Concept design of an ultra-light industrial robot

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André Jaber

Commissioned by: Robotdalen
Tutor (Company): Johan Ernlund
Tutor (University): RagnarTengstrand
Examiner: Rolf Lövgren

Abstract

The use of industrial robots are increasing in areas such as food, consumer goods, wood, plastics and electronics, but is still mostly concentrated in the automotive industry. A problem is that workstations in smaller and medium sized companies that produce small batches of products don't get productive enough by having a permanently placed industrial robot. A solution could be a lightweight robot that is adaptable to the product need. It would have lower moving mass that will reduce the power need and result in "greener" robotics.

The aim of this project has been to develop a concept of a lightweight robot using lightweight materials such as aluminum and carbon fiber together with a newly developed servo actuator prototype.

The main problem was how to place the servo actuators, to create a wrist that would be thin and durable, while keeping performance as an ABB IRB 2600 robotic wrist. The wrist also needs to be constructed for cabling to run through on the inside. It is expensive to change cables and therefore the designing to reduce the friction on cable, is crucial to increase time between maintenance.

A concept generation was performed based on the function analysis, the QFD and the specifications of requirements that had been established. From the concept generation, twenty-four sustainable concepts divided into four groups (representing an individual part of the whole concept) were evaluated. From the evaluations a few concepts from each group was chosen to do a more thorough investigation on. The best concepts from each group were then merged into a final concept that was taken for further development.

The chosen concept was more detailed designed, which seemingly did not fulfill the requirements as good as I had hoped, but during the further development a small change in the concept helped with fulfilling those demands. To evaluate possible component failure, an FMEA was established.

The chosen concept of this thesis could fulfill the problems of designing a lightweight arm while keeping the same performance as the IRB 2600 robotic arm. This was realized by using the newly developed servo actuator together with the design that resulted from the implemented design process. The chosen concept has a thin wrist, with smooth passages for cables to run through keeping costs down. The robotic wrist needs more thorough analysis and testing, and I recommend that a mechanical prototype is made to test the movements of the robot.

Acknowledgements

This thesis concludes my studies at Mälardalen University; a large portion of my learned academic knowledge has been tested in this report, spent at Robotdalen.

I especially want to thank Johan Ernlund and Ingemar Reyeir who gave me the opportunity to conduct a master´s thesis at Robotdalen. Both Johan and Ingemar have been very resourceful, and have supported with their expertise.

I also want to thank Torgny Brogårdh, my tutor at ABB. He has been very useful, taking time from his work to help me design the robotic wrist, and Ove kullborg, who has an extensive past designing industrial robots.

I want to thank Carl E Andersson who has conducted the other part of this project, and been great to bounce ideas with.

Finally I want to thank Ragnar Tengstrand and all others who have been a part of this project, making it possible to complete.

Glossary

Actuator – A kind of motor or mechanical part, used for moving or controlling a mechanism or a system.

Back bend – Explained in appendix 4, "Specification of requirements".

CAD – Or Computer aided design, is a tool used for designing 3D components.

Gantry – A crane system.

IRB 2400 and IRB 2600 – IRB stands for industrial robot, and the number that follows is pointing to a specific robot in a particular robot family.

Offline programming – Used to simulate and test a robot cell, which can also be transferred to be used in the actual cell.

Payload – The allowed carrying capacity.

Resonance frequency – The frequency an object starts to vibrate with if it moves and is suddenly stopped.

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1. Introduction

The use of industrial robots is still mostly concentrated to the automotive industry while the market shares are increasing for areas such as food, consumer goods, wood, plastics and electronics. With the interest to find applications outside the automotive industry there are examples where robot manufacturers develop more human like robots with arms having 7 instead of 6 axes. These robots require efficient servo actuators that are integrated in a modular arm system. A question for the future is, how the market will react on a robot that for example has 50% or less weight and still keeps the same load capacity and motion performance;

- And will it affect installations and make them easier and less costly?
- Can the robot's mobility and flexibility improvements make it competitive?

A major problem today is that workstations in small and medium sized businesses have several products that are produced in smaller batches. Therefore, it is difficult for a company to station a robot permanently in one place where it might not be productive enough. In this case, a lightweight robot would be a good solution if it was easy to move and adapt to the product need. If the robot is not needed at some point, it can be moved aside to allow manual production. In addition a lighter robot might cost less, have a more versatile work span and therefore be regarded as a lower investment risk.

The future of lightweight robotics aims to be safer, where security barriers around the robot won't be needed because of lesser moving mass or of its built-in collision detection system. Low moving mass will also drastically reduce the power needed for the robot and will result in real green robotics. When the robots are mounted on other manipulators as linear tracks, the lower robot weight will also reduce the power needed for the other manipulators and these will also be smaller, which results in a lower investment cost.

The goal of this master thesis is to see how far it is possible to reduce weight of a 6-axes robot concept by means of efficient use of the lightweight servo actuator types that have been developed for 7-axes robots.

1.1 Background

This thesis has been performed at Mälardalen University (MDH), at the department of Innovation Design and Technology (IDT). It concludes with a master in engineering with focus on Product and Process Development. The examination covers 270 credits.

The job initiator of this thesis has been Robotdalen through Mälardalen University. ABB has been involved and collaborated with this project but the official sponsor of the thesis is Robotdalen.
The work is seen as part of a project searching for new automation opportunities with lighter industrial robots. The project is made out of two theses. The first thesis is focused on design and the second thesis, conducted by Carl E Andersson, is focused on economic effects. The other thesis concentrates on understanding the benefits of a lightweight robot, the effect on the industry and exploring what new market opportunities and applications it would entail.

1.2 Project initiation

The need to automate the machine park in a company has different meanings, depending on what industry type it is based on. In the automotive industry where large amount of vehicles are produced, it is now of substantial importance to automate in order to be competitive. But even smaller enterprises have begun to see the opportunities automation can bring to their companies. Benefits of consistent quality, improved productivity, ergonomic improvements and decreased staffing have been important factors. But for many companies it is still too expensive, the robot is not productive enough and it requires great expertise in robotics. For companies with small batch production that often requires swapping products, a robot that is more flexible, easier to move and adjust is needed.

Below is a hierarchical chart over the market needs that have been established;

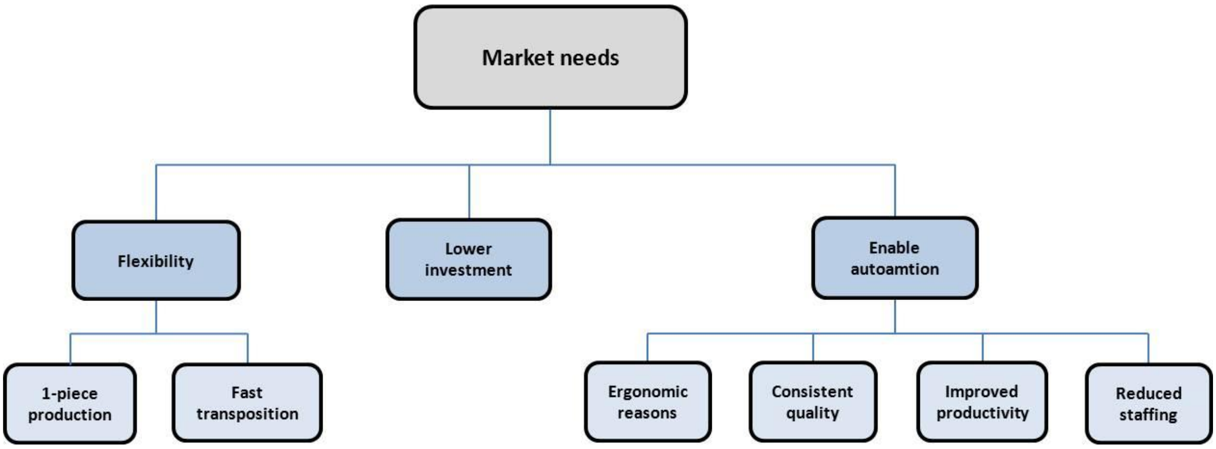


Figure 1: Market needs arises with the technological advancements.

These needs can be fulfilled by technological developments, including new materials that are both lighter and stronger, motors that become smaller and more powerful, and software that makes it easier, more accurate and more user-friendly to use robots. The technology development makes it possible for robot manufacturers to create robots that can satisfy new needs arising in the industry.

A hierarchical chart was drawn to illustrate the technological development, shown below;

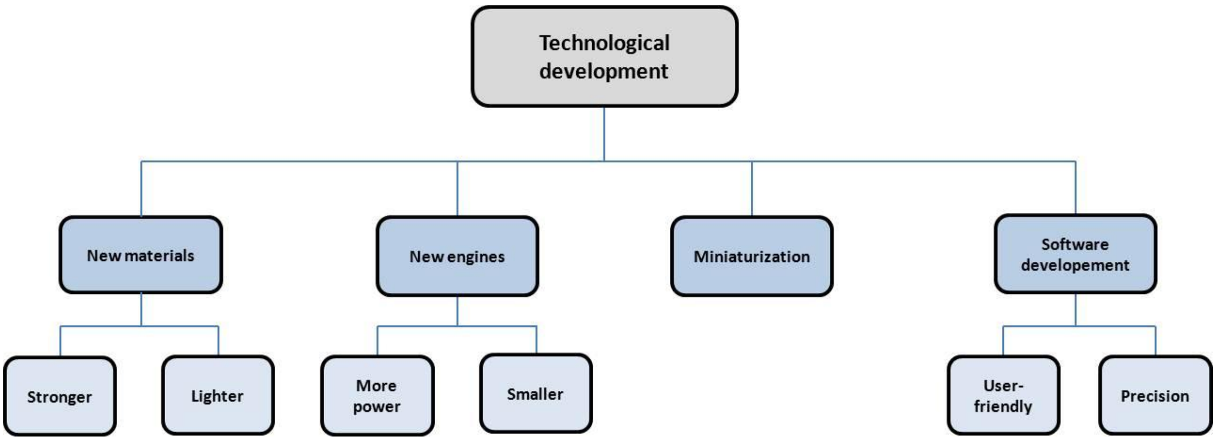


Figure 2: The advancement of the technological development.

1.3 Anthropomorphous robots

An industrial robot or manipulator is an automatically controlled and reprogrammable device, which is programmable in at least three axes. It can be mobile but today it is mostly mounted to stay in the same place. Industrial robots are used for a large spectrum of applications, which can be summarized by the following main areas;

- **Assembly**, where the robot puts components together.
- **Material handling**, the robot moves objects.
- **Manufacturing operations**, the robot performs work processes as painting, welding, cutting, polishing and grinding.

