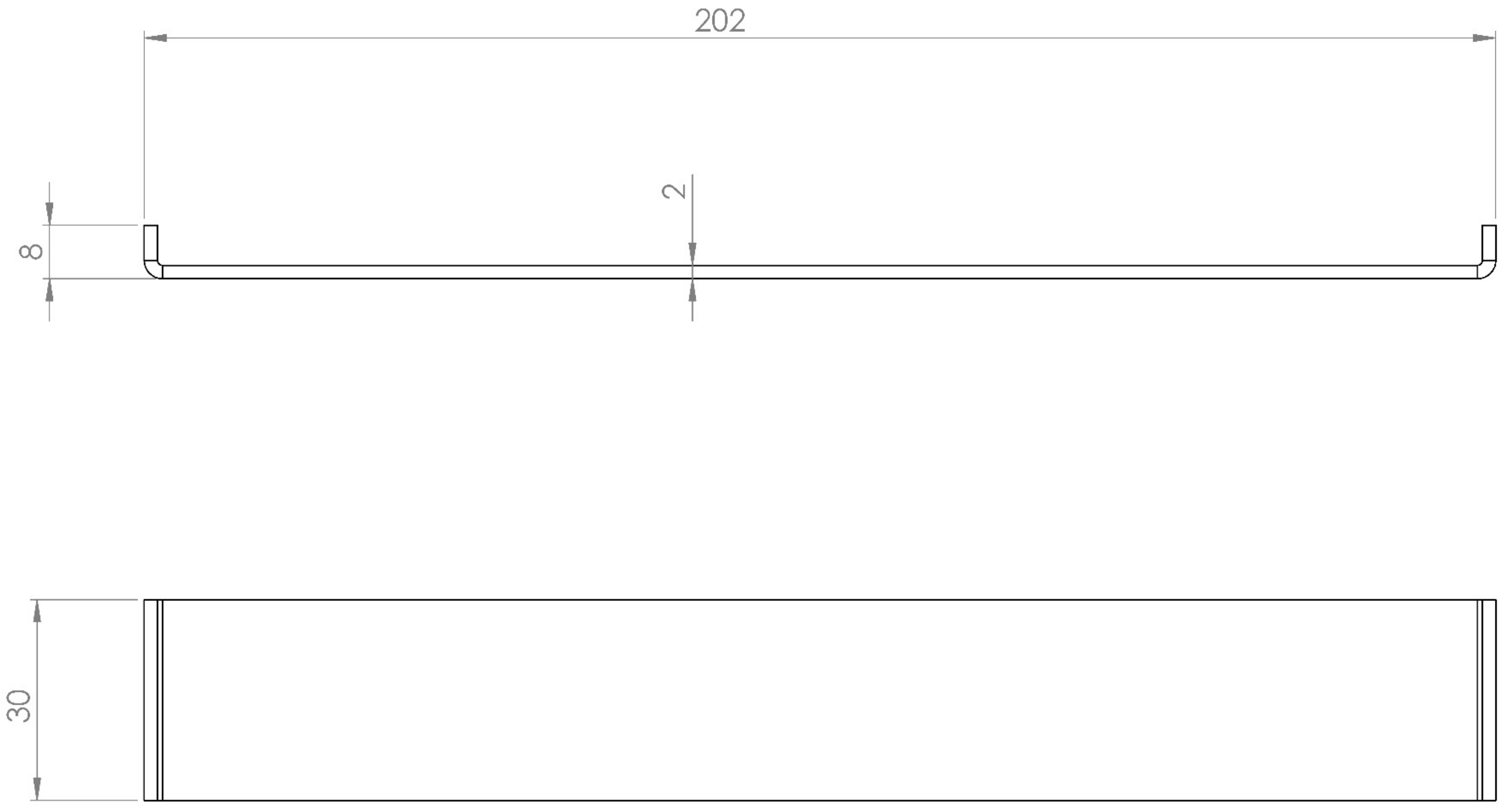
REVISION

MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

DWG NO. PS_03_001

SIZE: A3
SHEET 1 OF 1
SCALE 2:3
MATERIAL:



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TAMPERE UNIVERSITY OF TECHNOLOGY

	NAME	DATE
DESIGNED	PABLO ROMERO BERNAL	10.02.2017
DRAWN	PABLO ROMERO BERNAL	14.05.2017
CHECKED		

SIZE: A3
SHEET 1 OF 1
SCALE 1:1

REVISION

MECHANICAL DESIGN AND ANALYSIS OF AN ATTITUDE CONTROL SUBSYSTEM FOR PITCH ANGLE OF AN AUTONOMOUS EXPLORER SUBMARINE

DWG NO. PS_03_002

MATERIAL: