Norwegian University of Life Sciences
Faculty of Enviromental Science and Technology
Department of Mathematical Sciences and Technology

Master Thesis 2015
30 credits

Touch Screen and Switch Turning Tool for the DORIS Offshore Monitoring Robot

Øystein Olesen

Preface

This master thesis is the ending of my five year education at the Norwegian University of Life Sciences. I choose robotics after hearing about the exciting work many of my older students did the previous year, and decided I wanted to learn more about it. Despite the fascinating subject matter, there were some trepidations as I have no experience with robotics. However the prospect of working with robotics, mechanical design and the oil industry had me convinced, and in January I packed my bags and left for Brazil.

The following three weeks were highly educational. We were given a general introduction to robotics, as well as the opportunity to discuss our preliminary concepts with the students and teachers at the university. Back in Norway the work continued and different concepts for the parts of the tool were evaluated and picked. Finally parts were ordered, made in the workshop and 3D printed, and the assembly started. The final result is a tool which grips switches and turn, in addition it has touch screen capable edges. I hope the DORIS project finds a way to use my work and I am very thankful for them letting me work on such a big project and with the very talented people involved with it. In addition to the DORIS project I would like to thank CAPES-SIU for covering the traveling expenses to Brazil.

Back in Norway I would like to thank the guys at EIK ideverksted for helping me with the 3D printing of my components. And also the guys at the NMBU workshop for helping me with the remaining parts that had to be made. I would also like to thank my advisor Pål. J From for many constructive discussions, good ideas and invaluable feedback on my work. Finally yet importantly, I would like to thank my friends and family for supporting me through my five years of study and for helping me keep my motivation up during the writing of this master thesis.

Ås
15/5-2015

Øystein Olesen

Sammendrag

Denne masteroppgaven handler om designet av et verktøy til en offshore inspeksjonsrobot som skal kunne bruke touchskjermer og vri om brytere. DORIS prosjektet er et samarbeidsprosjekt mellom NMBU og UFRJ som er finansiert av Statoil og Petrobras. Prosjektets mål er å utvikle en skinnegående offshore inspeksjonsrobot som skal kunne erstatte mennesker i farlige arbeidsforhold, og kunne gi bedre, oftere og mer nøyaktig data om plattformens status. Prosjektet er nå i sitt tredje og siste år, med en fungerende prototype installert på Petrobras sitt testsenter som endelig mål. Om dette blir en suksess er det håp om finansiering til tre nye år, og da får roboten installert på en operativ plattform.

På grunn av det harde miljøet roboten skal jobbe i er det en del krav til roboten, disse inkluderer de oppgavene den skal gjøre, byggekvalitet, føyelighet/fjæring og kraft. Det er mange mulige designvalg og metoder tilgjengelig, og disse blir diskutert og evaluert for å finne den beste. Først ble det bestemt at den sjette og nødvendige frihetsgraden som trengs for å vri om en bryter skal bli inkludert i verktøyet. Videre har jeg valgt at touchskjerm verktøyet og bryter verktøyet skal kombineres til ett verktøy. Elektriske stepper motorer er valgt som kraftkilde, og rette, vinkel og innvendige tannhjul er valgt som kraftoverføringssystem. Når alle designvalg er gjort ble endelig design tegnet og en prototype av verktøyet blir laget med 3D printer og litt metallarbeid på verksted. Verktøyet blir testet og viser seg å fungere bra, men med noen problemer rundt mengden vridekraft verktøyet produserer mot den teoretiske verdien.

Oppsummert fungerer verktøyet bra, med for øyeblikket er det for tungt for robotarmen til DORIS da den bare har en kapasitet på 250g. Dette betyr at om verktøyet skal kunne tas i bruk må armen gjøres sterkere.

Abstract

This thesis covers the design of a touch screen and switch turning tool for the DORIS offshore monitoring robot. The DORIS project is a collaboration project between NMBU and UFRJ, financed by Statoil and Petrobras. The projects goal is to develop a rail guided offshore monitoring robot, which can replace humans in dangerous working conditions and supply better, more frequent and more accurate information on how a platform is operating. The project is currently in its third and last year, with a working prototype installed at the Petrobras testing facility as the final goal. If this is successful funding for a new three year period and the robot installed at an operational oil platform is the goal.

Because of the harsh working conditions there are many requirements to the tool, these include the functions, build quality, compliancy and power. There are a number of different design options and methods available, and these are discussed and evaluated in order to find the best option. First of it is decided that the 6th DoF needed to turn a switch will be incorporated in the tool. Further I have chosen to combine the touch screen and switch turning tool into one combined tool. Electric stepper motors are chosen as the power source, and spur, bevel and internal ring gears are chosen as the power transmission system. When all the design choices are made the final design is done and a prototype of the tool is made using a 3D printer and some metalwork in the workshop. The tool is tested and proves to function well, but with some trouble involving the amount of torque produced compared to the theoretical number.

Summarized the tool functions well, but at the moment it is too heavy for the DORIS manipulator arm which has a capacity of 250g. This means that in order for the tool to be useful the arm has to be made stronger.

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Abbreviations and symbols

BP	*British Petroleum*	**F_i**	*Force in direction i*
UFRJ	*Federal University of Rio de Janeiro*	**$\dot{x}$**	*Derivative of x*
NMBU	*Norwegian University of Life Sciences*	**k**	*Spring constant*
R$	*Brazilian reals*	**Δi**	*Change in variable i*
US$	*American dollars*	**T_i**	*Torque around rotational axis i*
NOK	*Norwegian kroners*	**DC**	*Direct Current*
DoF	*Degree of Freedom*	**z_i**	*Number of teeth in gear i*
kg	*Kilogram*	**NA**	*Not Available*
mm	*Millimeter*	**FEM**	*Finite Element Method*
cm	*Centimeter*	**τ_i**	*Torque around axis i*
UNK	*Unknown*	**Σ**	*Sum*
3D	*Three dimensional*	**σ**	*Stress*
g	*Gravitational pull*	**g_{ij}**	*Positional matrix from reference system i to j*
$\vec{i}$	*The vector i*	**R_i**	*Rotational matrix around axis i*
R_{ij}	*Rotational matrix from reference system i to j*	**p_{ij}**	*Positional vector from reference system i to j*

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Introduction

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Tool design and prototype

Discussion, conclusion and future work

Introduction

1. Background

Ever since the discovery of offshore oil and gas, huge investments towards getting these precious resources out of the ground and into homes, cars and industry across the world have been made, and the technological advances made have been extensive. The massive consumption has forced the petroleum industry to go further and deeper out to sea in order to discover new fields. Over 50% of Petrobras' oil production is today in the demanding pre salt layer [3]. This trend has led to the petroleum industry facing new problems and high productions costs caused by the remote and tough conditions. The petroleum industry however has to keep producing in order to stay profitable. This has led to a lot of money invested in new technology that will make the operation of remote oil fields cheaper, safer for humans, and more reliable. Many of the changes predicted by experts involve replacing humans with robots [4]. The idea of automating parts of the offshore operation gained a lot more followers and support after the 2010 BP disaster at the Deepwater Horizon oilrig, which caught fire and sank (figure 1.1). 11 people died and an enormous oil spill into the sensitive habitat surrounding the platform was the result [4] [5]. By making oil platforms more autonomous, many of the costs involved with transporting and housing people on remote platforms may be reduced. During 2014 the oil prices have dropped and the Norwegian Petroleum Directorate predicts that costs has to be cut in order to keep making money [6], cutting employees and introducing robots is one of the ways they predict this will be done.

Figure 1.1: Fire at the Deepwater Horizon, image courtesy of the American coast guard [7]

2. The DORIS project

The DORIS project is a collaboration between UFRJ, NMBU, Petrobras and Statoil. It is a three-year project currently in its final year, with the potential for another three-year expansion if the financial sponsors sees potential [8]. The goal after these three years is to have a working prototype installed at the Petrobras test center in Rio de Janeiro. The project has been funded by Statoil and Petrobras for a total of 3,2 million R$ which translates to roughly 8,2 million NOK.

2.1. *Motivation behind the project*

The motivation behind the project is to design an offshore monitoring robot that can replace humans in dangerous working conditions. In 2013 there were 348 reported incidents on the Norwegian continental shelf which caused the worker to require medical attention and/or miss one or more shifts [9]. It is desirable to get the workers out of the environment where these accidents happens. In addition to this, an offshore monitoring robot will be able to give more accurate feedback faster than humans, which means potential problems can be identified and fixed faster and production does not have to stop. On a non-autonomous platform there are many sensors placed around the platform that has to be inspected by workers to gather information about how the platform is running. These sensors have to be calibrated regularly, which means that workers continuously have to calibrate and adjust sensors. This leads to sensors not always being calibrated on time, and as different workers will never be able to do a job identically there will be some variations in the calibrations and the way a specific task is performed. This is often referred to as the human factor. When an offshore monitoring robot is introduced a lot of these smaller sensors can be replaced by a couple of high quality sensors attached to the robot. The human factor is minimized by not having workers do the data collection, and because the calibration can be done in a controlled environment by one or a few specially trained engineers. At last one cannot ignore the potential profit of reducing staffing on oil platforms. In 2014 the average wages for oil workers in Norway were close to 800 000 NOK, which puts the cost to the employer of one worker to over 1 000 000 NOK [10] [11]. If this number is multiplied by the number of oil workers that can be replaced across hundreds of active oil platforms, the numbers are substantial. Summarized there are three main goals Statoil and Petrobras wish to achieve by implementing DORIS at their platforms:

- Move workers out of dangerous working conditions
- Gather better and more frequent data on a platforms performance at a given time

- Increase profitability by reducing the number of workers and stops in production due to insufficient data on the platforms status.

3.2. Technical specifications

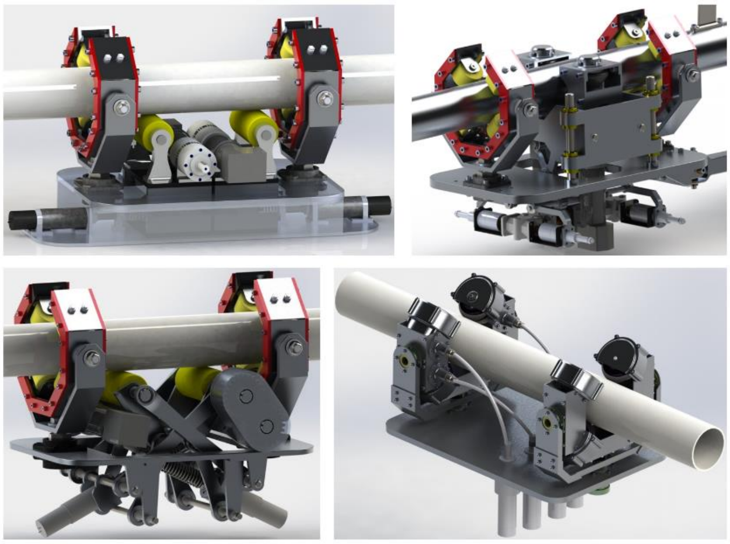


Figure 2.1: Previous versions of the DORIS traction module[1]

Since the start of the project, the design of the robot has gone through several different options before the final design was chosen. Figure 2.1 shows some of the earlier designs of the traction module. The final design consists of four modules: one active traction module, which provides propulsion, and three passive modules, which will contain the manipulator arm, batteries, sensors and control system. Seeing as the manipulator arm is the most important part of the robot for this thesis, I will focus on the arm in the technical descriptions. From figure 2.2 we can see that the manipulator arm is attached to the second module of the robot. The arm is attached to the underside of the robot to stop the manipulator arm from interfering with the wheels and the rail. The arm currently have four joints and a reach of 850 mm. More specifics on the arm in table 2.1. Initially the idea was for the arm to operate the camera, and not actually touch anything on the platform. After a while the vibration sensor was introduced, and after a new meeting between the project group and Petrobras in January 2015 the need for the robot to operate touch screens was identified. After a visit to the Petrobras testing facility later in January with our group of students from Norway, one of the engineers presented the need for the robot to turn switches.

Table 2.1: Specifications of the DORIS manipulator arm

DoF	4	
Weight [kg]	<4	
Arm length [mm]	850	
Payload [kg]	0,25	
Joint velocities [°/s]	360	
Height in rest position [mm]	125	

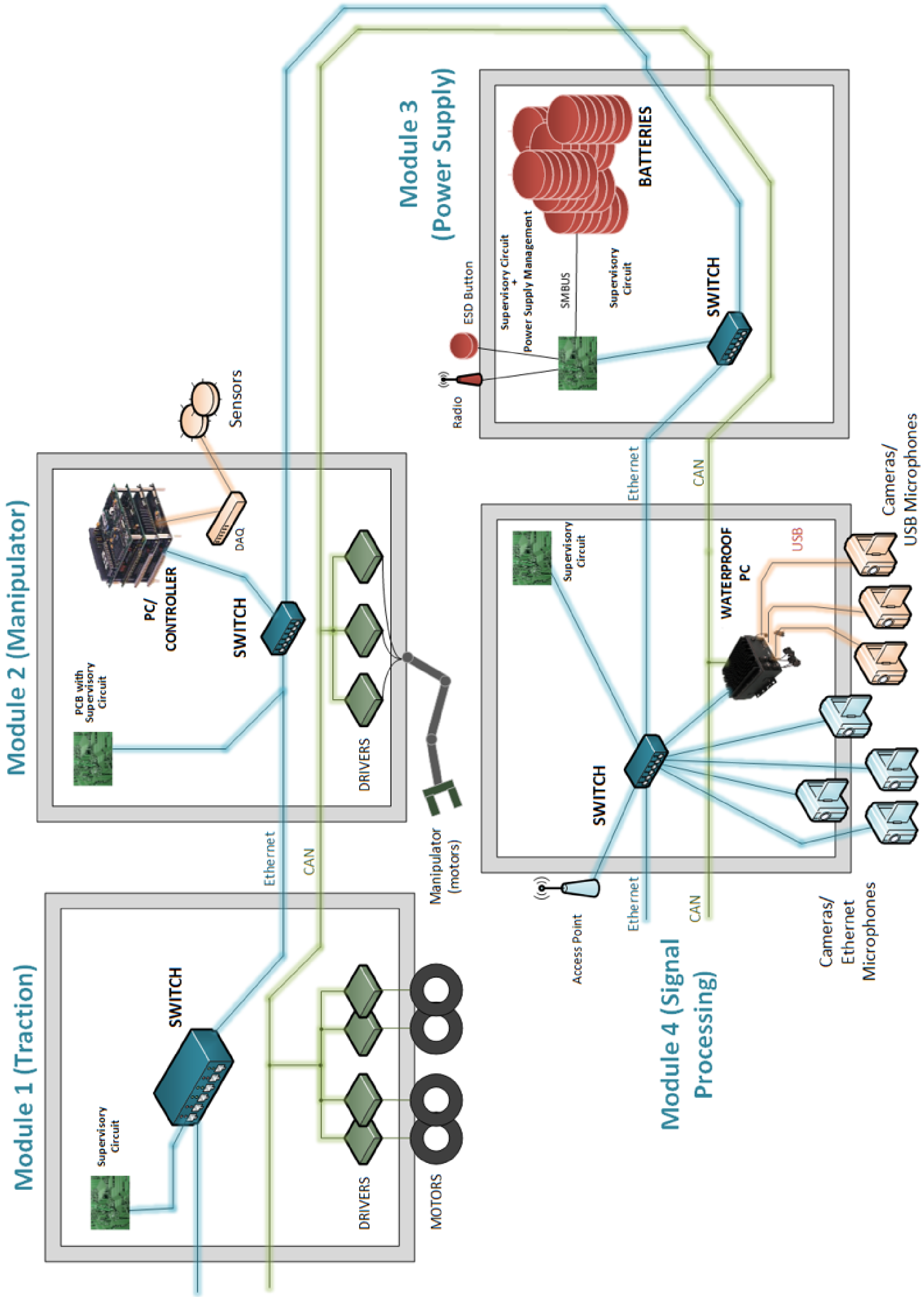


Figure 2.2: Overview of the modules in the DORIS robot [12]

3. Scope of this thesis

There is one main goal in this thesis:

- Design a tool making the robot able to operate touch screens and turn switches, and produce a working prototype of the tool.

In order to arrive at a working prototype a number of ideas and concepts for the different parts of the tool have to evaluated. The first and very important step is determining where and how a 6th DoF will be added to the arm. With that done the evaluation of tool designs and concepts can begin. These include in what configuration the tools will be attached to the arm, how the tool will be powered and how the power will be transmitted and issues regarding the compliancy of the arm. The results of all these evaluations will result in the building of a working prototype of the tool. Further the prototype will be tested and any potential points of improvement will be presented. Figure 3.1 show how the thesis is build up and what subjects are covered in each part.

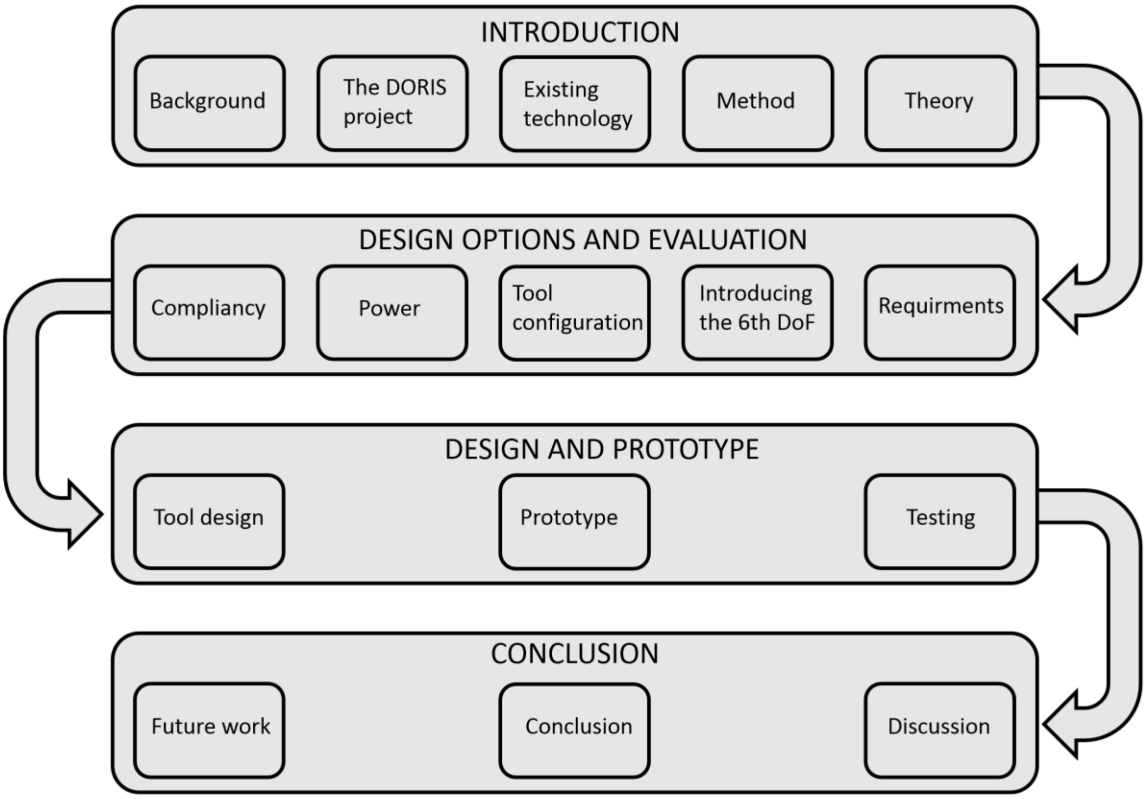


Figure 3.1: Overview of the different parts of the thesis

4. Existing Technology

Many companies work with the development of robotics for all sorts of applications, including but not limited to industry, offshore, surgery and the service industry. These robots can perform from one single task to a wide variety of different operations. These robots are placed in different categories dependent on their function and form, and following are some of the categories one would expect to be able to operate a touchscreen and turn a switch.

4.1. Humanoid robots

Seeing as touchscreens are made for use by humans, it is natural to look to the humanoid robots to find a robot that is able to use a touchscreen. Humanoid robots are robots that attempts to mimic human behavior, this may include walking, running, climbing, talking, dancing and lifting objects. Some of the most advanced humanoid robots available today are: ASIMO, ATLAS, HUBO-2 and ROMEO. Description of these robots in table 3.1.

Table 4.1: Specification of ASIMO [13], ATLAS [14], HUBO-2 [15] and ROMEO [15]

	ASIMO	ATLAS	HUBO-2	ROMEO
Figure				
DoF	57	28	40	37
Height [cm]	130	188	130	143
Weight [kg]	50	150	45	UNK
Price [US$]	2 500 000	UNK	400 000	330 000

The common feature of all these robots are that their main focus is copying larger motions like walking and climbing. They are often designed to do human jobs that are physically exhausting for humans to perform, and seeing as the use of a touchscreen is not considered exhausting to most people it's not a priority to give the robots these capabilities. For example the ATLAS robot is designed for emergency response to accidents like fires and collapsed buildings. It is without a doubt a very advanced robot which is capable of walking, climbing, lifting and navigating obstacles. However its hard metal exoskeleton is badly suited for delicate touch screens. This is a common denominator for all the humanoids; they all have exoskeletons which means they have hard plastic or metal surfaces which are not suitable for touch screens. Some humanoids do have more advanced hands or hand like grippers, either designed specially for the robot or commercially available. These hands can perform smaller and more delicate tasks, and are covered in the following chapter.

4.2. Robot hands

Even though the humanoids in most cases are not delicate enough, there are companies that specializes on the hand, and making robot hands that are as close to the real thing as possible. These hands often have all the joints you would find in a human hand and advanced touch sensors in the fingertips. The most noteworthy of the robot hands is the Shadowhand [16], it has 27 degrees of freedom, 5 fingers, and BioTac [17] sensors in each fingertip. The most important specifications of the Shadowhand can be seen in table 4.2. The sensors make the hand compliant, which means it adjusts the force needed to lift or move an object based on the objects weight and surface. This is important when using touch screens, as they’re often made from glass and too much force can crack or destroy the screens. The Shadowhand however meets a problem opposite of the humanoids; its fingertips are soft and made of silicone. This will make accuracy difficult, and silicone is not a conductive material. Which means the finger will not work on the most common kind of touchscreen, capacitive screens [18]. These highly advanced hands are also very expensive, with price tags reaching hundreds of thousands NOK. Using a hand this advanced would be a slight overkill, seeing as only one finger is necessary to operate the functions on the touch screens the robot will encounter on the platform. And only two finger are needed to grip and turn a switch.

Table 4.2: Specifications of the Shadow Robot hand [2]

DoF	27	
Weight [kg]	4,2	
Height [mm]	448	
Materials	Aluminium, brass, acetyl, polycarbonate, polyutherane flesh	
Features	Left/right hand, ROS capable, EtherCAT ports, Cyberglove integration	

4.3. Touchscreen testing robots

Figure 4.1: Some available robot arms: #1: DENSO [21], #2: Mitsubishi [22], #3: KUKA [23], #4: EPSON [24]

On today’s market, there is a large selection of robotic arms that can be programmed to perform a vast variety of functions, including operating a touchscreen. A selection of these arms can be seen in figure 4.1. SONY for example, uses an EPSON G3 SCARA robot arm to test the latency and accuracy of the touch screens on their mobile devices [19]. This is simply a robotic arm with a brass cylinder simulating a finger that is programmed to touch the screen in a given sequence. A slow motion camera films the sequence, and the film is examined to find the reaction time and accuracy of the screen. SONY is not alone in utilizing this technology and on YouTube there are many different robot arms with a stylus pen attached to the end using touchscreens. There is even an open source robot called tapster that can be 3D printed and assembled at home [20]. The founder says it’s aimed at app developers who wish to perform repetitive performance tests of their apps. The tapster can perform the same sequence of touches as many times as you wish. The one thing all of these arms have in common is that they all use some sort of stylus touch pen to operate the screen. Stylus pens are pens with a tip in a plastic material that have some conductive properties, which allows them use capacitive screens. These pens are cheap and easily accessible in electronics stores, and gives the user far better accuracy than when using a finger. The pens come in a variety of shapes and sizes, as seen in figure 4.2, and can easily be modified to fit most arms.

Figure 4.2: Various types of stylus pens

5. Theory

5.1. Robotics

Robotics and automation are today commonly known terms which most people associate with the replacement of humans by machines and robots. How these robots work and how they are controlled however, is far less common knowledge. In order to understand the problems faced in this thesis one must have a basic understanding of how robots move and orientate in space. The theory in the following subchapters is based on notes from lectures in the course introduction to robotics, held by Pål. J From, and the book "Vehicle Manipulator Systems" [25].

5.1.1. Rigid body and degrees of freedom

A Robot or the part of a manipulator arm one wants to find the location of, can be considered a rigid body. A rigid body is defined as three or more non-collinear points in space, and how this rigid body is able to move is of great importance. In figure 5.1 we can study these three points closer. Point 1 is simply placed in space with an x, y and z coordinate. Point 2 has to be a given distance away from point 1, but apart from that, it is free to move. From this we can see that point 2 can move in a sphere around point 1. Which means it rotates around two axes. Point 3 has to be a given distance from point 1 and 2, which means it is limited to rotating around one axis; the line between point 1 and 2. Summed up we have the following allowed movements:

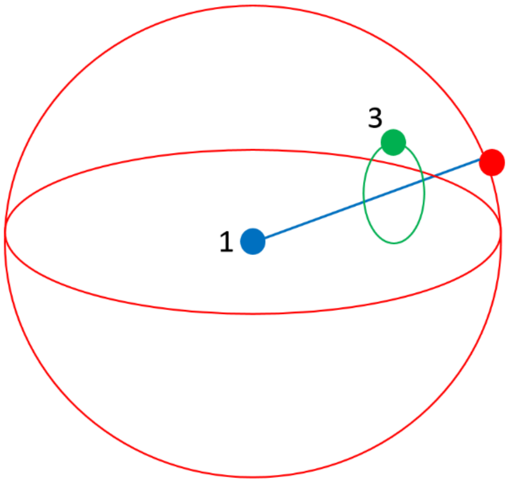


Figure 5.1: The three points and their range of motion in a rigid body.

- Point 1: placement in space with x, y and z coordinates, which gives 3 DoF.
- Point 2: rotation around two axis, which gives 2 DoF.
- Point 3: rotation around one axis, which gives 1 DoF.

Combining these 3 points, we get that a rigid body has a total of 6 degrees of freedom, three describing the position, and three describing the orientation.

5.1.2. Position in space

The next step is to describe the rigid body's position in space, to do this matrices are used. Matrix A shows the general shape of the matrix used to describe the position of a rigid body.

R_{oe} is the rotational matrix, and describes the rotation of the rigid body. p_{oe} is the positional vector, and describes the position of the rigid body.

$$A = \begin{bmatrix} R_{oe} & p_{oe} \\ 0 & 1 \end{bmatrix} \qquad p_{oe} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

The positional vector p_{oe} is fairly straight forward, it is a 3x1 matrix which describes each of three DoF x, y and z. The rotational matrix R_{oe} is a bit more advanced. There are three “basic” rotations, around each of the three axes x, y and z. These three rotations are described by the three matrices R_x, R_y and R_z. However the rotation can also be a result of combining the three “basis” rotational matrices, which results in 12 different possible rotational matrices.

$$R_z = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{bmatrix} \quad R_y = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix}$$

Hence the matrix describing all six DoF is 4x4 matrix, for example the matrix for a rigid body placed in space with a x, y, and z coordinate, and rotated around the z axis θ degrees, the matrix would look like this:

$$\begin{bmatrix} cos\theta & -sin\theta & 0 & x \\ sin\theta & cos\theta & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

5.1.3. Kinematics

Kinematics is the study of the movement of each link in a robotic system in order to determine the position, velocity and acceleration of the end effector. Using the simple two link arm from figure 5.2 as an example, kinematics aims to describe the position F_e in relation to F_0 using the rotation in the two joints q_1 and q_2. F_e is the local coordinate system of the end effector, and F_0 is the coordinate system of the base. q_1 and q_2 is the rotation in each joint given in degrees. To do this I will look at the position of each link in space, and multiply them to find their effect on the end effectors position. The matrices for the two individual links are as follows:

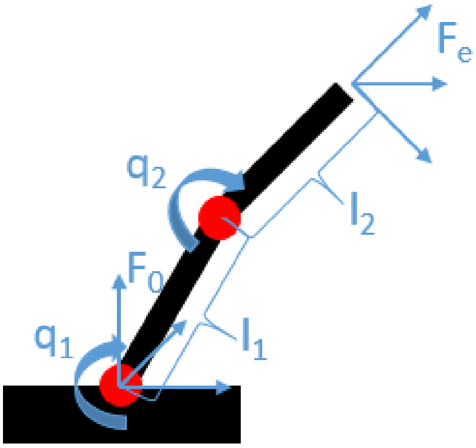


Figure 5.2: Two link robot arm, both joints rotate about y-axis

$$g_{01} = \begin{bmatrix} R_{01} & P_{01} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} cos\, q_1 & 0 & \sin\, q_1 & l_1 \times \sin\, q_1 \\ 0 & 1 & 0 & 0 \\ -\sin\, q_1 & 0 & \cos\, q_1 & l_1 \times \sin\, q_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$g_{12} = \begin{bmatrix} R_{12} & P_{12} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} cos\, q_2 & 0 & \sin\, q_2 & l_2 \times \sin\, q_2 \\ 0 & 1 & 0 & 0 \\ -\sin\, q_2 & 0 & \cos\, q_2 & l_2 \times \sin\, q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

When multiplying these two matrices I can find the position and orientation of the end effector in relation to the initial reference frame F_0.

$$g_{0e} = g_{01} \times g_{12} = \begin{bmatrix} cos(\, q_1 + q_2) & 0 & \sin(\, q_1 + q_2) & l_1 \times \sin\, q_1 + \, l_2 \times \sin(\, q_1 + q_2) \\ 0 & 1 & 0 & 0 \\ -\sin(\, q_1 + q_2) & 0 & \cos(\, q_1 + q_2) & l_1 \times \sin\, q_1 + \, l_2 \times \sin(\, q_1 + q_2) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This principle is the same for all robot arms, regardless of rotational direction and number of links. For a fully defined 6 DoF arm the position g_{0e} is found by multiplying the effect of the rotation in all the previous joints:

$$g_{0e} = g_{01} \times g_{12} \times g_{23} \times g_{34} \times g_{45} \times g_{56} \times g_{6e}$$

5.1.4. The Jacobian

The Jacobian is defined as the time derivative of the kinematic equations. If $x = f(q)$ the time derivate is $\dot{x} = \frac{\partial x}{\partial t}$, which can be rewritten on the following form:

$$\dot{x} = \frac{\partial x}{\partial t} = \frac{\partial x}{\partial q} \times \frac{\partial q}{\partial t} = \frac{\partial x}{\partial q} \times \dot{q} = J\dot{q} \;\; \rightarrow \;\; J = \frac{\partial x}{\partial q}$$

The Jacobian is used to relate the joint rates to the linear and angular velocity of the end effector, which means that by using the Jacobian, one can find the velocity of the end effector by knowing the angular or linear velocity of each individual joint.

In addition to this the Jacobian is used to identify singularities. When the determinant of the Jacobian is equal to zero, there is a singularity. Singularities are when a robot arm has redundant or collinear rotational axis, which means the number of joints does not match the number of DoF. Which means the arm can not move or rotate in a given direction. It is very important to be able to identify these configurations as they might prevent a manipulator arm from doing its intended job.

5.2. Mechanics

In addition to the robotics theory, some basic mechanic principles are used through out this master thesis. Following is a brief description of the principles used, all formulas and descriptions are from the book “Physics For Scientists and Engineers” [26].

Force:

Force is any interaction that causes or intends to cause a change in motion. The force on an object is found by Newtons second law, which states:

$$F = ma$$

F is the force, *m* is the mass and *a* is the acceleration. For a stationary object, the force it exerts on the ground when sitting still on a level surface is given by:

$$F = mg$$

Where g is the gravitation pull, which equals 9,81m/s^2.

Torque:

Torque is when a force causes or intends to cause a rotation around an axis. The amount of torque is determined by the force and the distance from the axis to where to force is applied. Mathematically torque is expressed as the cross product of the lever arm and force, the lever arm is the distance from the rotational axis to the point where the force is applied.

$$\tau = \vec{r} \times \vec{F}$$

Assuming the force is applied with a 90 degree angle on the lever arm, the expression can be simplified to:

$$\tau = rF$$

Where *r* is the length of the lever arm, and *F* is the force.

Static equations of equilibrium:

For an object in rest, the net forces acting on the object is equal to zero. This is important in statics because it allows us to use the three static equations of equilibrium:

$$\Sigma\tau = 0 \qquad \Sigma F_x = 0 \qquad \Sigma F_y = 0$$

These equations state that the sum of forces in the vertical and horizontal direction as well as the torque has to be equal to zero, if not the object would move. They allow us to find unknown forces by inserting all relevant forces into the equation and solve.

Hooke's law:

Hooke's law states:

$$F = -kx$$

It says that if a spring with spring constant *k* is pulled a distance *x* from resting position, a force *F* is needed. If the spring is compresses from resting state instead of being pulled, *x* becomes negative and the equation can be rewritten as:

$$F = kx$$

Von Mises stress criterion:

The Von Mises stress criterion is widely used in the analysis of ductile materials. It is especially useful in situations with irregular shapes and multiple forces acting on the object. Simplified the Von Mises stress is the maximum occurring stress in the material, and engineers use it by comparing the Von Mises stress to the strength of the material. If the yield strength of the material is higher than the Von Mises stress, the material is strong enough. The formula for the Von Mises stress is:

$$\sigma = \sqrt{\frac{\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2}{2} + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2\right)}$$

Note that in the above formula τ is the shear stress, and not the torque as in the other equations. Due to the complicity of the formula the Von Mises stress is often found by using computer programs like Solidworks, which analyses the entire part and identifies the point where the stress is highest.

Safety factor:

Safety factor is the difference between the yield strength and maximum occurring stress in a given part. It is given as a ratio between the two numbers:

$$SF = \frac{yield\ strength}{maximum\ occuring\ stress}$$

If the safety factor is >1 the material is strong enough and it will not brake. If the safety factor is <1 there is a risk of the material failing. All though the material is strong enough when SF>1, it is normal to have a safety factor which is at least 2-3. This is to take account for unforeseen events, inaccuracies in the calculations and irregularities in the materials.

Gear ratio:

Gear ratio is the ratio between two given gears. When gears have different sizes and number of teeth, the torque transmitted and the rotational speed changes. If the gear ratio is >1 the torque increases and the rotational speed decreases, and if the gear ratio is <1 it is the opposite. The gear ratio between two given gears is given by the following equation, which is taken from “Grunnlag i Drivverkteori” [27].

$$i = \frac{z_{out}}{z_{in}}$$

The torque transferred is given by the following equation:

$$\frac{\tau_{out}}{\tau_{in}} = i \times ɲ \quad \rightarrow \quad \tau_{out} = \tau_{in} \times i \times ɲ \quad or \quad \tau_{in} = \frac{\tau_{out}}{i \times ɲ}$$

In the above equations $ɲ$ is the gear efficiency constant. It is added to take account for a loss in torque due to friction, heat and noise production and other external factors. For steel gears $ɲ$ is usually >0,95.

6. Method

This master thesis is the result of various methods of data gathering and evaluation, as well as the design, building and testing of the prototype. This chapter describes the methods used during the writing of my thesis.

6.1. Data gathering

The first step of any master thesis is gathering information on the topic chosen. My data is based on three main sources: interviews, relevant literature, and material produced by the DORIS project group.

6.1.1. Interviews

The first month of my master thesis term was spent in Rio de Janeiro where I was fortunate enough to be able to talk to several people involved with the DORIS project, robotic hands, and robotics in general. Following is a brief description of the interviews I found most relevant and educational for my thesis.

- Mauricio Galassi – Project Leader for the DORIS project at Petrobras.
- Matheus Ferreira dos Reis – Robotics student at UFRJ, specializes in robot hands.
- Antônio Caladeia Leite – Professor at UFRJ,

6.1.2. Literature

The study of relevant literature is very important to gain an understanding of the concepts that lay the foundation of this master thesis. My literature studies include textbooks, catalogs, press releases, web pages and web forums.

6.1.3. DORIS project material

As DORIS is a project that is currently in its last of three years, it is natural that they have produced a substantial amount of data on the work that has been done this far. I have been fortunate enough to have access to a lot of this work. My main sources of data from the DORIS crew have been power point presentations and Solidworks models of the manipulator arm.

6.2. Data and concept evaluation

A big part of this thesis is evaluating the data and concepts gathered in order to determine which concept is best for the tool. I have decided to use two tools, which allow me to gain an overview of all relevant properties of a concept, and evaluate how a concept scores on a number of relevant criteria. The two tools I will be using are SWOT and PUGH analysis.

6.2.1. SWOT

The SWOT analysis appeared in the 1950's, it is an easy qualitative method which is generally applicable regardless of the problem [28]. SWOT stands for Strength, Weakness, Opportunity and Threat, and the analysis is basically a description of the truth within four different categories. The categories are split into the external and the internal, and the negative and positive. Table 6.1 shows the setup for the analysis. The SWOT analysis is a general tool, which is used early on in the evaluation face in order to gather and evaluate information.

Table 6.1: The setup for a SWOT

Strength (internal) -	Weakness (internal) -
Opportunity (external) -	Threat (external) -

6.2.2. PUGH

The PUGH analysis is used to pick the best out of a number of options, it was developed by Stuart Pugh, a professor at the University of Strathclyde in Glasgow [29]. The PUGH is useful towards the end of a decision making process as it gives a more concrete number on the value of each option against the chosen criteria. There are many different variations of the PUGH, I have chosen to give a score of 1 to 5 on each of the criteria, and weigh each criteria on a scale of 1 to 3. Each options weighed score is the score on a given criteria multiplied with the weight of that criteria. The option with the highest total weighed score is the best option according to the PUGH. Table 6.2 shows how the PUGH is set up.

Table 6.2: Setup for PUGH analysis

Criteria	**Weight**	**Option 1**		**Option 2**	
		Score	*Weighed score*	*Score*	*Weighed score*
Criteria 1	1-3	1-5	weight × score	1-5	weight × score
Criteria 2	1-3	1-5	weight × score	1-5	weight × score
SUM	-	-	Σ (weighed score)	-	Σ (weighed score)

6.3. Design

When the concepts are evaluated the design of the tool starts. I will be using Solidworks, which is a solid modelling CAD (computer aided design) program. Solidworks allows me to design all the components of the tool, and assemble them into a 3D representation of the finished tool.

In addition to the 3D designing which is the main function of Solidworks, I will be using two very useful add-ins; the toolbox and simulation.

The toolbox allows the user to create standard parts like gears, bolts, nuts and other basic machine parts. Each part can be modified to suit your needs by adjusting the length, threads, number of teeth, module, etc.

In simulation a part or assembly can be inserted into an environment and various forces can be added. This allows the user to test how a part will act in a simulated environment. One can for example add forces to a part and identify the size and position of the maximum occurring stress, which can be used to determine if a part is strong enough or not.

6.4. Prototype and testing

When building the prototype the main tool is a 3D printer, the 3D printer works by melting thin plastic filament, which is then applied to a flat surface through a nozzle. The part is built one layer at the time, from the 3D representation of the tool which is uploaded to the printer. In addition to the plastic parts some smaller parts will be made from metal in the NMBU workshop.

Since the testing of the tool will be a straight forward test of the functions and the tools strength, I will perform the tests by calculating a theoretical baseline based on the design choices made throughout the thesis. The actual strength of the tool will be measured and compared to the baseline in order to see how it performs.

Design options and evaluation

7. Requirements

In order to start the design of the new tool for the manipulator arm it is important to know what requirements there are to the tool. In addition to requirements to the actual functions, there are requirements to the build quality, compliancy and the power.

7.1. Functions

The objective of the tool this thesis aims to design is to make the robot able to operate touch screens, in addition we want the arm to be able to turn switches. Operating touch screens is a fairly straight forward, and only requires the ability to point and press. Turning switches is slightly more advanced as it requires moving parts and power.

7.1.1. Touch screens

Making the tool able to use touch screens, means we have to know what kind of screens the tool will be operating. The different kinds of touch screen technologies require different objects to operate. The most common screen; the capacitive, needs a conductive tip to operate, for example a human finger or a stylus pen. Resistive screens are often used in more industrial settings and can be operated by all objects, table 7.1 shows relevant properties of the different types of touch screen technology available today.

Table 7.1: Some properties of the different touch screen technologies available today [30]

	5-wire resisitive	**Capacitive**	**Projected capacitive**	**SAW**	**Infrared**
Needed to activate	Any object	Finger or capacitive stylus	Finger, capacitive stylus or surgical glove	Finger, gloves, soft/pliable stylus	Most objects
Sensitivity	Good	Very good	Very good	Very good	Best
Accuracy	Very good	Good	Best	Very good	Very good
Scratch resistance	Poor	Very good	Best	Best	Best

The screens on the oil platforms are mostly resistive today [8], but it is unknown how this will evolve in the future. Because of this, the most versatile choice is to make the tool capable with all kinds of touch screens from the start. From table 7.1 we know that for the tool to be able operate all kinds of touch screen technology the tip has to be conductive, like a finger or stylus.

Figure 7.1: Photo of one of the touch screens from the Petrobras test center.

The screens in the test center were Allen-Bradley Panelview plus 600 [31]. Its measurements are 115x86 mm, and it is in a plastic frame approximately 10 mm deep. The buttons on the screen are fairly large with a minimum size of 15x15 mm, the screen can be seen in figure 7.1. Based on this we know that the tip of the tool has to be conductive, and with a maximum diameter of 7 mm. 7 mm is chosen because it is half the width of the button, which leaves some room on both sides. In addition to this, it would be preferable to make it in a semi-soft material, more on this issue in chapter 7.3 on compliancy.

The amount of force that can be applied to the screen varies based on the screen, the Allen Bradley screens at the Petrobras testing facility has an operating force of 340g [32]. Implementing a safety factor to take account for measuring errors and variables in the screen, I will set the maximum force allowed when operating the screen to be 500g.

7.1.2. Turn switches

This function is slightly more advanced as it requires movement. The tool will have to gip the switch, and then turn it. The requirements to the gripping part is that it has to grip the switch with enough force to withstand the torque that arises when turning, without damaging the switch, and it has to be a material that provides sufficient friction between the gripper and the switch. To make sure the gripper does not damage the switch or the surroundings it would be preferable to have the touch area of the gripper in a semi-soft material similar to that in the touch tip, this would also help increase the friction. When the switch is securely gripped, the next step is to turn it. The robot has to be able to turn the switch a minimum of 90 degrees to both sides (left and right), and with enough torque to overcome the resistance of the switch itself. The torque needed to grasp and turn the switch will be covered in chapter 7.4.

7.2. Build quality

As the robot is going to operate in rough conditions the tool has to be tough and durable, this includes two important factors it has to fulfill. Those are that it has to be waterproof, and it has to be explosion safe.

7.2.1. Waterproof

Table 7.2: IP rating classes [33]

Level	Object size protected against	Effective against
0	Not protected	-
1	Dripping water	Dripping water(vertically falling drops) shall have no harmful effect.
2	Dripping water when tilted up to 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position.
3	Spraying water	Water falling as a spray at any angle up to 60°from the vertical shall have no harmful effect.
4	Splashing water	Water splashing against the enclosure from any direction shall have no harmful effect.
5	Water jets	Water projected by a nozzle(6,3mm) against the enclosure from any direction shall have no harmful effect.
6	Powerful water jets	Water projected in powerful jets (12,5mm nozzle) against the enclosure from any direction shall have no harmful effect.
7	Immersion up to 1 m	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time(up to 1m of submersion
8	Immersion beyond 1 m	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. Normally, this will mean the equipment is hermetically sealed. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects.

Knowing that the robot will operate in conditions where it is subject to dirt and splashing water, it is necessary for it to be waterproof. In addition to this the tool also has to be resistive to corrosion, this is because of the exposure to salt water and other contaminants. To what degree of waterproofness the tool must be designed will be decided based on the predicted exposure to water by using the IP (Ingress protection) water resistance rating system [34]. The different degrees of waterproofness is described in table 7.2. We know that the tool will not be submerged in water, so level 7 and 8 are unnecessary. However, the tool might be subjected to water jets during cleaning, and the rough conditions can easily be classified as more than splashing water. With these facts in mind it would be wise to make the tool water proof on level 6.

7.2.2. Explosion safe

When the words explosion safe are used, it does not mean that the tool has to withstand explosions. What it means is that all electrical components that could produce sparks or enough heat to ignite flammable gasses, have to be sufficiently isolated and sealed. In the event of a spark, it will never be in contact with the atmosphere, and there is no chance of the spark igniting any gasses present and causing an explosion. This is very important on oilrigs as the presence of flammable gasses in the atmosphere is a permanent concern. The standards and control of equipment used in hazardous areas are controlled by the *International electrotechnical commission system for certification to standards relating to equipment for use in explosive atmospheres*(IECEx) [35]. The level of safety/isolation required is determined by which zone the tool is operating in, IECEx divides hazardous areas into three zones, these zones are described in table 7.3:

Table 7.3: IECEx hazardous zones rating[36]

Zone	**Description**
0	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is present continuously, for long periods, or frequently.
1	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist can for occasionally in normal operation.
2	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is not likely to occur in normal operation but if it does occur, will persist for a short period only (usually no longer than 2 hours).

Looking at the descriptions, zone 0 can be ruled out, as an explosive atmosphere is not continuously present on an oilrig. The choice between zone 1 and 2 is harder to make, and due to this, the safest option is to go with zone 1. It is better to make the tool safe for use in zone 1, instead of only making the tool safe for use in zone 2 and risk it not being sufficiently isolated. Summarized the tool has to fulfill the standards set by the IECEx for a machine operating in a zone 1 environment.

7.2.3. Weight

Due to the limited payload capacity of the arm, there is a weight limit for the tool. From table 2.1 the payload is 250g, further I know from the Solidworks model of the arm that the combined weight of the camera and vibrations sensor is 200g, which means the total weight of the tool cannot be more than 50g.

7.3. Compliancy

Knowing that the robot is going to operate in areas where there are lots of delicate instruments and precise machinery, it is very important to know that robot will not damage any of the things it is going to meet; the robot has to be compliant. If the robot were to come in to contact with something it is not supposed to, or touch a screen or switch with too much force, the consequences could be severe. Seeing as the robot is going to be rail mounted at an offshore oil platform, there will be vibrations as well as some movement. Because the arm is fairly weak with a payload of 250g (table 2.1) it is important for it to retract if it comes into contact with something, this is to prevent the arm from breaking. Because of this in combination with the vibration and movement present at an oil platform, the arm needs a combination of passive and active suspension.

7.3.1. Passive suspension

Passive suspension is the most common kind of suspension, it involves a spring or other kind of material, which can be compressed and regain its original shape. The suspension in a car for example (given its not a modern car which has electronically aided suspension) is passive. The shock absorbers are always "on" and any force on them causes them to compress and absorb the force, after the force is applied the absorber returns to its original shape, and it is ready absorb the next force. The negative aspect of passive suspension is that there is only a given force F and distance Δl the suspension is able to absorb. For springs these limitations are set by the spring constant k, and the difference in length Δl from unloaded to compressed state. After these limits are passed the spring will no longer have any effect.

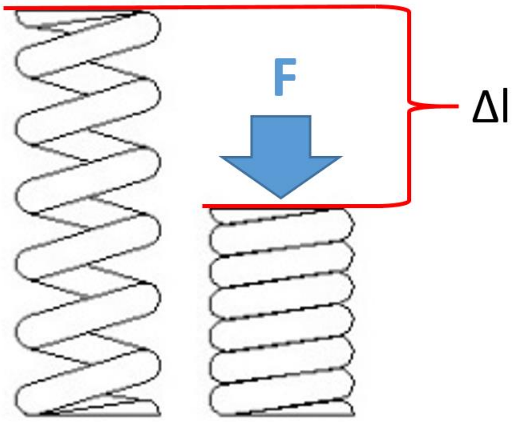


Figure 7.2: Properties of a passive spring

On an oil platform there will vibration due to the various kinds of running machinery, and on occasion outside factors like the weather may cause the rail or other objects to move. To make

DORIS able to do its tasks despite these factors it has to have a passive suspension system between the tool and the arm, which will absorb and eliminate these vibrations and movements. The passive suspension is limited as it is unable to absorb movement larger than the length of the spring. It is also limited to dealing with forces determined by the spring constant k. If the force is too big or small relative to the springs dimensions, it will either not compress or fully compress to fast and not absorb the force. Summarized the tool will need a passive suspension system with a spring dimensioned for vibrations and small movements.