Here are some of the parts that are associated with industrial robots and might be raised in the context of this thesis;

- Manipulator, the robotic arm
- Control cabinet
- Program
- Camera
- Tool
- Sensors
- Auxiliary equipment

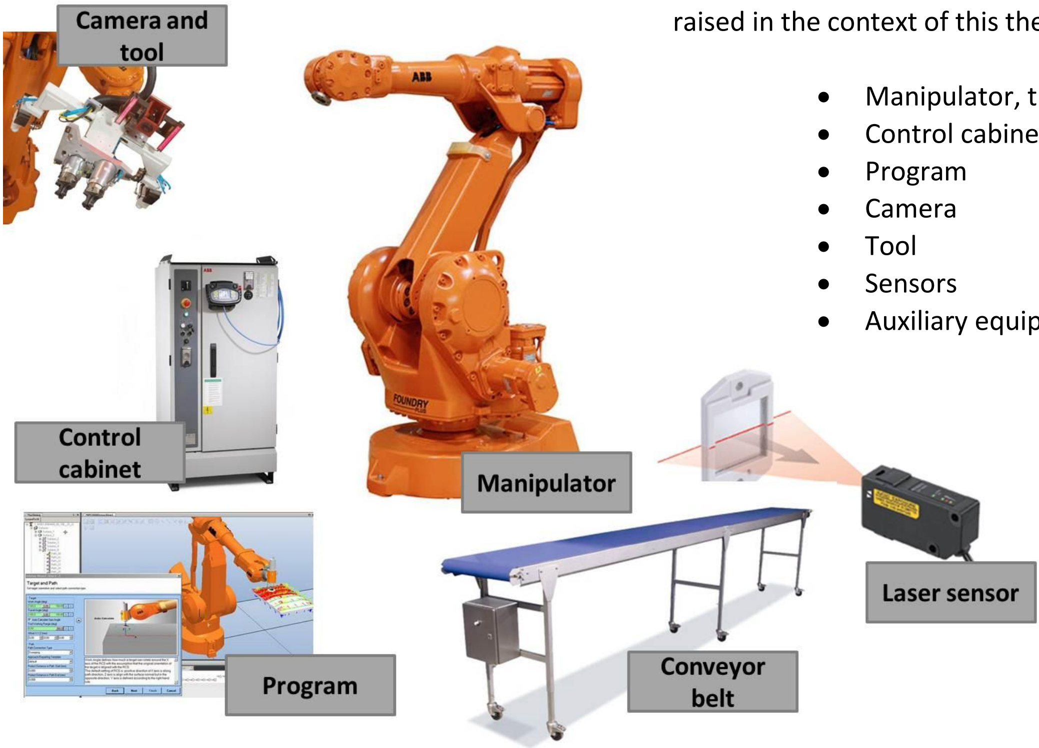


Figure 3: Automation products.

The robotic arm that in this case is the most interesting part for this thesis, resemble a human arm in several ways. It consists of a forearm, an upper arm and a wrist. The robot is standing on a base or foot. As seen in the figure 4 below, there are six arrows representing the rotational axes of the robot. When counting axes, you start from the base with axis one, and end up with the tip of the wrist which is axis six. Axes 1, 4, 6 (yellow) are rotation axes, and 2, 3, 5 (red) are bending axes.

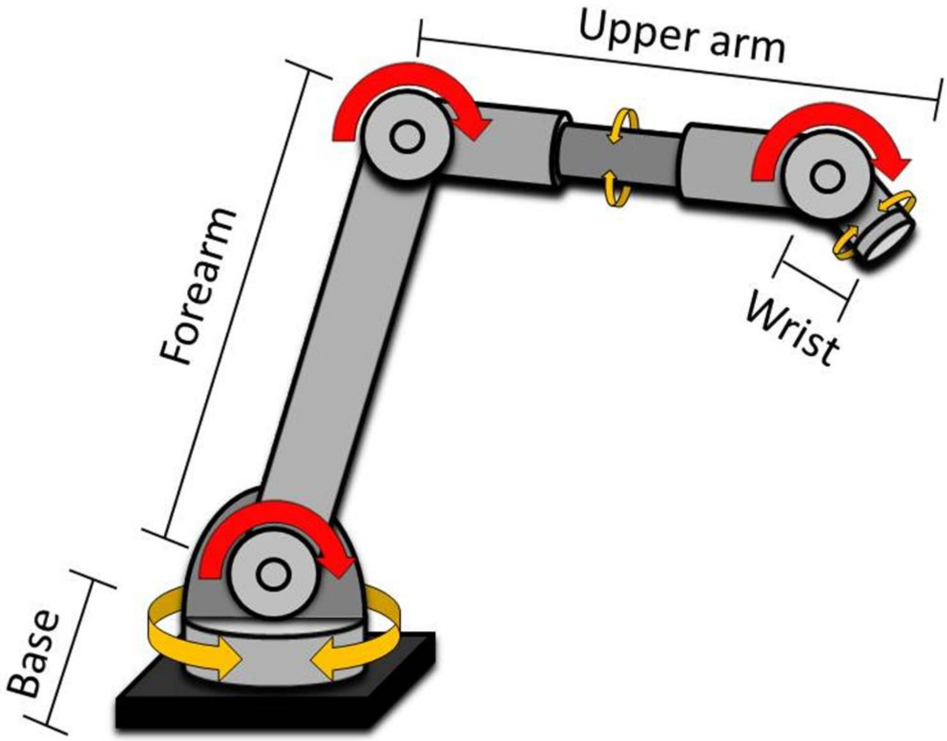


Figure 4: The axes and parts of a robotic arm.

The control system (control cabinet), also called controller, handles all the communication between the robot and all other equipment. This is done by sending motion signals to and receiving sensor signals from the different motors. One control system can be able to control more than one robot.

The program is telling the control system what has to be done.

The working tool like a gripper or a welding tool is mounted at the end of the wrist.

The camera can be used to show the robot where to grab parts that lay in a random order at a conveyor belt. The camera takes a picture to capture the position and rotation of the object, the program then tells the robot how it has to move to be able to pick it up.

Sensors are used to detect events that the robot system should react on. It could for example be a sensor which gives a signal because a component is in the right place and is waiting to be picked up.

Auxiliary equipment is the extra equipment that is needed to run a robot installation, it could for example be a conveyor for the objects to be handled by the robot or a gantry manipulator, on which the robot is mounted, usually upside down.