7.3.2. Active suspension

Active suspension involves the manipulator arm measuring the force when touching objects and if it detects it is applying to much force it retracts the arm reducing the force on the object. This is a more complicated system as it involves sensing, signals and movement. However, the force the arm can absorb can be adjusted and the distance the arm can pull back to decrease the force can be adjusted to each individual situation.

There are several ways of measuring the force the tool is applying to an object, the two most common are to use a force sensor in the tool which directly measures the force between the tool and the object. The second way is to measure the resistance in the motors in each joint, if the resistance is increased the force on the arm is higher than it was. The difference in resistance is sent to a computer and a program converts the difference to the force on the end effector. In addition to the force measured at the end of the arm, I would recommend adding an IMU(inertial measuring unit) to the base of the arm. This unit will detect any unforeseen motion in the base and the software will compensate the movement by adjusting the position of the end of the arm. This way the end of the arm will stay still and make sure it does not bump into anything and break. This could be considered as a sort of “preventive” measure but I consider it important because it reduces the chance of the secondary system with the force detectors having to be used.

Because of the arms payload of 250 g it is important to incorporate an active suspension system to make sure that when the arm senses that the force on the end of the arm approaches 250 g, the arm can move in a direction that reduces the force and prevent damage to the arm.

7.3.3. Materials in touch tip and gripper

Compliancy is defined as the ability to conform with the surroundings. Softer materials like rubber which when pressed against a surface compresses to distribute the force evenly over the surface, can be considered compliant. For the parts of the tool which will be in contact with other objects it would be preferable to have the contacting areas in a softer material like rubber. There are a number of reasons to this:

- Softer materials generally have higher coefficients of friction meaning there is more friction between the material and the object it is contact with. This is an advantage when gripping the switch as it will reduce the chance of the tool slipping. It will also reduce the chance of the tool slipping when it its touching the screen.
- Softer materials will compress on impact reducing the force on the screen or switch, this will reduce the risk of the tool damaging the machines due to movement and vibration. A soft material in the gripper and touch tip will add to the effect of the passive suspension described in chapter 7.3.1.

7.4. Power

We know that the tool will have to perform two moving operations: the gripping of the switch, and the rotation. Both these operations needs power and in the following subchapters the amount of power required will be determined.

7.4.1. Rotation

This is the motion that will turn the switch after it has been gripped. To determine the torque needed one have to study the switches in question and measure the torque needed to turn them. This however is not doable in real life as the number of switches are considerable, and the torque needed to turn them can vary greatly based on what they control, cleanliness, age and corrosion. Therefore, I have determined to base my numbers on switches observed at the Petrobras testing facility and the NMBU workshop, and deduce a “worst case” number from my findings. Testing the switches and comparing them to a torque meter, I have found that the average force needed is approximately 1,5Nm. Due to the inaccuracy of the measurements and the dirty and corrosive environment the actual switches are in, I have decided to use a safety factor of 2, which sets this number to 3Nm (3000Nmm) for my calculations on power requirements. This means that the rotational joint in the tool will have to produce 3Nm of torque.

7.4.2. Gripper

Figure 7.3: example of switch

Knowing the maximum torque, we can calculate the force the gripper has to apply to the switch in order to withstand the torque when turning. Figure 7.3 shows a switch similar to the ones the robot will encounter at an oil platform. Based on the shape of the switch we can set up a sketch of the forces in action while turning. This sketch can be seen in figure 7.4. The resistance in the switch is represented by S, and the force applied by each of the two grippers to withstand the torque are represented by the forces F_A and F_C. Assuming the distance from the center where the torque works to the point of attack for the two forces are equal, we can say that $F_A = F_C = F$ for the following calculations. Further I will assume that the figure under represents the point right before the switch turns, meaning I can use the static equations of equilibrium. Which means that the force has to be slightly higher than the calculated force in order for the switch to turn. With these assumptions I get the following equation:

$$\Sigma\,\tau_B = -(F_A \times 30mm) + S - (F_C \times 30mm) = 0$$

Remembering that $F_A = F_C = F$ and $S = 3000Nmm$ we get:

$$2 \times (F \times 30mm) = 3000Nmm$$

$$F = \frac{3000Nmm}{60mm} = 50N$$

From the above equation we can see that the amount of force exerted by each gripper on the switch has to be >50N.

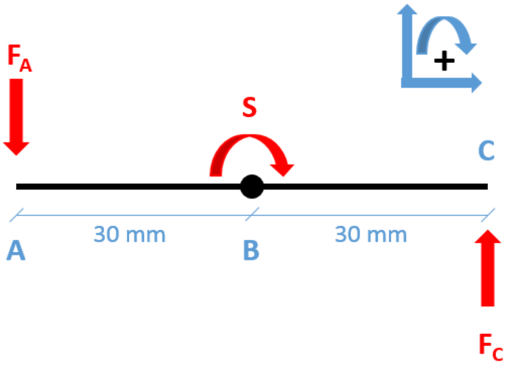


Figure 7.4: Forces acting on centerline of switch

8. Mobility/introduction of the 6th degree of freedom

Before starting the design of the actual tool, it is important to determine where the 6th DoF will be introduced. There are two main ways of doing this; adding a 5th joint to the arm itself, making the DORIS robot a fully maneuverable platform, which has the potential to perform different and more advanced task in the future. The second option is making the 6th DoF a part of the tool by adding the rotational movement to the tool itself, this is a cheaper and easier way to do it, however it limits the potential applications of the robot in the future.

8.1. The problem

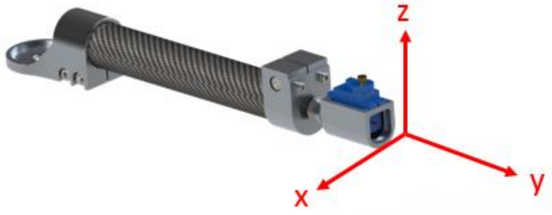


Figure 8.1: last link of DORIS arm with local coordinate system

The DORIS manipulator arm currently have four joints and the ability to move along the rail for a total of 5 DoF. From basic robot theory (chapter 5.1) we know that a manipulator arm needs 6 DoF to be fully maneuverable, three DoF to place the end effector in space, and three DoF to rotate the end effector around each of the 3 axes(x, y and z). The figure in table 2.1 shows the arm and the rotational direction of each joint, and one can easily see that to be able to turn a switch one has to be able to turn around an axis parallel to the last link of the arm, which is the y-axis in figure 8.1. This means that the 6th DoF has to be introduced in the last link and provide rotation around the y-axis from figure 8.1. Which rotational direction the last jont needs can also be proved mathematically by setting up the Jacobian for the arm, and then finding the determinant. In this case one would find that if the last joint rotated about the x- or z-axis, the determinant would be equal to zero, which means a singularity and an arm not able to perform certain movements.

The reason the arm at this point does not have this ability is because it was originally designed to operate the vibration sensor and camera only, which would not require that kind of rotation [8]. When adding the new tool this rotation becomes necessary because of several reasons:

- In order to turn a switch one must rotate around the y-axis.
- The arm will now have several tools attached to the end, which means it has to be able to rotate around the y-axis to select which tool to use.
- When the end effector becomes bigger in size, giving the arm all 6 DoF makes it easier for it to maneuver in tight areas.

8.2. Option 1 – introducing a 5th joint

Designing and implementing a new joint in the DORIS manipulator arm is the most long sighted option as it will make the manipulator arm a fully maneuverable platform, which can have other tools added in the future and still have full range of movement. This will make the arm able to perform different and more advanced tasks in the future without changing the arm, and it would allow for the use of commercial tools/end effectors. However the implementation of the new tool is a more complicated task as it would involve redesigning parts of the arm. The arm with its current design has been set in to production in Brazil and changing the design now would cause big financial and time consequences.

8.3. Option 2 – rotation in tool

Making the rotational movement needed to turn a switch a part of the tool, instead of changing the arm will involve less complicated engineering. However it will limit the future use of the DORIS manipulator arm as it will not be a fully maneuverable platform for future tools. The actual execution of adding the rotation to the tool is pretty straight forward; a small electromotor and a rotational joint has to be added, the motor can be controlled individually apart from the arm, making the control less complicated. However there are some potential issues that has to be kept in mind. Mostly it is important to make sure the rotational movement has enough torque to turn the switch without the tool becoming too heavy and/or big.

8.4. Evaluation and choice of solution

In order to evaluate the effect each option will have on the project, one must look at the potential in each option. What can the project gain from choosing one option over the other? To get an overview of the weak and strong aspects of both option I will start by doing a SWOT analysis.

Table 8.1: SWOT analysis of the two options for the introduction of 6th DoF

Strength		**Weakness**	
Option 1 Fully maneuverable platform	*Option 2* Easy construction Easily adjustable	*Option 1* Expensive and time consuming design process	*Option 2* Temporary solution, strength of joint limited by weight limit
Opportunity		**Threat**	
Option 1 Unlimited future use of the arm, commercial tools can be fitted without modification	*Option 2* Light weight arm suitable for inspections, 6th DoF can be added in tools if needed	*Option 1* Arm will become heavier, decreased battery capacity	*Option 2* Future tools may require extra design time/modifications

The SWOT analysis is a good first look at the different properties of each option, but in order to gain a better evaluation I will perform a PUGH analysis to get more concrete numbers on the perceived strength of each option.

Table 8.2: PUGH analysis of the two options for intrducing the 6th DoF

Criteria	**Weight**	**Option 1**		**Option 2**	
		Score	Weighed score	Score	Weighed score
Production cost	3	1	6	5	15
Production time	2	2	4	3	6
Complicity	2	1	2	4	8
Future use	3	5	15	2	6
SUM	**-**	**-**	**27**	**-**	**35**

From the weighed PUGH option two is the best option, this might come as a surprise due to some of the very apparent advantages of option one, like the future potential. But if we look at it from a more realistic point of view the decision makes more sense. Following are the reasons to why I will choose option two and incorporate the rotation in the tool.

- The production of the arm has already begun, and to change it now would not be doable in the timeframe set by the project with the goal of a working prototype by 2015.
- The effect of the rotation is the same, regardless of where and how the joint is placed, so at this point it is smart to choose the easier option to prove the concept. A more permanent solution can be considered in the next version of the arm if the project receives funding for a new three year period.
- By having both the rotation and gripping motion in the tool I can easily test the tool to see if it operates as expected as soon as its built. The rest of the arm is not needed to test the prototypes of the tool.

9. Tool configuration

The DORIS manipulator arm will with the new touchscreen and switch turning tools, have three tools that has to be attached to arm at once: the vibration sensor, the touch tool, and the switch turner. How these tools are attached and in what configuration has to be determined. The attachment of the tools could affect the mobility and functionality of the manipulator arm, and it is important to the function of the robot to find the best configuration.

9.1. *Configuration options*

From looking at similar robots and multi tool machines, there are four ways I consider to be potential tool configurations.

9.1.1. *Option 1 – 90 degrees between tools*

Having the tools mounted 90 degrees apart, as seen in figure 9.1, provides lots of room between the tool, which will ensure the inactive tools does not interfere with the one in use. However with this configuration there are challenges involved with making the desired tool usable. If the tools perpendicular to the axis of the last link in the arm is to be used, one would with the current design of the arm (table 2.1) have to use the last joint in the arm to choose which tool to use. This involves maneuvering the entire last link at an awkward angle in order to get the tool where you want it. This could cause problems like the arm colliding with the surroundings.

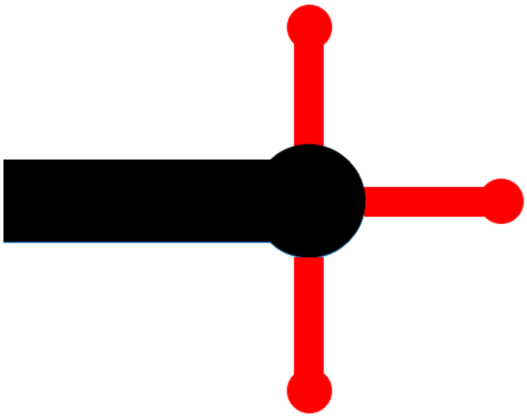


Figure 9.1: Tool configuration option 1

9.1.2. *Option 2 – 30-45 degrees between tools*

Mounting the tools closer together will make it easier to choose which tool to use as it requires less movement in the last joint as described in option 1. However when we reduce the distance between the tools, it will increase the possibility of the inactive tools colliding with the surroundings, which is undesirable. One could also modify this option by arranging the tools in a tripod pattern instead of the 2 dimensional

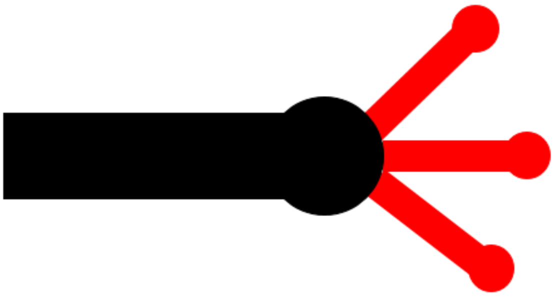


Figure 9.2: Tool configuration option 2

configuration in figure 9.2. This would not affect the choice of tools, but it could make the chance of the inactive tools colliding with the surroundings smaller.

9.1.3. Option 3 – exchangeable tools

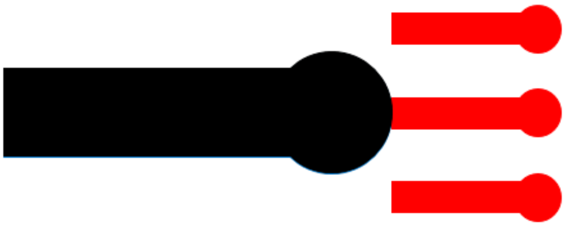


Figure 9.3: Tool configuration option 3

Using exchangeable tools will eliminate the problems involved with using the last joint to choose tool. Only one tool is attached to the arm at the time, and one changes the tool attached to perform different tasks. This will give the arm optimal maneuverability and there is no chance of the other tools interfering with the surroundings as they are stored apart from the arm. However there are some problems involved with this system: if one chooses to have the spare tools stored at a “pitstop”, it could involve a lot of driving back and forth on the rails to retrieve tools. On a full size oilrig the rails can become very long, and it would take a lot of time and battery capacity to change tools. If one chooses to have the other tools with the robot in one of the modules, one would have to design a system that allows DORIS to change between tools by itself, this system requires a degree of exposed moving parts, that after time will become dirty, which might stop the system from working. In addition to this, the weight of the additional tools and tool change system has to be pulled around by the DORIS traction module, this will affect the battery capacity of the robot, and in a worst case scenario it would require the motors in the traction module to be changed in order to pull the extra weight.

9.1.4. Option 4 - combined touchscreen and switch turning tool

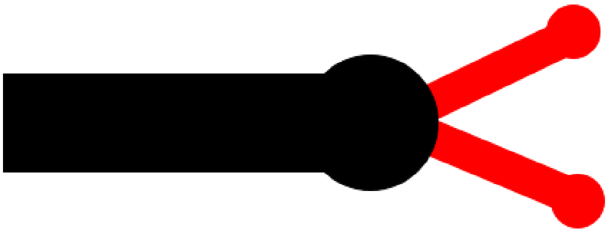


Figure 9.4: Tool configuration option 4

Combining the touch and switch turning tool could make the configuration and attachment the to the arm easier, given that a design combining the two is possible. From chapter 7.1.1 we know that the only requirement to the touch screen tip is that it has to be a conductive material, preferably something soft like rubber or the tip of an existing stylus pen. Because this is the only requirement to the touch tip, it can be included into to the edges of the gripper. So when the gripper is closed, the gripper can be tilted and the edges used as the touch tip. Using this configuration will mean there are only two tools attached to the end of the arm, which in turn means more space between the tools and less chance of the inactive tool interfering with the surroundings.

9.2. Evaluation and choice of configuration

The different options all have strengths and weaknesses, the options has to weighed against each other in order to determine which option is the best and will be used in the design of the tools. To gain an overview of each option I will start the evaluations with a SWOT analysis:

Table 9.1: SWOT analysis of the four options for tool configuration

Strength		**Weakness**	
Option 1 Space between tools	*Option 2* Less movement to change tools	*Option 1* Awkward to choose tool	*Option 2* Inactive tools could interfere with surroundings
Option 3 Maneuverable Add extra tools in future	*Option 4* Only two tools More space between tools	*Option 3* Complicated, heavy, affected by conditions (dirty)	*Option 4* Requires more advance design
Opportunity		**Threats**	
Option 1 Room for two more tools in the future	*Option 2* Full function without changing the arm design	*Option 1* Damage to the environment and arm from collisions due to reduced maneuverability	*Option 2* Damage to inactive tools due to collisions with the surroundings
Option 3 Unlimited number of future tools	*Option 4* Easy use without modifications to existing system	*Option 3* Function failure due to dirt in connections	*Option 4* Higher chance of errors with the more complicated design

From the general overview presented in the SWOT analysis, a few things become apparent. Option 1 and 2 demand no changes to the arm, but they do cause some problems with the operation and maneuverability by either the arm or the inactive tools running the risk of interfering with the surroundings. Option 3 and 4 does not limit the maneuverability, but they do demand more detailed and time consuming designs. This means more time and money spent on development, and they are more prone to errors and malfunction due to their complicity. To get a more detailed view of each options strength I will perform a PUGH analysis that can be seen in table 9.2.

From the PUGH analysis we can see that the option with the highest score is option 4. This makes sense in many ways as it does not put limits on the maneuverability of the arm, and the financial consequence of the extra design and production costs are miniscule compared to the profits that can be made from a fully functional robot. Based on the results of the PUGH analysis and the great profit to be made versus the relatively small extra costs, I have decided to choose option 4, which is the option to combine the touchscreen tool with the switch-turning tool. And in turn only have two tools attached to the end of the arm, this will allow for enough room between the tools, and only one inactive tool to worry about.

Table 9.2: PUGH analysis of the four tool configuration options

Criteria	**Weight**	**Option 1**		**Option 2**		**Option 3**		**Option 4**	
		score	*weighed score*	*score*	*weighed score*	*score*	*weighed score*	*score*	*weighed score*
Tool change/choice	3	2	6	3	9	5	15	4	12
Tool spacing	2	4	8	2	4	5	10	4	8
Maneuverability	3	1	3	3	9	5	15	3	9
Production cost	2	4	8	4	8	1	2	4	8
Design time	1	5	5	5	5	1	1	2	2
Durability	2	5	10	5	10	2	4	5	10
Maintenance cost	2	5	10	5	10	2	4	5	10
SUM	**-**	**-**	**50**	**-**	**55**	**-**	**51**	**-**	**59**

10. Power and power transfer

The previous chapters describe the motions needed to perform the tasks demanded of the tool, in order to achieve these motions actuators are necessary. In addition to this, I must decide on how the motion from the actuator will be transferred to the rotational and gripping motion.

10.1. Actuator options and choice

To provide the rotational and gripping motion I need two actuators, one for each motion. There are different types of actuators available; the two that are most applicable to my case are electro motors, or hydraulic actuators.

10.1.1. Electro motors

Electro motors are the most commonly used actuators in robotics, this is because of the availability of sizes, types, strengths and possibility of precise control [37]. There are a number of different electro motors available, the ones that are most relevant to my use are brushed DC motors, brushless DC motors, servo motors, and stepper motors. The following table will list the most important properties of each motor, more on each motor type can be seen from the following source [37].

Table 10.1: Properties of relevant electro motors

Motor	Size	Range of motion	Torque	Control	Price
Brushed DC	Variable	Unlimited	Low	Easy, only power	Low
Brushless DC	Variable	Unlimited	High	Medium, needs controller	High
Servo	Usually smaller	Limited +- 200 degrees	High	Advanced	Medium
Stepper	Variable	Unlimited	High	Medium, needs driver	Medium

From the calculations in chapter 7.4.1 I know that some torque is required to overcome the resistance in the switch, which means that the low torque actuators are out of the question. This leaves brushless DC, servo or stepper motors. Because of the limited funding for the prototype, and a desire for easy control that allows me to program and perform the testing myself, I think stepper motors are a good choice. It supplies fairly high torque at low revolutions, which will allow for controllable motions and easy testing. In addition they are easy to drive and control using Arduino. The negative aspect of stepper motors are that they are heavy, and in order to have motors that will provide enough torque, the total weight of the tool could exceed the maximum weight.

10.1.2. Hydraulic actuators

Hydraulic actuators are actuators powered by pressurized oil, both linear and rotational actuators are available and their capacity is based on size and what pressure the system can withstand. The key components of a hydraulic actuator system are the pump providing pressure, the actuator providing motion, a reservoir for excess oil, a valve controlling flow and hoses to connect the components. The positive aspect of hydraulic actuators is that the components can be located at different places. Which means that for the DORIS robot the pump, reservoir and valves can be placed in one of the modules, and only the actuator itself has to be in the tool. This will reduce the weight of the tool meaning more powerful actuators may be used before the weight limit is passed. One big drawback of this system is that the actuator needs to be connected to the other components by hoses transporting the pressurized oil. This will reduce the mobility of each joint, and decrease the maneuverability of the entire arm. The hoses are usually placed outside the arm due to their size, and the hose has to be longer than the arm in order to allow movement. This involves a risk of the hoses hooking onto things when the arm is operating and potentially breaking.

10.1.3. Choice of actuator

From the previous two chapters the choice has been limited to electric stepper motor vs hydraulic actuators. Using a SWOT analysis the properties of each option is presented in order to make a more informed choice.

Table 10.2: SWOT analysis for choice of actuator

Strength		**Weakness**	
Electric Easy to control, easy wiring and power from existing batteries	*Hydraulic* Light weigh actuators compared to strenght	*Electric* Heavy	*Hydraulic* Complicated system, potentially problematic hoses
Opportunity		**Threat**	
Electric Easy setup and control for testing, easily replaceable motors	*Hydraulic* Lots of commercially available hydraulic tools	*Electric* Not enough strength compared to weight	*Hydraulic* Damage to hosing, leakage, entire system is heavy

From the SWOT analysis some properties emerge that make the choice of actuator easy. A hydraulic system will require lots of parts and time involved with building, control and testing. Which I do not have financial capacity to perform in this thesis. In addition to this the added effect of the limited maneuverability and total weight of the system also have me convinced that electric stepper motors are the best choice. Even though a hydraulic system will provide a lighter end effector, the entire system is much heavier due to all the components needed, this added weight will reduce the capacity of the batteries on DORIS, which in turn will reduce the operating time of the robot. Even though the stepper might be too heavy at this point, they will do their job by allowing me to test function, and they can easily be replaced by lighter and stronger geared brushless DC motors later on if it becomes necessary.

10.2. Power transfer

Having chosen to use stepper motors, which provide rotational movement, the most commonly used transfer system is gears. Gears allow for transfer of motion between parallel, skew and perpendicular axis and are well suited for my use as I have transfer between both parallel and perpendicular axis. In addition to this, gears allow me to reduce the rotational speed and increase the torque by changing the gear ratios. This allows med to get smooth and controllable motion, with enough torque to turn the switches. The design will require two separate gear systems, which will provide power to each of the two motions, table 10.3 describes the gear systems that are relevant, and during the design chapter the gear system most relevant will be chosen for each motion, based on the design. More information on the gears listed in table 10.3 can be found from the following sources [38] [39] [27].

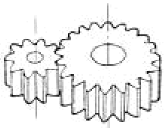
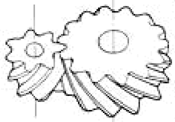
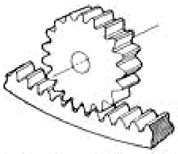
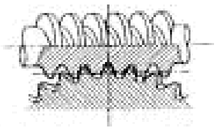
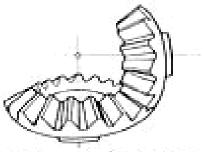
From the theory in chapter 5.2 we have the following equations for the torque transmitted in a gear connection:

$$\frac{\tau_{out}}{\tau_{in}} = i \times \text{ɲ} \quad \rightarrow \quad \tau_{out} = \tau_{in} \times i \times \text{ɲ} \quad or \quad \tau_{in} = \frac{\tau_{out}}{i \times \text{ɲ}}$$

Due to the low number of revolutions and low torques that will be transmitted by the gear connection, I will set $\text{ɲ} = 1$. The heat and noise production when the torque and revolutions are as low as they will be in the tool is negligible. When $\text{ɲ} = 1$ the equations can be simplified to:

$$\frac{\tau_{out}}{\tau_{in}} = i \quad \rightarrow \quad \tau_{out} = \tau_{in} \times i \quad or \quad \tau_{in} = \frac{\tau_{out}}{i}$$

Table 10.3: Relevant gear systems, all figures courtesy of engineers edge [39].

Gear type	Teeth	Transfer between axis	Action	Figure
Spur	straight	Parallel	Noisy at speed	
Helical spur	helical	Parallel	Smooth	
Internal ring	both	Parallel	Smooth, capable of high ratios	
Worm	Straight and helical	Perpendicular, non intersecting	High reduction	
Bevel	Tapered conical	Perpendicular, intersecting	Medium torque and speed	

11. Compliancy

In chapter 7.3 the need for both a passive and active suspension system to make sure the robot is sufficiently compliant was presented, and the initial plan was to incorporate this in the base of the tool. However, in the final design of the robot arm the end effector has been spring loaded and a piezoresisitve force detector has been added, which makes all the suspensions system first planned redundant. In figure 11.1 the last design of the vibration sensor, camera and attachment to the arm is shown. The red circle marks where the spring and force sensor is incorporated. Knowing that both suspension systems are a part of the arm already, the only thing that has to be done now is to make sure they are both correctly dimensioned.

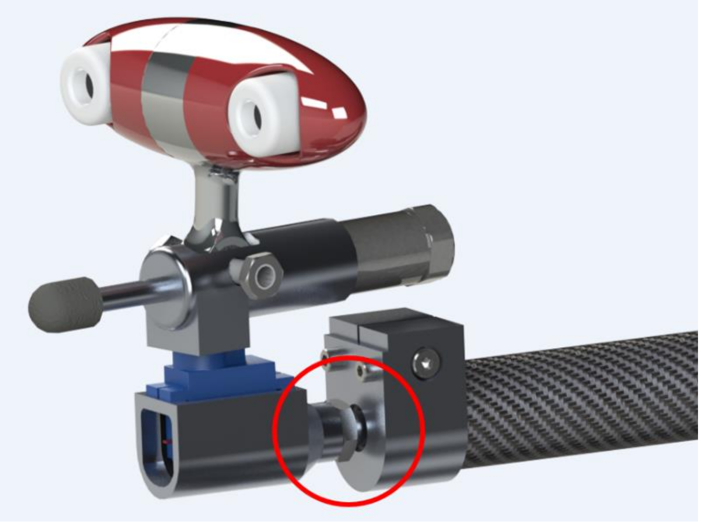


Figure 11.1: attachment of vibration sensor and camera to arm, latest update.

11.1. Passive suspension

When the spring suspension system is already a part of the arm, we have to make sure the spring used has the right length and stiffness in order for it to absorb the force its designed for. From chapter 7.1.1 we know that the operating force on the touch screen is set to maximum 500 g, which equals a force:

$$F = mg = 0{,}500kg \times 9{,}81\, {}^{m}/_{s^2} = 4{,}905N \approx 5\ N$$

Further we know from chapter 7.1.1 that the passive suspension is primarily intended for absorbing vibration, which means small movements. Based on this I will set the length of compression for the spring (Δl from figure 7.2) to be 10 mm. Because we don't want the spring to fully compress under normal operating conditions we will multiply the force needed to fully compress the spring by two. Which means that in order for the spring to fully compress 10 N has to be applied to the spring.

Knowing that x = 10 mm and F = 10 N for the spring to fully compressed, we can use Hooke's law to calculate the spring constant:

$$F = kx \rightarrow k = \frac{F}{x} = \frac{10\,N}{10\,mm} = 1\ {}^{N}\!/_{mm}$$

Summarized the spring in the arm needs to have a spring constant equal to 1 N/mm.

11.2. Active suspension system

Because the active suspension system is part of the programming that controls the robot, there is not much I can do at this point. What I can do is specify the parameters that will lay the foundation of the system. As mentioned on the previous page the maximum operating force on the screen is 5N. Which means that if the force sensor senses a force over 5N when the arm is operating a screen, it needs to pull back in order to reduce the pressure on the screen. When the arm is turning switches the surrounding material can take a lot more pressure as it is mostly metal or hard plastics (seen in the photo of the screen from figure 7.1). This means that the force limit that has to be passed before the arm retracts can be set higher. However I don't think that is necessary because more pressure in that direction is not necessary in order to get a good grip on the switch. So by having the limit at 5N for all operations will save some complications in the programming, and one does not have to specify which operation the arm is performing in order for the active suspension to be in the right settings. Summarized the active suspension system will be a program that tells the arm to move in a direction that will reduce the force on the arm when the force sensor measures more than 5N.

Tool design and prototype

12. Tool design

Keeping the requirements and concepts chosen from chapter 7 – 11 in mind, the actual design of the tool can begin.

12.1. Touch screen tip/gripper

The first step is to design the gripper in a way that will provide sufficient grip on the switch, and have one or more edges touch screen capable. To do this on must first decide on the shape of the touch tip.

12.1.1. Material and shape of tip

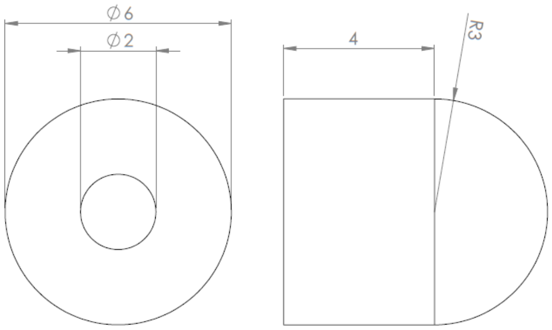


Figure 12.1: Key measurements of the chosen Wacom touch tip, all measurements in mm.

As discussed in chapters 7.1.1 and 7.3.3 I need the tip to be in a conductive, semisoft, rubberlike material and preferably with a diameter smaller than 7 mm. As the production of a tip fulfilling all these requirements will be expensive and time consuming, I have looked in to replacement tips for existing stylus pens to see if I could find a product that fulfills all the requirements listed above. The Wacom Bamboo Stylus Solo[40] has a tip that satisfies all my requirements, and spare tips are for sale, so this is the chosen touch tip for the tool. Information on the dimensions of the tip in figure 12.1.

12.1.2. Gripper

Knowing the size of the touch tip, the design of the actual grippers can start. This is the part of the tool that will be in contact with the switch, and it is important that they are designed in a way that provides enough friction and provides a good grip on all kinds of switches. In figure 7.3 one can see that the edges of the switch are almost flat, therefore the contacting surface is going to be flat, with a layer of rubber glued on to the surface. The flat surface is chosen because it is the most versatile, and provides a large contact area between the gripper and switch. The rubber is added to provide extra friction, and to compensate for any irregularities in the surface of the switch. The size of the gripper is set to 60 mm width and 15 mm depth. The length of the gripper arms are set to 55 mm.

The position of the touch tip has to be so the risk of the rest of the gripper interfering when the touch tip is used is minimized. This means that the touch tip will be attached to the corner of the gripper with a 45 degree angle, there will also be touch tips on both grippers at opposite sides. This will make it easier to operate the tool as one can choose which tip to use based on the position of the arm and where on the screen one wants to press. The shape of the gripper and position of touch tips can be seen in figure 12.2.