2. Aim of project

The project aim is to develop a concept for a lightweight industrial robot. The work will primarily deal with the design of a new robotic wrist that will be much lighter than an existing robot wrist with the same performance. The new design is going to be based on existing ABB robots (IRB 2400 and IRB 2600), and inherit some of their specifications. These have been listed in the *Specification of Requirements*[1]. Beside the wrist it was also possible in the scope of the thesis to create an esthetical design for the whole robot.

The two main goals of the project are as stated:

- Generate a constructional design of a new robot wrist including axes 4-6, where a design proposal should be verified and then delivered. The wrist is going to be based on a recently developed lightweight servo actuator prototype. The wrist concept is expected to be applicable on several robot models. In order to verify the design, stress calculations and FEM analysis will be used.
- Develop an esthetic design for the whole lightweight industrial robot, where design esthetics from the brand ABB will be implemented.

[1] Appendix 4

3. Project directives

At the start of the project, a number of project directives that are expected to be followed were presented by the job initiators (Robotdalen):

- Analyze competitors that are working with lightweight robotics.
- Define the design requirements.
- Generate concepts.
- Evaluate concepts.
- Chosen concept should have a more detailed mechanical design.
- Conclusion and recommendations to aid further work.
- Presentation of the project at Mälardalen University.

The design process will be well documented and the result published in a technical report. It should contain a final concept with a detailed mechanical design. The thesis should also include a 3D CAD model, designed in Solid Works.

4. Problem statement

As explained in the background section, the project was initiated because the need for a more flexible and mobile robot had emerged. Until now, these needs have been difficult to satisfy and were limited by the available technology. The problem to address in this report is, therefore, how we can make use of new technological advancements to develop a product that covers market requirements.

A review of other industrial robots might be necessary to help getting an understanding of the design basis and enable the possibility to develop a sustainable product concept. Some other problems that need to be answered for the project to be successful are stated below;

- How to make use of lightweight or composite materials to design a robot with a low weight and on the same time keep the price, the difficulty to produce and the nr of components to a minimum?
- How can the robot be designed to hold an idiom that appeals to users?
- How can a particular servo actuator module be placed to make the robot arm small and on the same time reduce torque and resonance frequency?
- How to design a robot concept that can be applicable on several robot models?
- How can the robot be designed to draw cabling through the inside of the robot wrist (axes 4- 6)?

5. Limitations

The thesis project covers 30 credits which is 20 weeks full-time work. The project will result in a technical report with a thorough description of the working procedure. The final concept should be presented as a 3D-CAD model. A scaled physical model is not created of the robot, due to the size of the project.

The extent of this thesis is to produce a conceptual design for a lightweight industrial robot where the main constructional work will be done on axes 4, 5 and 6. It should also result in a functional design of the entire robot in which ABBs idiom should be expressed.

Cost calculations are not addressed in this thesis.

This thesis does not investigate how a lighter robot affects the use of robots. For example, if lower requirements on auxiliary equipment cut costs, and if increased flexibility and mobility creates new opportunities for small batch production.

6. Theoretical background & solutions methods

This chapter describes the theory, tools and methods that have been applied in the analysis of this project.

6.1 Gantt-chart

A Gantt chart is used to plan a project. It´s a schedule where you can follow activities over time, and ensuring that critical activities are ready in time to avoid delays. When creating a Gantt chart, the time axis is adjusted according to the project scope. Depending on the scope of the project, there is several milestones and review opportunities to keep track of the project. When dealing with larger projects it could be an advantage to divide the scheme into several smaller schemas and thus be able to plan each part of the project more closely.

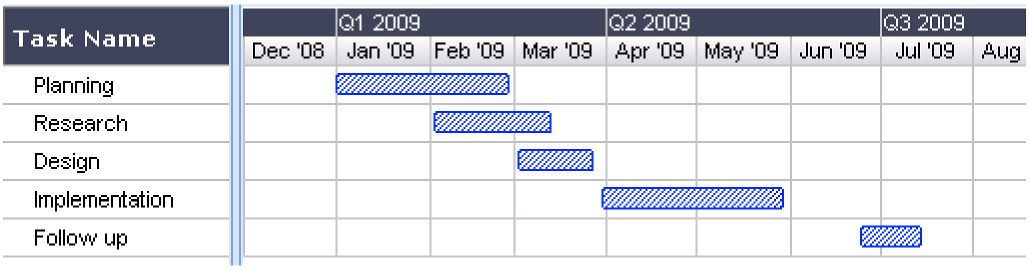


Figure 5: A Gantt chart in Microsoft Project.

It is an advantage to follow up planned time with the actual outcome; this gives an overview of the project situation and providing experience to future projects. A Gantt chart shows us;

- Which activities are included in the project
- When an activity start and end
- How long each activity lasts
- If activities overlap each other
- Project scope, when does the whole project start and end[2]

6.2 Product development model

Regardless of what kind of product is being developed, a similar process is used in most cases. The process chosen follows the same character of this project and can be used almost as it is, with minor changes and additions. It is constructed by a linear approach where you work with the phases sequentially, instead of what is known as concurrent engineering where you work with the various phases in parallel.