Figure 12.2: Design of the gripper with touch tips

12.2. Gripping motion

In order for the tool to actually grip the switch, the two parts of the gripper has to move towards each other and grip the switch between them. Due to the shape of the motors (appendix 1) I want the drive shaft to be parallel with the rotation to make the tool as small and sleek as possible. This means the drive shaft is perpendicular to shaft providing the motion. From table 10.3 I know that a worm gear or bevel gear is best suited to transfer the power from the driveshaft to the gripper. Because a worm gear requires non intersecting axis, it is not suited because it would lead to the motor having to be offset from the gripper making the tool unbalanced. Therefore a bevel gear is my choice for power transmission. A bevel gear has two parts, the pinion and the bevel. The pinion goes on the drive shaft and the bevel goes on the shaft of the gripper. Figure 12.3 shows how the pinion and bevel is placed, as well as the shaft providing the gripping motion. Because I want to have as much power as possible in the gripper a gear ratio with a small pinion and large bevel is preferable. Due to space limitations a 12 tooth pinion and a 36 tooth bevel is used. This makes the gear ratio:

$$i = \frac{z_{out}}{z_{in}} = \frac{36}{12} = 3$$

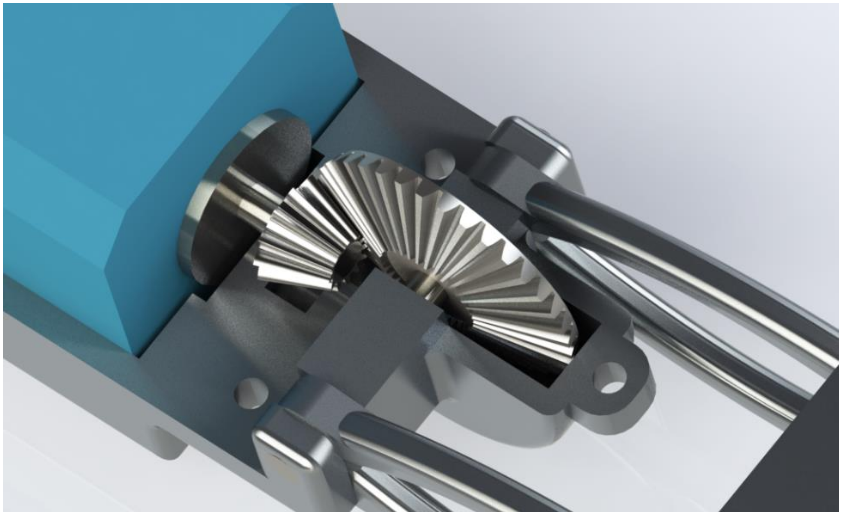


Figure 12.3: configuration and position of the bevel gear

12.3. Rotational motion

In chapter 8 I determined that the rotational motion needed to turn a switch would be made part of the tool, a second motor will provide this motion. Due to the desired sleek design the motor will be placed with the driveshaft in the same direction as the other motor, which means the driveshaft will be collinear with the rotation. From table 10.3 there are three gears suitable for transfer of power from the motor to the rotation. Because I want the gear ratio to be as high as possible to make the torque in the rotation as high as possible, I will use an internal ring gear in combination with two small straight spur gears. I have decided to not use helical gears as they are unnecessary complicated for connections that have relatively low rpm and torque. I need two spur gears to keep the ratio high at the same time as I want the shaft of the motor to be in the middle of the tool to keep the tool balanced. As described in chapter 10.2 the loss of torque between gears is negligible, so the extra spur gear does not have any negative effects on the performance. The internal ring gear is fastened to the end of the rotational part, the first spur gear goes on the driveshaft of the motor, and the second is free to rotate on a shaft between the first spur gear and the internal ring gear. The gear configuration is illustrated in figure 12.4. When the motor turns the internal ring gear fastened to the rotational part turns the entire front end of the tool. The size of the internal ring gear is decided by the size of the tool, and the spur gears are decided by the size of the internal ring gear. The internal ring gear has 34 teeth and the spur gears have 11 teeth, which makes the gear ratio:

$$i = \frac{z_{out}}{z_{in}} = \frac{34}{11} = 3{,}1$$

The two cylinders are the surfaces that hold the two parts of the tool together and move in relation to each other when the tool is turning. These surfaces are polished and coated in grease to decrease friction. The whole rotational joint is shown in figure 12.4.

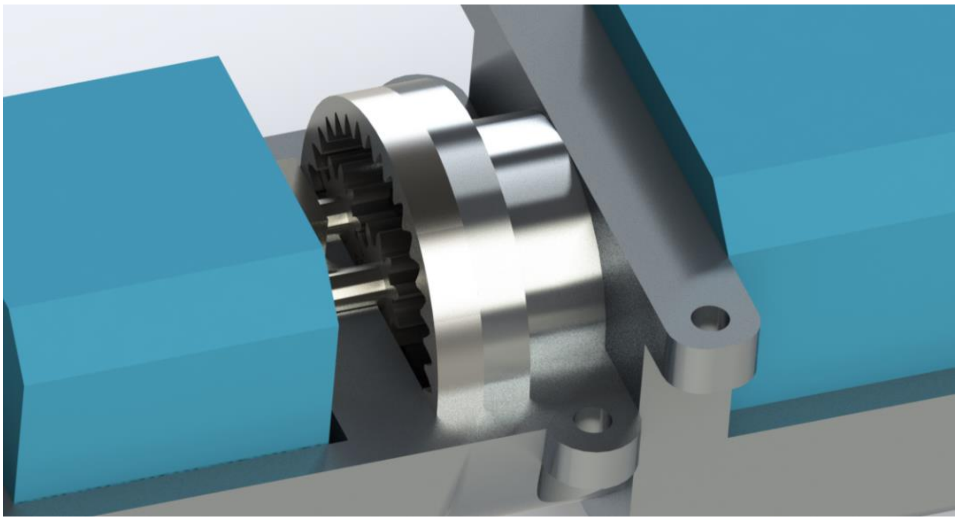


Figure 12.4: gears in rotation joint and joint design

12.4. Chassis

Knowing how the moving parts and the gripper are designed it is time to take a look at the actual body of the tool. The main goal of the chassis is to hold the motors, gears and other moving parts in place and safe from water and dust. Beside from that I want the chassis to be as light and small as possible. Further it is preferable to have the body in as few parts as possible to reduce the number of gaps between parts that could potentially allow water or dirt into the tool. Therefore the body of the tool is split into five main parts, the top and bottom of the base, the top and bottom of the rotating part and the upper part of the gripper. The parts are designed with holes for the bolts that hold the parts together, and the holes are placed in order to not intefere with function, keep the balance and keep the parts securly fastened. The five parts can be seen in in figure 12.5. A drawing with the most important measurements can be found in appendix 2, and more detailed measurements can be found from the Solidworks files on the accompanying CD.

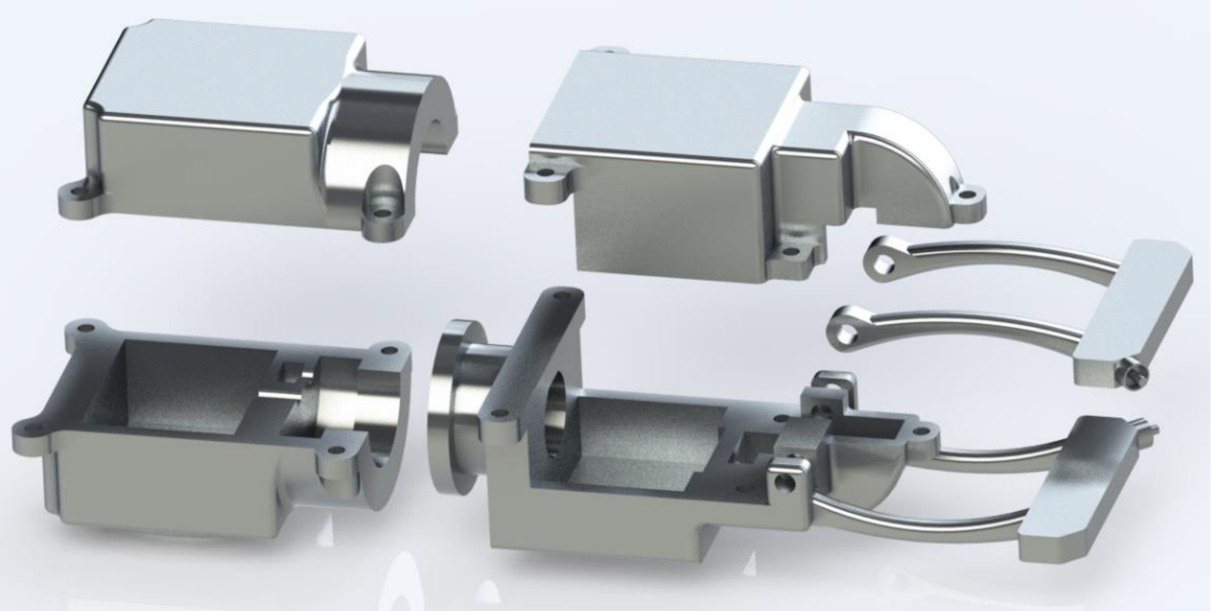


Figure 12.5: The five main body parts, base to the left and rotating end to the right

Regarding materials I know that the material has to be lightweight and strong enough to withstand the forces it is subject to during operation. Because of this I have choosen aluminum. Aluminum is easy to work with, it doesn’t corrode and it is strong compared to its weight. I have chosen to use the aluminum alloy 6061-T6 [41] because it is widely used in everything from bicycles to cameras, and is therefore easily accessible and well known to most external resources that might be involved with the production of the parts.

In order to make sure the chassis designed is strong enough I will do some simulations in order to test the parts. From studying the parts the gripper arms are clearly the weakest point and I will do simulations on these first to see if they are strong enough. I know that under the worst case scenario each gripper is subject to a force of 50N and a torque of 3Nm. When the force and torque is applied to the model and simulations are done using Solidworks Simulation, I got the results seen in figure 12.6 and 12.7. The maximum occurring Von Mises stress in the two components is 97 MPa. Knowing that the yield strength of 6061-T6 aluminum is 275 MPa [41], the tool is strong enough, with a safety factor of 2,8.

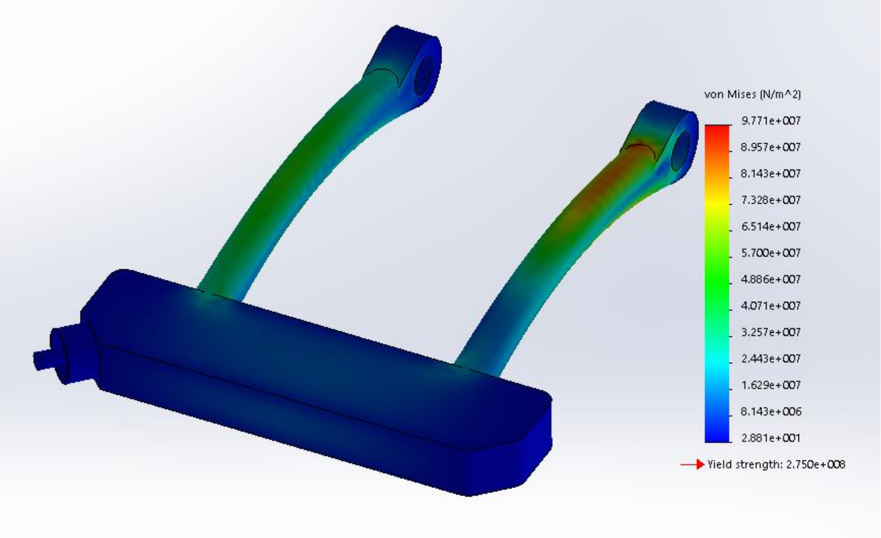


Figure 12.6: stress in upper part of gripper, from Solidworks Simulation

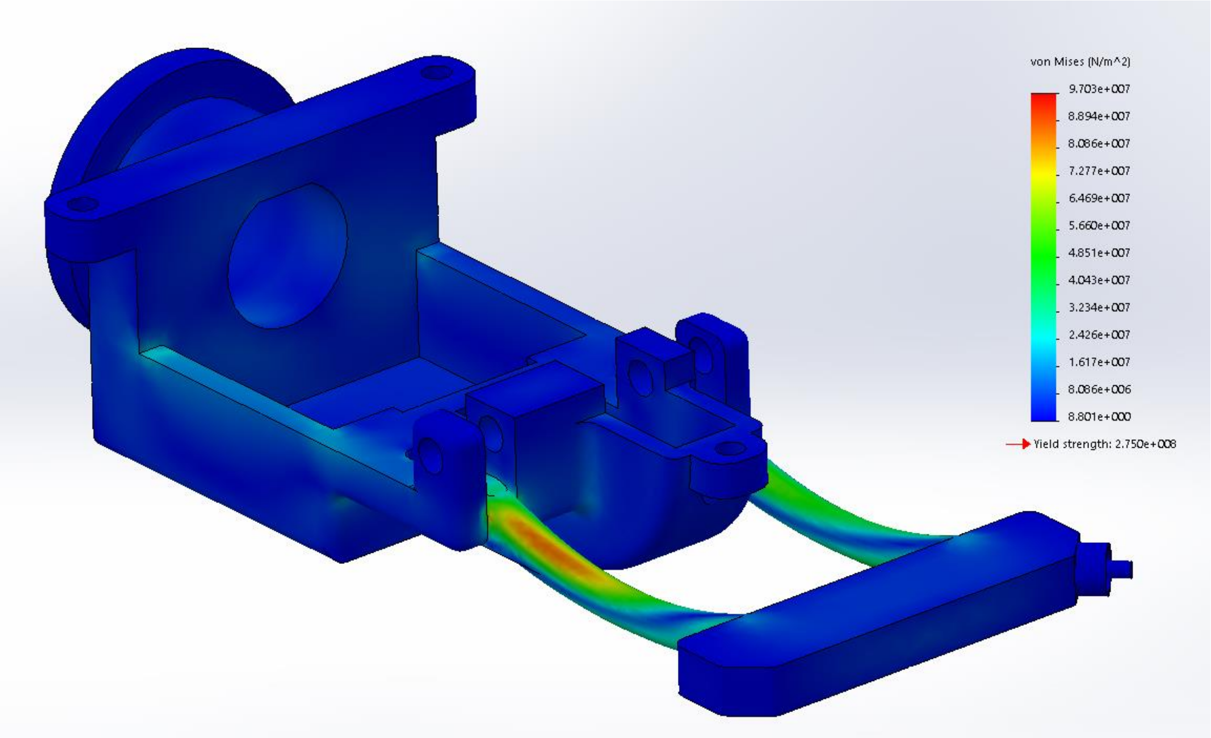


Figure 12.7: stress in base of rotating front end, from Solidworks Simulation

12.5. Standard parts

In addition to the designed parts from the previous chapters, the tool uses some standard parts. These includes gears, bolts, nuts and motors.

12.5.1. Motors

I have already decided to use stepper motors (chapter 10.1) but I have to know how powerfull motors I need. From chapter 7.4 I know that the rotation requires 3Nm and the gripper needs to apply a force of 50 N onto the switch in order to resist the torque, further the gear ratios have been set to 3 for the rotation and 3,1 for the gripper. From the formula in chapter 10.2 I can calcualte the required torque from the motor in the rotational joint:

$$T_{in} = \frac{T_{out}}{i} = \frac{3Nm}{3} = 1\ Nm$$

For the torque in the gripper motor, the length of the gripper arm has to be taken into account, which was earlier set to 55mm. Figure 12.8 shows how the forces and lenghts relate. We know that T_{out} has to be equal to the effect of the force on the end of the arm, which gives us the following equation:

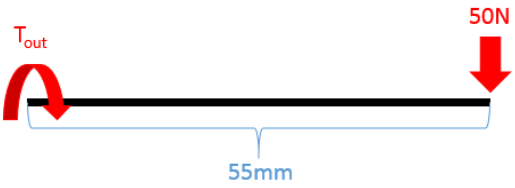


Figure 12.8: Forces acting gripper arms

$$T_{out} = 50N \times 55mm$$

Further the effect of the gear ratio in the gripper is the same as in the rotation, making the equation:

$$T_{in} = \frac{T_{out}}{i} = \frac{50N \times 55mm}{3,1} = \frac{50N \times 0,055m}{3,1} = 0,9\ Nm$$

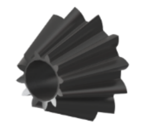
Since the required torque from the two motors are so close it is easiest to use two identical motors with a minimum torque of 1Nm.

Due to fincancial contstraints and limited availability of correct motors, I have decided to use weaker stepper motors for the first prototype of this tool. The motors will be able to test all the functions of the tool, and if the tool is going to be taken into operation the motors can be replaced by stronger and more expensive high quality motors. For example the JVL MST11x mini steppermotors [42] are very similar to the chosen motors, and are available with sufficient torque. The chassis can easily be adjusted to accommodate different motors. The motors choosen are ROB-09238 Stepper motors[43]. Its specifications can be seen in appendix 1.

12.5.2. Gears in gripper

As described in chapter 12.2 the gear used is a straight bevel gear system is used, the gear system has two parts and the properties of each part is listed in the following table.

Table 12.1: Properties of the gears in the bevel gear system

Gear	Number of teeth	Outside diameter[mm]	Module	Shaft diameter[mm]	Figure
Pinion	12	14,2	1	5,0	
Bevel	36	36,4	1	5,0	

12.5.3. Gears in rotational joint

The rotational joint described in chapter 12.3 has two types of gears, two straight spur gears, and one internal ring gear. The properties of these gears are listed in the following table:

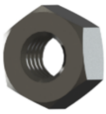
Table 12.2: Properties of the spur and internal ring gears in rotational joint

Gear	Number of teeth	Outside diameter [mm]	Thickness [mm]	Module	Shaft diameter [mm]	Figure
Spur gear	11	13,0	4,0	1	5,0	
Internal ring gear	34	40,0	5,0	1	NA	

12.5.4. Bolts and nuts

A total of nine bolts and nine nuts are used to hold the parts together, four bolts for the base and five bolts for the rotating front. Bolts were chosen because they allow for easy assembly and easy access to the internal components of the tool in case a need for repairs or replacement of parts arises. The bolts have socket heads and the nuts are ordinary hex bolts. Sockets heads allows for tightening from the top, which means it requires less space around the bolt. This is ideal for the intended use as the bolt holes are close to the body of the tool.

Table 12.3: Nuts and bolts used in tool

Item	**Dimension**	**Length/height [mm]**	**Thread length [mm]**	**Tightening method**	**Figure**
Bolt	M4	16,0	16,0	Socket head	
Nut	M4	3,2	NA	Hex	

12.6. Assembly

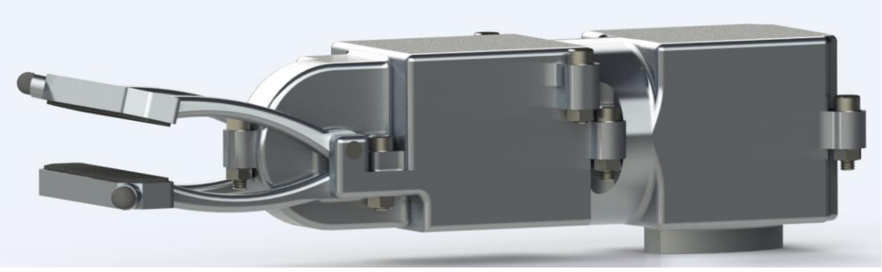


Figure 12.10: Rendered represenation of the assembled tool

With all the elements of the tool described in the previous chapters, it is time to look at the complete assembly. Detailed information on how the tool is assembled is provided in the prototype chapter. Figure 12.10 shows the rendered assembly of the tool, and figure 12.9 is an explosion view. From the solidworks model,

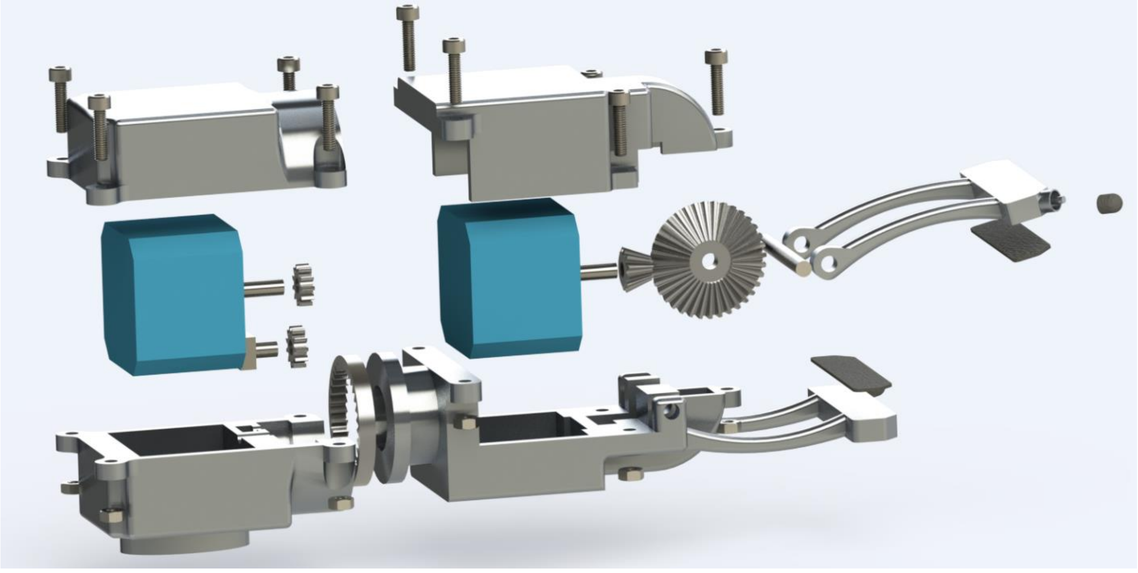


Figure 12.9: Explosion view of all the components in the tool

the total weight of the tool excluding motors is approximately 200 g. From the datasheet in appendix 1 the weight of each motor is 200 g. This makes the total weight of the tool 600 g.

12.7. Mounting method

Figure 12.11: Tool, vibration sensor and camera added to last link of arm.

In chapter 9 I decided to have a combined touch and switch turning tool, which means there are only two tool attached to the end of the arm in addition to the camera. The current attachment of the vibration sensor is with a single bolt, I will use the same system and adapt it to two tools, with the camera mounted between them. This way the camera can monitor both tools without moving. Figure 12.11 shows the configuration with both tools and camera mounted. The tool and the vibration sensor is mounted with 60 degrees between them, and the camera pointing in a straight line between them.

12.8. Production cost

An important part of the tool design is giving an estimate on what it will cost to produce. Due to the extensive licensing and testing that is involved before a tool is accepted for offshore use, I will focus on the price of producing a fully functional metal prototype. To get from that stage to a point where the tool can be sent offshore, the cost will at a minimum have to be multiplied 15-30 times.

The main cost involved in the production of the prototype is the production of the chassis. The body parts has to be CNC machined from solid pieces of aluminum, which requires them to be made by a company who does CNC machining. With new CNC machines it takes roughly one hour pr body part including set up, and the price is 1200NOK/hour. My price estimate is based on Norwegian prices, which means the price can most likely be cut by producing the tool in an other country. The other components of the tool can be bought and ordered from commercial suppliers. The gears vary in price based on the gear, so the price for the gears is an average set to get an idea of the price. This is done because the exact specifications of the gears might change if the motor does, and so will the prices. The same goes for the motors, the price is set as an average of what motors that can be used cost. Table 12.4 lists the cost of the different components of the tool.

The total cost of the tool comes out to 8545,75 NOK, factoring in some inaccuracy and shipping cost for the components that has to be ordered I will round up to an even 9000 NOK. Keeping in mind that this is the price for an aluminum prototype, the price for a fully certified tool will be much higher.

Table 12.4: Production cost for tool

Component	Price	Quantity	Cost
Chassis	1200 NOK/hour	5 hours	6000,00 NOK
Nuts	1,25 NOK	9	11,25 NOK
Bolts	0,50 NOK	9	4,50 NOK
Gears	300,00 NOK	5	1500,00 NOK
Motors	400,00 NOK	2	800,00 NOK
Drivers	115,00 NOK	2	230,00 NOK
SUM	**-**	**-**	**8545,75 NOK**

13. Prototype

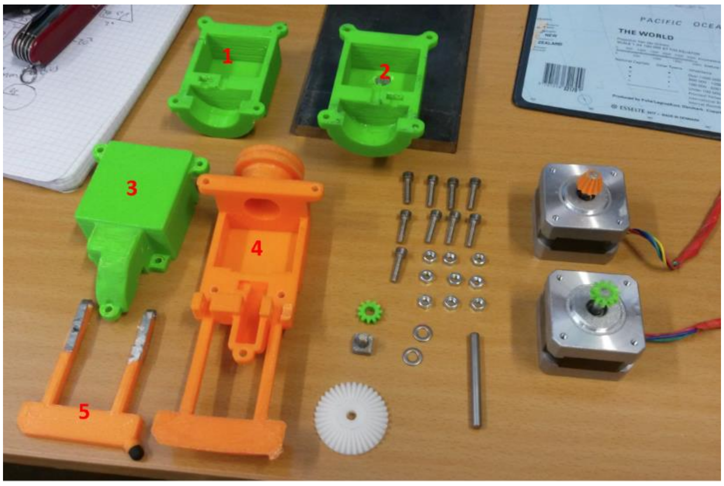


Figure 13.1: All components of the prototype before assembly

In order to further evaluate the design and to easier spot errors and possibilities of improvement, a prototype of the tool is made. A 3D printer was used to print all the main body parts and gears. The motors, nuts and bolts were bought and the gripper axel and axel for the gear in the rotational joint was made at the NMBU workshop. Figure 13.1 shows all the components of the tool pre assembly, note that the spur and pinion gears are already glued on to the shaft of each motor, and that the internal ring gear has been glued on to the end of body part 4.

13.1. Assembly

The assembly of the tool is fairly straight forward as the number of components is limited, the following list describes each step of the assembly and figure 13.2 shows the assembled tool.

1. Mount the motors in each of the motor compartments in body parts 1 and 4.
2. Add the spur gear with axel in the rotational joint and add the gripper by inserting the axel through the holes of the gripper (body part 5) and the bevel gear.
3. Combine body parts 1 and 4 by fitting the spur gears inside the internal ring gear, this might require some work as it is a tight fit. The contacting surfaces between the two parts are covered with grease to decrease friction when rotating.
4. Mount the top parts by bolting body part 2 and 3 on to its respective bottom, this will require a total of nine bolts and nuts. Make sure the wires from the motors are not pinched between the body parts.
5. The assembly is now done, the wires have been taped to reduce the chance of damaging them. The next step is now to hook the wires up to the motors control and test the function of the tool.

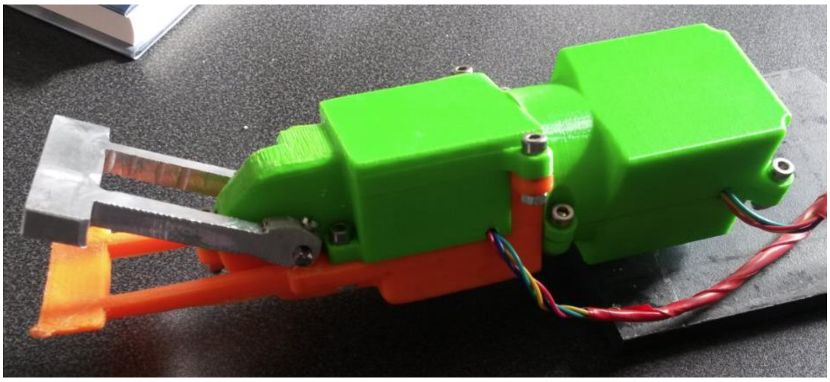


Figure 13.2: The assembled prototype of the tool.

During the assembly of the prototype one minor issues arose with the upper part of the gripper. The 3D printer had some problems with the geometry of the part, and the holes for the shaft didn't have enough material surrounding them. The solution was to make the part in aluminum. In addition I added a track in the shaft of the gripper in order for the bevel gear to slide on without slipping when rotating, and I threaded holes in the top part of the gripper to securely fasten the gripper to the shaft. The fastening screw can be seen in figure 13.2.

13.2. Motor control

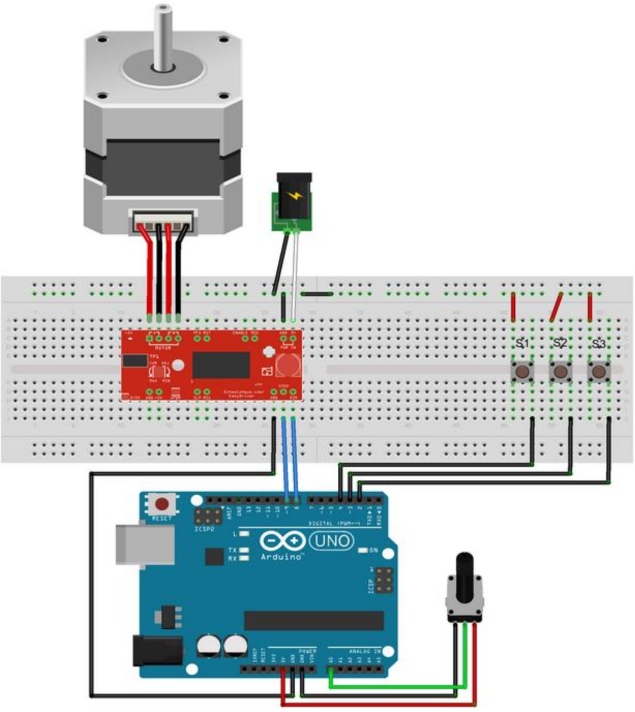


Figure 13.3: circuit chart for motor control, courtesy of Brian Schmalz [37]

In order to test the functions in the tool I have to be able to control the motors. I chose to use Arduino as it is easy to use and easily accessible. The drivers for the motor are Easy Drivers [44]. They were hooked up as shown in figure 13.3, and the code courtesy of Brian Schmalz [45] was uploaded to the Arduino UNO board. The potentiometer controls the rotational speed, and the three push buttons send signal for rotation to the left, rotation to the right and stop. A 12 Volt, 1,5 Ampere power source is used. As I have limited experience with coding, I chose to use two Arduino UNO boards, one for each motor. This was done so I would not have to change the code written by Schmalz. It requires some extra wiring, but apart from that the results is the same.

13.3. Price

Because this is the first version of the tool, it will most likely be redesigned before a final version is set into production. Which means that more prototypes will probably be built, and an estimate of the price of the prototype is useful. As mentioned most of the components in the prototype are 3D printed, which only leaves the cost of the materials. The 3D printer uses thin plastic filament, and the amount of material used is measured in meters of filament. In addition to the 3D printed parts some components have been bought. Table 13.1 list all the costs involved with the production of the prototype.

Table 13.1: Cost of building first prototype

Component	Price	Quantity	Total cost
3D printing	1,50 NOK/m	100 m	150,00 NOK
Bolts	1,25 NOK	9	11,25 NOK
Nuts	0,50 NOK	9	4,50 NOK
Motors	115,00 NOK	2	230,00 NOK
Touch tips	33,00 NOK	2	66,00 NOK
Driveshafts (metal parts)	25 NOK/kg	0,1 kg	0,25 NOK
Motor drivers	115,00 NOK	2	230,00 NOK
SUM	-	-	**692,00 NOK**

The total cost is 692 NOK, which is not bad for a first prototype. In addition the motors, drivers, and hardware can be used again if on wants to change design. Which mean that the costs involved with future prototypes is much less. This allows for several design to be tried in order to find the optimal one.

13.4. Testing and test results

Having assembled a working prototype the next step is to test how it work. In order to have a baseline number to compare the test results against I will calculate the torque I expect the prototype to able to produce when turning a switch with the current motors. From appendix 1 the maximum torque from the motor is 0,23 Nm. By using the equation from chapter 10.2 the theoretical value is:

$$T_{out} = T_{in} \times i = 0{,}23 \times 3 = 0{,}69\ Nm$$

With the expected value in place the actual testing can begin. Before measuring the torque and force some tests without any resistance were done to see if the tool and motor control works. Besides some errors in the wiring, which were quickly fixed, everything worked and the parts moved as expected. One important note is that the gears did bend a little when some resistance was added, which may indicate that the plastic material is not strong enough for the small detailed gears.

The next step of testing is to check the strength of the tool, which was done with a force sensor and a rig made illustrating a switch. The tool grips the flat handle of the bar, and the other end rotates and applies pressure to the sensor, the torque can easily be calculated. The rig used can be seen in figure 13.4. Since I am calculating the torque the tool as an assembly is able to create, I have to keep an eye on the gripper to see if it is able to withstand the force when rotating.

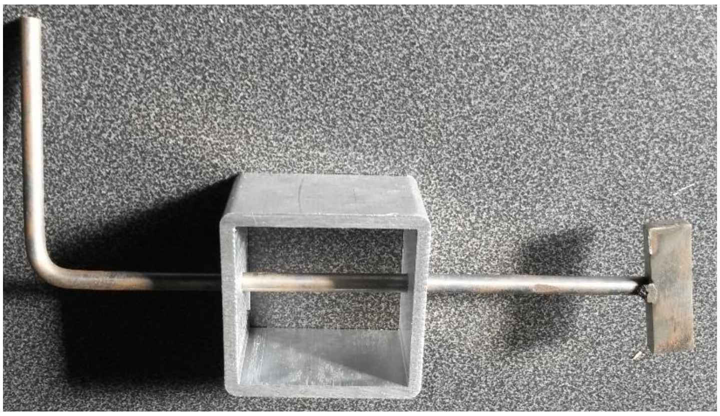


Figure 13.4: Rig made to measure torque in the tool

After running several test I have found the maximum torque to be 0,24 Nm, this is significantly lower than the baseline. The tool creates 35% of the theoretical torque. I think a lot of the loss in power is due to the plastic gears, but also the fact that the entire tool is plastic, which does flex a little and absorb a lot of the force that is supposed to go into the torque. A positive observation is that even when the maximum torque was registered the gripper still kept is grip on the “switch”. Which indicates that the motor and gear transfer in the gripper is strong enough compared to the strength of the rotation.