The design process chosen is based on a holistic approach which is characterized by;

- It is a structured work process to give fast results
- Simplifying the production process in an early stage to reduce cost
- By creating a better product from a user perspective will increase the revenue

[2]Gantt, 2010

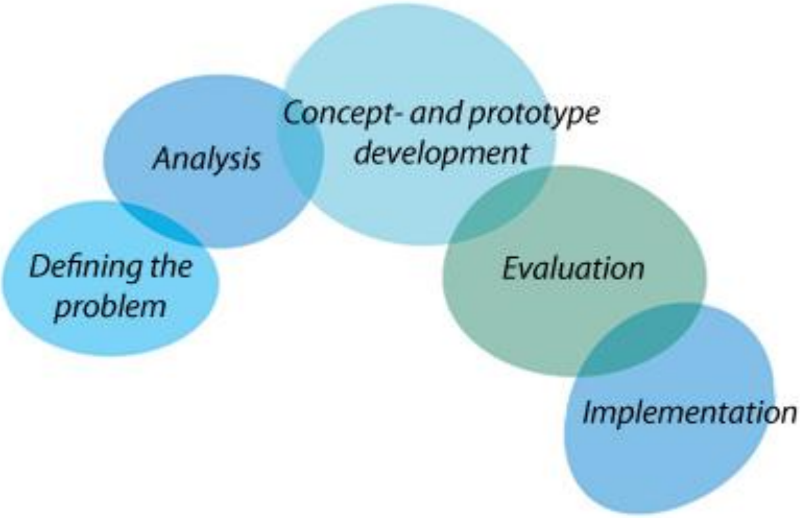


Figure 6: Arlander Design product development model.

The different parts of the development model are further explained below;

Defining the problem
- The assignment is defined with the customer

Analysis
- Understanding the problem situation
- Knowing the intended target customer of the product
- Use text and image to document
- Establish the specifications of requirements

Concept and prototype development
- Generate ideas by using sketches and models
- Use functional prototypes to verify the mechanical principles
- Evaluate the shape and size by sketching models

Evaluation
- Evaluate the concepts form and function
- Correct any deficiencies

Implementation
- Create CAD-models of the product
- Adjust the details for production
- Choice of material[3]

[3] Arlander, 2010

6.3 Function analysis

A function analysis is used to get a hold of the products different functions and performances without looking at its technical solutions. This analysis helps to think more freely, to not look only at the technical solutions, but instead at the product as a function, and in turn describe the functions that meet the needs and demands of the specification of requirements.

A function is usually described with a verb and a noun, i.e. "transfer torque". A hierarchy of functions is created and can be illustrated with a tree structure;

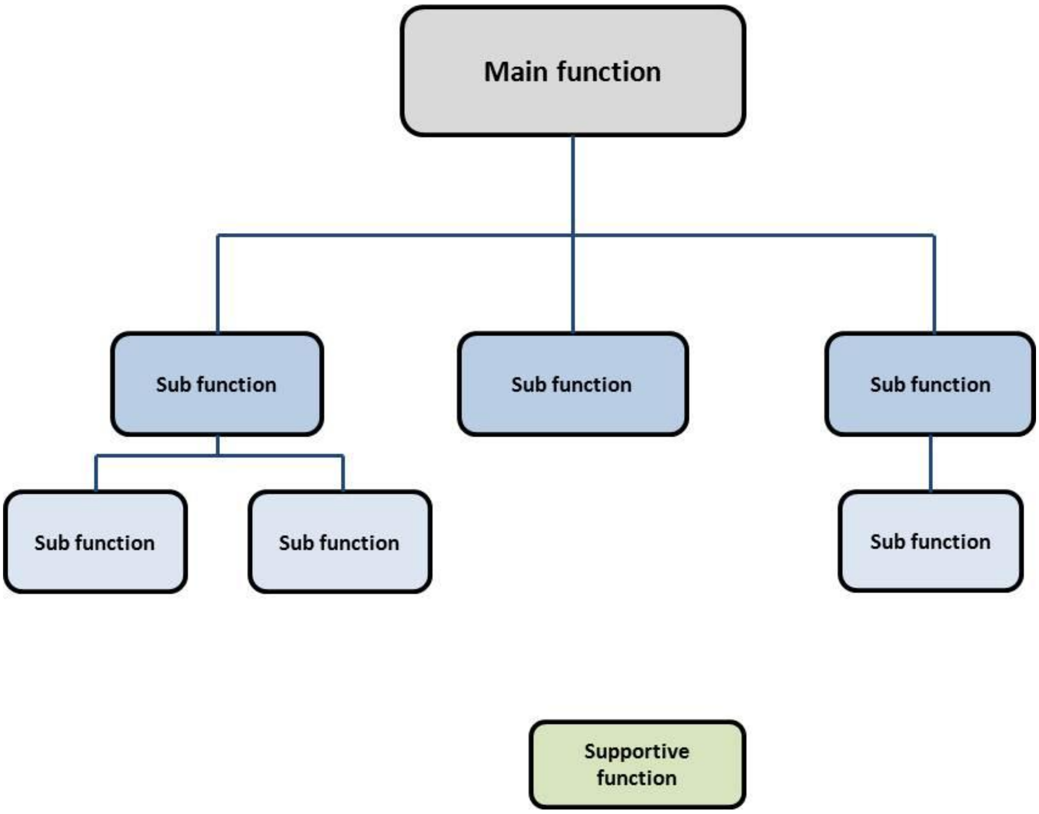


Figure 7: A general function analysis.

The Function analysis consists of a main function, some sub functions, and mostly one or more supportive functions;

Main function
Describes the main purpose, in this case "own lifting capacity"

Sub function
The Main function can be divided into Sub functions, which together allow the main function to work. Removal of a sub function will result in an unfulfilled main function.

Supportive function
Supports a superior function, but is not necessary for it to work.[4]

[4]Österlin, 2007

6.4 Quality function deployment (QFD)

The Quality function deployment is a method used in product development. By matching customer requirements (1) with Technical requirements (3), it can indicate which product functions are most important for customers. It can be used on a single product, or to compare two or more existing products. The QFD helps to understand the problem, but it is also a fundamental part in establishing the specifications of requirements.

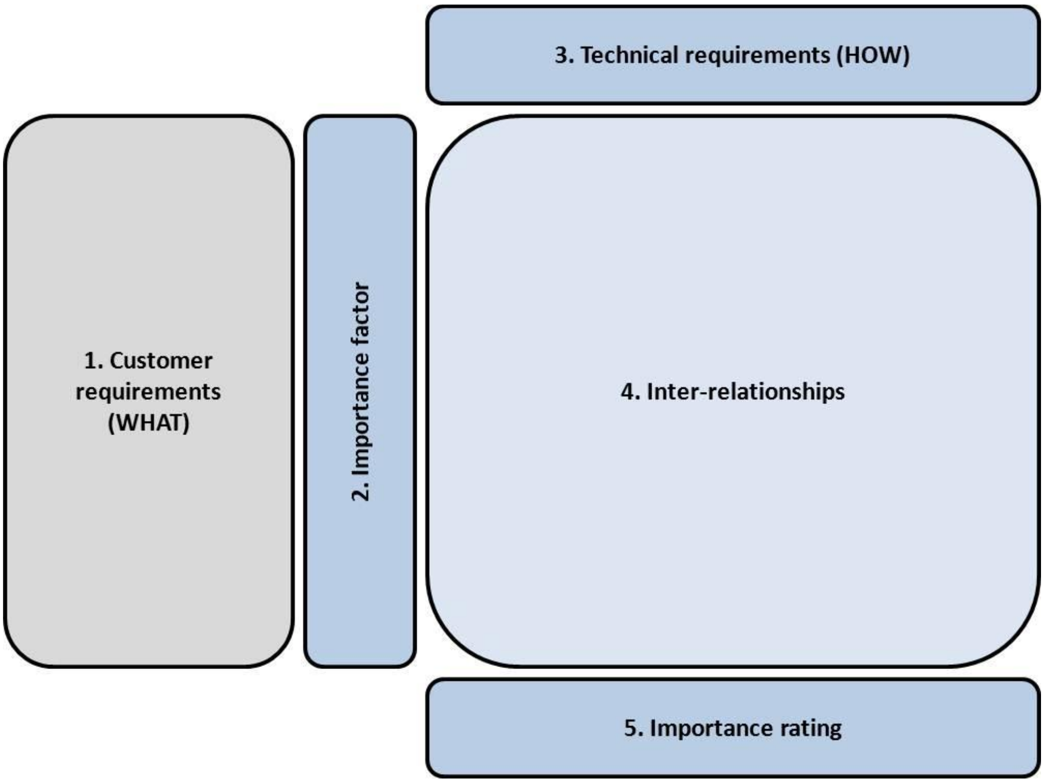


Figure 8: A simplified QFD

The five blocks in the QFD is explained in order below;

1. **Customer requirements (WHAT)**
   These are market demands that answer the question WHAT, for example; the robot has to be able to lift objects and have a long reach.

2. **Importance factor**
   Here we state the importance of these demands with a scale from 1-5 with 5 being the most important.

3. **Technical requirements (HOW)**
   Product properties are identified to satisfy the market demands, for example; the choice of motor is one property that will help to satisfy the need to be able to lift objects.

4. **Inter-relationships**
   The relation between market demands and product properties are presented here with 1, 3 or 9. Use 9 if there is a strong relation and 1 for weak. If there is no relation at all there will be a blank space or 0.

5. **Importance rating**
   By multiplying the inter-relationship (4) with the corresponding importance factor (2) and then summoning each row we will get an importance rating. The result is then used to see which product parameters are the most important.[5]

6.5 Specification of requirements

In the beginning of a new project, conditions and goals are examined for the planned product. By looking at business opportunities and market demands a list of functions can be created. In the specification of requirements, product needs are gathered and organized. The document is updated during the course of the project and keeps detailed information about the deliverables and is used in the development process as a steering document. The QFD has been a helpful tool in creating the specification of requirements.[6]

6.6 Generating concepts

When generating concepts we use the ability to find new combinations or solutions to different problems to get fresh ideas. The point is to solve the problems defined earlier. The use of the function analysis, QFD and the specification of requirement will aid the generating process. Methods used for concept generating are brainstorming and brain writing. These tools help to stimulate the creativity.[7]

6.6.1 Brainstorming

Brainstorming is one of the most known methods when generating ideas. It is used in a group and is most effective with 3-6 people. The purpose is to speak openly and try to discuss ideas together. Some of the rules that should be followed when brainstorming;

- It is strictly forbidden to criticize and judge during the meeting
- A large variety of ideas are preferred
- Try to think “outside the box”, wild ideas should be pursued
- Try to complete and combine ideas that have been produced[8]

An effective way to generate ideas is by using the function analysis as a foundation for brainstorming, and trying to solve each of the sub-functions.[9]

6.6.2 Brainwriting

Brainwriting is a method that can be used individually but will be more effective in a group where there are more perspectives, which in turn will generate more ideas. It works as brainstorming, but instead of discussing the ideas together, they are written down separately. This is a good way of keeping the ideas more versatile without getting stuck on each other’s ideas. Another great way to use this tool is to pass on ones ideas to another member in the group, for that person to develop further.[10]

[5]Ullman, 2010
[6]Ulrich, Eppinger, 2008
[7]Österlin, 2007
[8]Österlin, 2007
[9] Olsson, 1997
[10]Mycoted, 2010

6.7 Evaluating concepts

Evaluating concepts is an important step; just having plenty of ideas doesn't make a product. This method is used after a number of concepts have been generated. There are also a variety of tools for deciding which ideas are better than others. Something to beware of is "falling in love with a certain solution"; it makes it hard to see the problems and limitations of that solution, and will as a consequence steer the outcome when using the evaluation tools. A way around it would be to present the solution to someone else, who hasn't made an opinion and can do a fair evaluation.[11]

6.7.1 Pugh´s method

A Pugh matrix is used for evaluation concepts; it compares concept with different requirements to see how well they fulfill the criteria. The criteria's preferably comes from the specification of requirements.