Discussion, conclusion and future work

14. Discussion

After going through the design options, design and testing of the prototype, some things have worked out well, while other aspects have been less successful.

14.1. Functions

From the testing done both functions work well, independently and simultaneously. Which proves that the gear systems chosen in chapter 12.2 and 12.3 is working well. One clear point of improvement that should be looked into is the possibility of using one motor instead of two, this will require the turning and gripping mechanisms to be more advanced, but if successful it could remove a lot of weight from the tool. A tool using only one motor would require much more complicated mechanisms in the tool, and have therefore not been covered in this thesis due to the time limit and the goal of having a working prototype. After covering the requirements to the touch screen tip in chapter 7.1.1 and studying the design of the vibration sensor (figure 11.1). A solution where the tip of the vibration sensor is also used as the touch screen tip is possible, since the spring and force sensor has been added to the arm the tip of the vibration sensor can be used to operate touch screens if it is made from a material that works on resistive screens.

14.2. Weight

With the current design of the tool it weighs 600 g, which is with the weaker motors. These motors can be replaced by lighter, more expensive motors to reduce the weight. However I have not been able to find sufficiently strong motors which will make the tool light enough, and when the weight of the camera and vibration sensor is taken into account the tool is far from light enough. This leaves three options: increasing the strength of the arm, revisiting the possibility of hydraulic actuators or shortening the links in the arm, which will increase the strength but reduce the range. Increasing the strength of the arm would mean redesigning the arm with stronger components, which means the arm becomes heavier. With hydraulic actuators one could achieve the required power in the tool while staying under the weight limit, however the solution adds weight to the base of robot because of the pump, reservoir and valves described in chapter 10. Which leaves the question of which option results in the lowest total weight increase: stronger arm or hydraulics. The total weigh of the robot is the most important factor to consider because it directly affects the battery capacity of DORIS, and to keep the robot running as much as possible the battery capacity is vital. Whether the weight is added to the arm or the base is less important as the robot has to pull both parts around anyways. Shortening the links of the arm will keep the weight the same, but it will reduce the range of the arm. If this is a realistic solution might be easier to determine when the rails and prototype is installed at Petrobras, and one can observe how much reach is necessary. Petrobras have given indications on their wish to strengthen the arm to make it capable of doing more “hands on” work in the future. Which means that the tool might be within an acceptable weight range in the future. If this is done by reducing range or increasing weight remains to be seen. If the decision to strengthen the arm is made, one could also do more detailed FEM analysis on the chassis to see where one could reduce the material thickness without compromising the strength. From the simulations done in chapter 12.4 one can see that the stress in the body of the tool is far from the limit of the material (<25MPa). Which means that the thickness in the walls can be reduced to decrease weight. The possibility of one motor presented in the previous chapter will also contribute to reducing the weight a lot, but most likely not enough to eliminate the need to strengthen the arm.

14.3. Size

From figure 12.7 we can see that the tool is much bigger than the vibration sensor, this could lead to problems when the vibration sensor is in use. Due to the size of the tool it is a risk of it interfering with the surroundings as it sticks out a lot further than the vibration sensor. When the decision on tool configurations in chapter 9 was made I assumed the tools would be approximately the same size. One solution to this problem could be a setup where the vibration sensor is mounted on the tool itself, this would have the added effect of the camera being in line with both the tool and the vibration sensor. The size is also a good argument for the option on only using one motor in chapter 14.1. Using only one motor will reduce the size substantially, and result in a tool that is closer to the vibrations sensor in size.

14.4. Build Quality

Because the current prototype is in plastic, there is not a lot one can say about the build quality so far. I have decided on using Aluminum 6061-T6 for the body of the tool, because of the low weight and resistance to corrosion. This however is a truth with modifications, as aluminum also rusts if it is subject to sufficiently rough conditions. Due to this more research must be done to find a material which is better suited. Due to the small size of the tool more exclusive materials like magnesium, carbon fiber or custom alloys should be considered. Because of the plastic prototype no testing regarding the requirements set to waterproofness and explosion safety have been done. But due to the design of the tool, where all joints between the body parts are straight flat surfaces, this should not be a problem if the body parts are made with sufficiently high levels of accuracy and surface treatment. If the aluminum prototype is made testing can be done by subjecting the tool to conditions equal to those at an oil platform, and the tools performance can be monitored.

14.5. Power

Because of price and availability I used weaker motors for the prototype, which in itself is not a problem because stronger motors in very similar sizes are available. When testing I found that the tool only produced 35% of the expected torque. This is a problem because it means that even stronger and heavier motors are necessary, which in turn takes the tool even further from the goal weight. However the entire body of the tool and all the gears are in plastic, which under strain flexes a lot. This means that a lot of the power in the motors goes into deforming the material and not the rotation. Due to this effect I will not put too much weight on the test results regarding the torque. From chapter 12.8 I know that about 6000 NOK is needed to produce all the parts in aluminum, and 1000-2000 NOK is needed to buy steel gears. So I think it would be smart to invest in an aluminum prototype and proper gears before any decisions on increasing motor power is made. The price of an aluminum prototype is a fraction of the costs involved with increasing the strength of the arm more than necessary. In order to reduce the torque required from the motors, it would be possible to use bigger gear ratios by using more gears to transmit the power. This will increase the weight because of the added gears, but the weight one can cut from using smaller motors might higher than the weight of the gears.

14.6. Necessity

When reading this master thesis it easy to ask the question why? Why would you need to have a robot operating touch screens? Wouldn’t it be easier to have all the electronics remotely controlled by humans and eliminate the need for the robot. The answer to this is partially given in the introduction where it says that the goal of the DORIS project is to *replace* humans, meaning that the robot will be introduced to an environment originally intended to be operated by humans. The robot will be installed at operating oil platforms where the touch screens are already installed, and the costs involved with replacing all the touch screens with a remote controlled systems is very high compared to the cost of installing DORIS.

15. Conclusion

The design options done during the thesis seems to be working well together, and the tool performs all its intended motions as expected. The motion is smooth and easily controllable. However the weight of the tool is currently sitting at 600 g which is higher than the current capacity of the arm. So at this point in time the tool is useless to the DORIS manipulator arm. If Petrobras' plans for strengthening the arm and having it perform more physical "hands on" work are carried out, the tool can become very useful as it is easy to control and cheap to produce compared to human labor. If the arm is strengthened more testing and research into finding the optimal components and materials must be done to make sure the tool is as light as possible and fulfills all the requirements to an offshore tool.

16. Future work

Because of the issues regarding the weight of the tool there are some work that has to be done in order for the tool to be used by the DORIS project. There are also a couple of points in the design process that can be investigated further. The following list sums up the points I feel are natural next steps that have to be done in order for the tool to be a useful asset to the DORIS project.

- Look into options for strengthening the arm, either by using stronger motors or shortening the length of each link in the arm.
- Research and find the best possible motor with and ideal weight to power ratio.
- Research possibilities of decreasing the weight of the tool by using one motor or gear combinations providing a higher gear ratio.
- Do more detailed FEM analysis on the body of the tool to determine areas where material can be removed to save weight.
- Research materials to determine the optimal material for the chassis of the tool, keep in mind that the amount of material is fairly little, and exclusive materials like carbon, magnesium or custom alloys should be considered.
- When introducing the 6th DoF the Jacobian for the entire manipulator arm should be calculated to determine with 100% certainty which rotational direction the last joint needs in order to give the arm full range of motion.
- To be able to use touch screens at an earlier stage, it is possible to look into a solution including using the rubber tip of the vibration sensor as the touch tip and incorporate an active suspension system using the existing force sensor. This adds no weight to the tool, but makes it touch screen capable.

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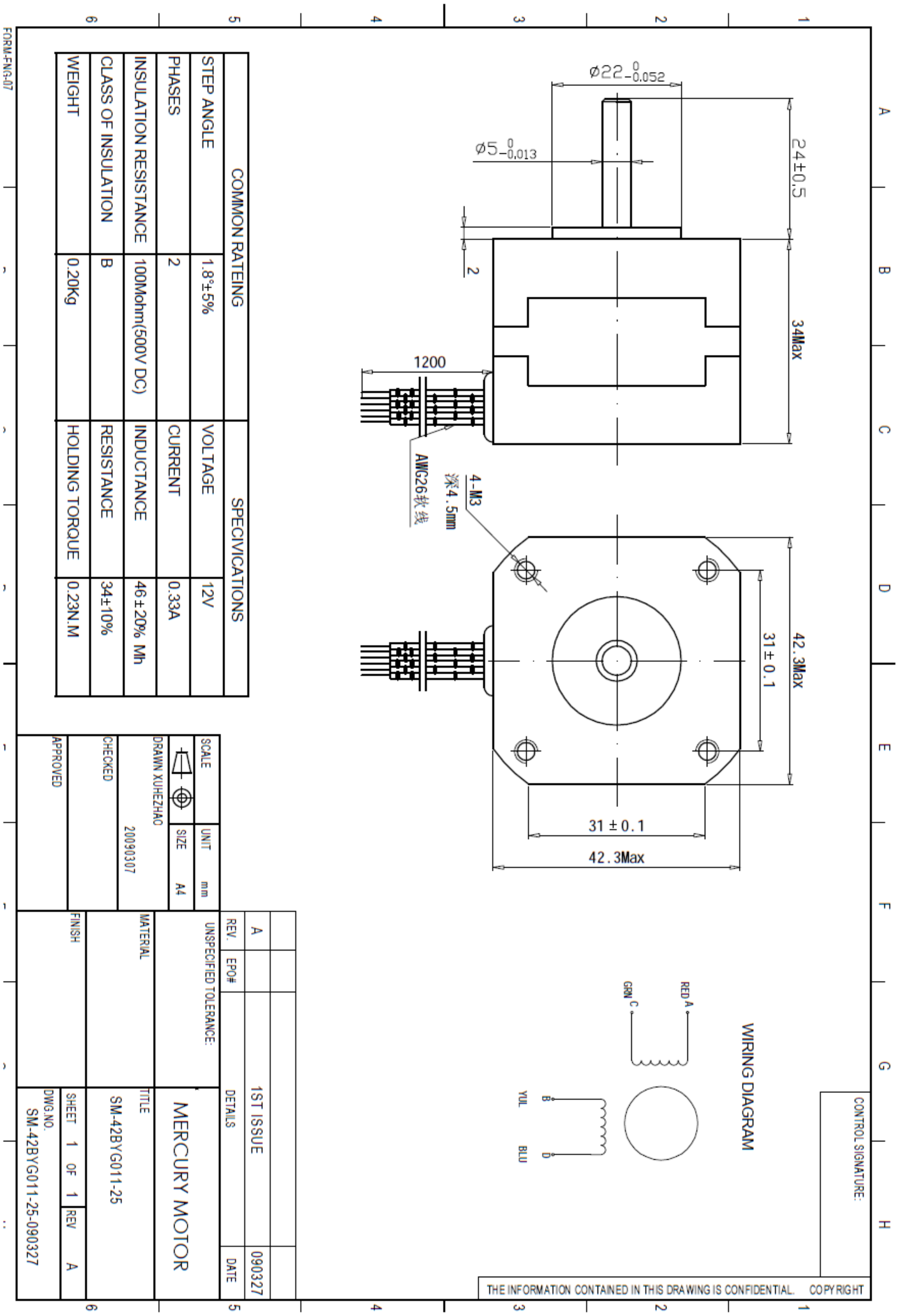
18. Appendixes

Appendix 1 – data sheet on stepper motor

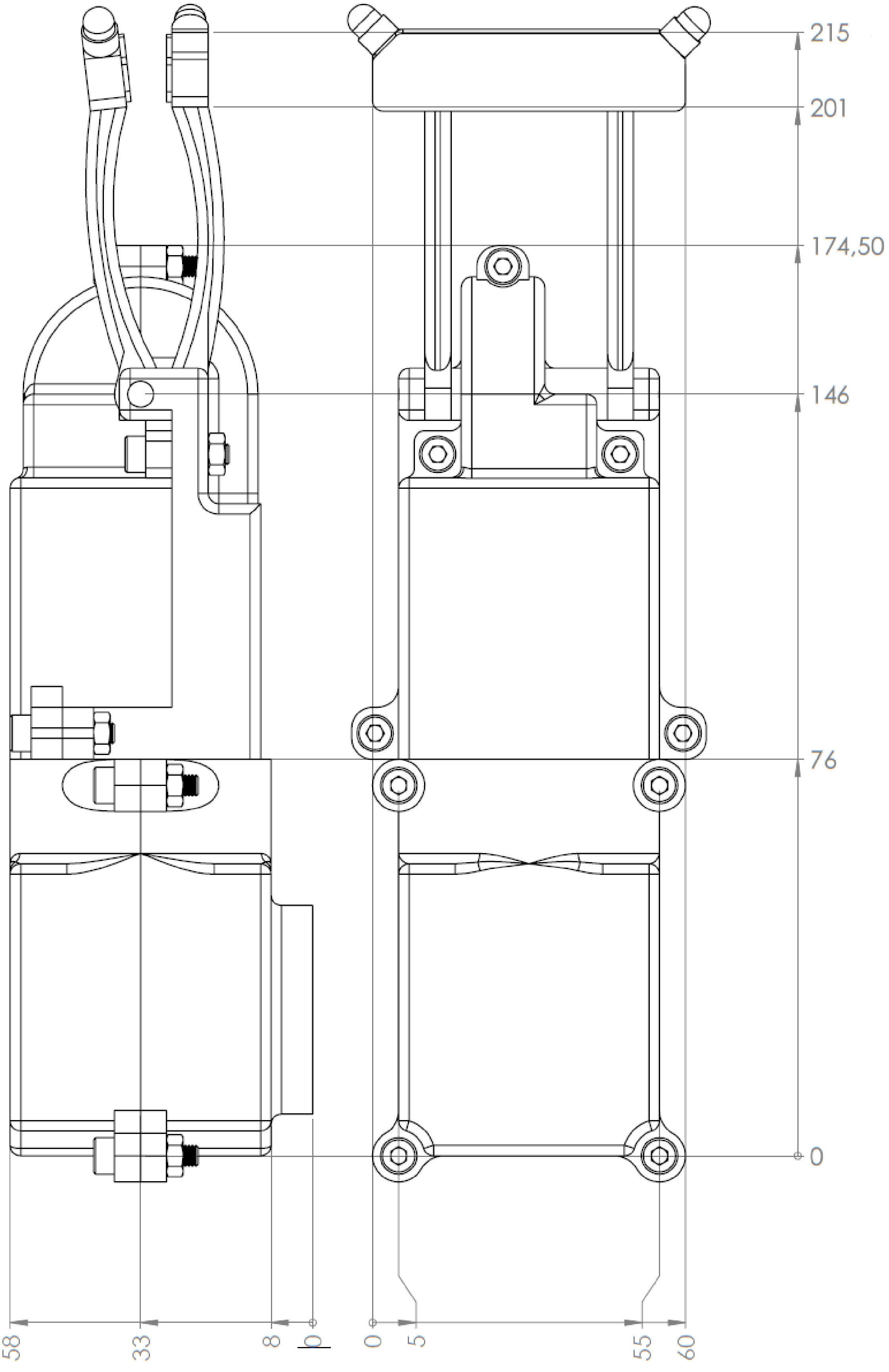


COMMON RATEING		SPECIVICATIONS	
STEP ANGLE	1.8°±5%	VOLTAGE	12V
PHASES	2	CURRENT	0.33A
INSULATION RESISTANCE	100Mohm(500V DC)	INDUCTANCE	46±20% Mh
CLASS OF INSULATION	B	RESISTANCE	34±10%
WEIGHT	0.20Kg	HOLDING TORQUE	0.23N.M

REV.	EPO#	DETAILS	DATE
A		1ST ISSUE	090327

SCALE
UNIT mm
SIZE A4
DRAWN XUHEZHAO 20090307
CHECKED
APPROVED
UNSPECIFIED TOLERANCE:
MATERIAL
FINISH
MERCURY MOTOR
TITLE SM-42BYG011-25
SHEET 1 OF 1
REV A
DWG.NO. SM-42BYG011-25-090327

Appendix 2 – Main measurements of assembled tool



Appendix 3 – CD with Solidworks files

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no