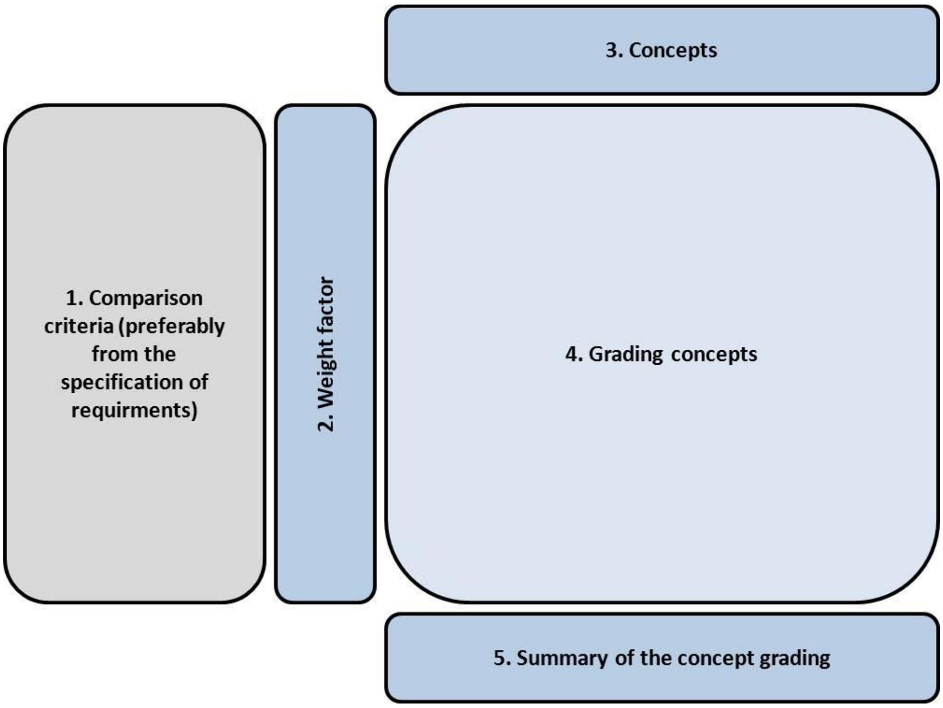


Figure 9: A general Pugh matrix.

The evaluation is made in five steps;

1. **Comparison criteria**
   Here are the criteria used for comparison placed, it is suitable to use the criteria from the Specification of Requirement.

2. **Weight factor**
   These criteria's are given a weight factor from 1-5 depending on its importance, with 5 being the most important and 1 the least.

3. **Concepts**
   Concepts are lined up, with one concept in each column. The concept that is spontaneous considered the best, or an already existing concept is put as the reference for evaluation.

[11] Österlin, 2007

4. **Grading concepts**
   All other concepts are compared with the reference concept. They will then be graded on each of the criteria's In comparison to that. The reference concept will be given 0 in all rows of grading. The grading ranges between a five-point scale.

   +2 The concept fulfills the criteria a lot better than the reference
   +1 The concept fulfills the criteria better than the reference
   0 The concept is as good as the reference
   -1 The concept is worse than the reference
   -2 The concept is a lot worse than the reference

5. **Summary of the concept grading**
   The summary is made in four steps;
   Number of +
   Number of –
   The summary of (the number of +) – (the number of -)
   The summary where all the + and – are multiplied with the weight factor[12]

6.7.2 Failure Mode and Effect (FMEA)

FMEA is a method that is used for reliability analysis. The method decides the relationship between possible failure modes of a design and what affect these causes. FMEA is a tool to systematically identify a design process potential failure mode, their causes and consequences.

In brief, it involves trying to locate every possible failure the product might encounter, to assess its likelihood, seriousness, the possibility of discovery, and to seek corrections. Experience, imagination and judgment are the mental tools needed.[13]

6.7.3 Simulations

Simulations can be made with a FEM analysis (Finite Element Method) to test the durability of components. FEM analysis is used to test and illustrate, bending and twisting on structures, and also indicate stress distribution and displacements. This results in a detailed visualization, which can simplify construction of components.

[12] Olsson, 1997
[13] Olsson, 1997

7. Applied solution procedures

This chapter will demonstrate the results compiled from the tools and methods that have been applied in the previous chapter.

7.1 Gantt-chart

In the beginning of the project a document was created to establish a structured work process. As explained in the earlier chapter, Microsoft Project is a tool often used when managing projects. This project is however quite small and I have therefore used Microsoft excel to organize weekly planned activities. Activities have been put into seven categories which I have also used as the project milestones, these are; *Defining the project, gathering information, product development tools, wrist design, designing the robot, presentation* and *resource time*. The Gantt chart can be found in appendix 1.

7.2 Function analysis

A function analysis was created together with the people involved in the project, with the purpose to describe the different functions the industrial robot need to fulfill. The function analysis has been an important tool when creating the QFD, setting up the specifications of requirements and for generating the concepts. In the function analysis we found that the main function of the robot is to be able to move an object to a point in space and that the most important sub functions are; Allow movement, Allow lifting, Allow grabbing, Allow communication and Safety. The function analysis can be found in appendix 2.

7.3 Quality Function Deployment (QFD)

In order to set up the QFD, information from customers and users have been collected from meetings with the people involved in the project, interviews with companies[14] working in the automation business and by looking at existing solutions. The market demand that has been used in the QFD was based on three categories; Function, Assembly/Maintenance and General, see appendix 3.

The purpose of the QFD has been to see the connection between market demands and product features. The most important product characteristics were;

- Choice of material
- Dimensioning
- Motor choice and placement

From the QFD one can see that these three product characteristics are mostly affecting the function categories from which we can draw the conclusion that the robot´s function is the most important area. In addition, it seemed that the idiom (esthetics) and industrial design was very important. Manufacturing cost and the number of components were also an important factor.

Knowing the importance of different characteristics helps when setting up the specification of requirements and will later be useful when evaluating the concepts.

[14] Appendix 7

7.4 Specification of requirements

To set up a specification of requirements, my tutors and I have gone through the specifications that were initially requested in this project. We complemented the list of needs and demands with results given from the QFD and through brainstorming at meetings. Some of the specifications have come from the conclusions of a pre-study made by Torgny Brogårdh where he studied the possibilities of lightweight robotics.[15]

The requirements is explained more thoroughly in Appendix 4, the requirements have been categorized into "general", "technical" and "desirable" to best be explained. Below follows a list of the requirements:

The main applications of the robot;
Machine tending, material handling, arc welding

7.4.1 General

- Mounting: Floor, wall, shelf, tilted, inverted
- The robot should use lightweight materials
- A carbon fiber tube should be used in the upper arm to connect the robots wrist with the robots elbow
- The robot wrist will be constructed using the newly developed servo actuator
- The robotic wrist should be designed to be as thin as possible, reduce torque and resonance frequency
- The wrist concept must be applicable on several robot models
- Cabling needs to go through the inside of the robotic wrist (axes 4- 6)
- It needs protection Standard IP67
- Outer robot dimensions should not be larger than IRB 2400 and 2600, preferably thinner in some parts
- The robot should be able to back bend

7.4.2 Technical

Features

- Reach 1,65 m
- Payload 12 kg
- Armload 15 kg (will not be tested in the thesis)
- Number of axes: 6

Physical

- Robot weight: Max 60 kg (Will not be tested in this thesis)
- Upper arm weight: Max 15 kg

Movement

Table 1: Axes movement working range.

Axis	Working range
Axis 1	Rotation + 180° to 180°
Axis 2	Bend + 155° to 95°

[15]Brogårdh, 2007

Axis 3	Bend + 75° to 180°
Axis 4	Rotation + 400° to 400°
Axis 5	Bend + 120° to 120°
Axis 6	Rotation + 400° to 400°

The robot should have the same movement area as IRB 2400, below;

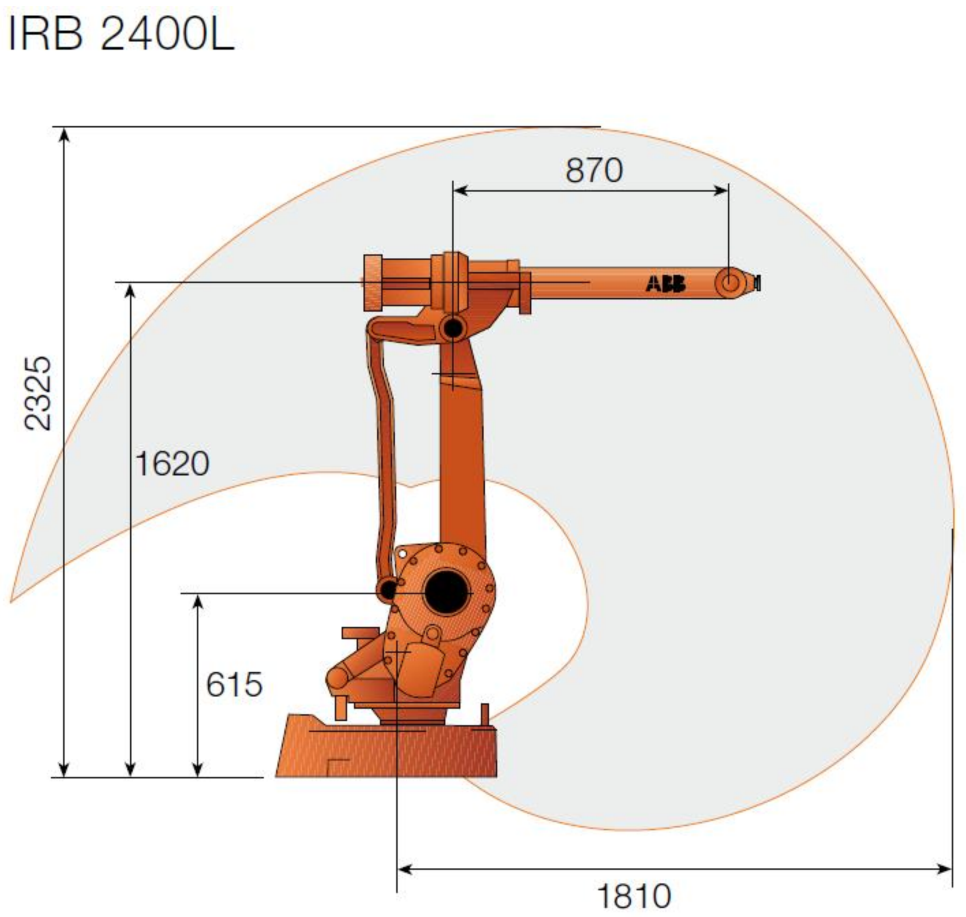


Figure 10: IRB 2400 movement area.

7.4.3 Desirable

- The esthetics of the robot should express quality and fit into its surroundings. It also needs to reflect the company's brand.
- Low manufacturing cost
- Few number of components

7.5 Generation of concepts

Before looking at different concepts, brainstorming meetings were conducted together with the tutors from Robotdalen and ABB. These sessions mostly consisted of discussion about the robot wrist and how it should be designed. For reference we used IRB 2400 and IRB 2600, both as a basis for designing the robot but also to make quick assessments. Sketching was a useful tool for discussing and evaluating ideas. Below are a few of the sketches that emerged and were discussed during the meetings;

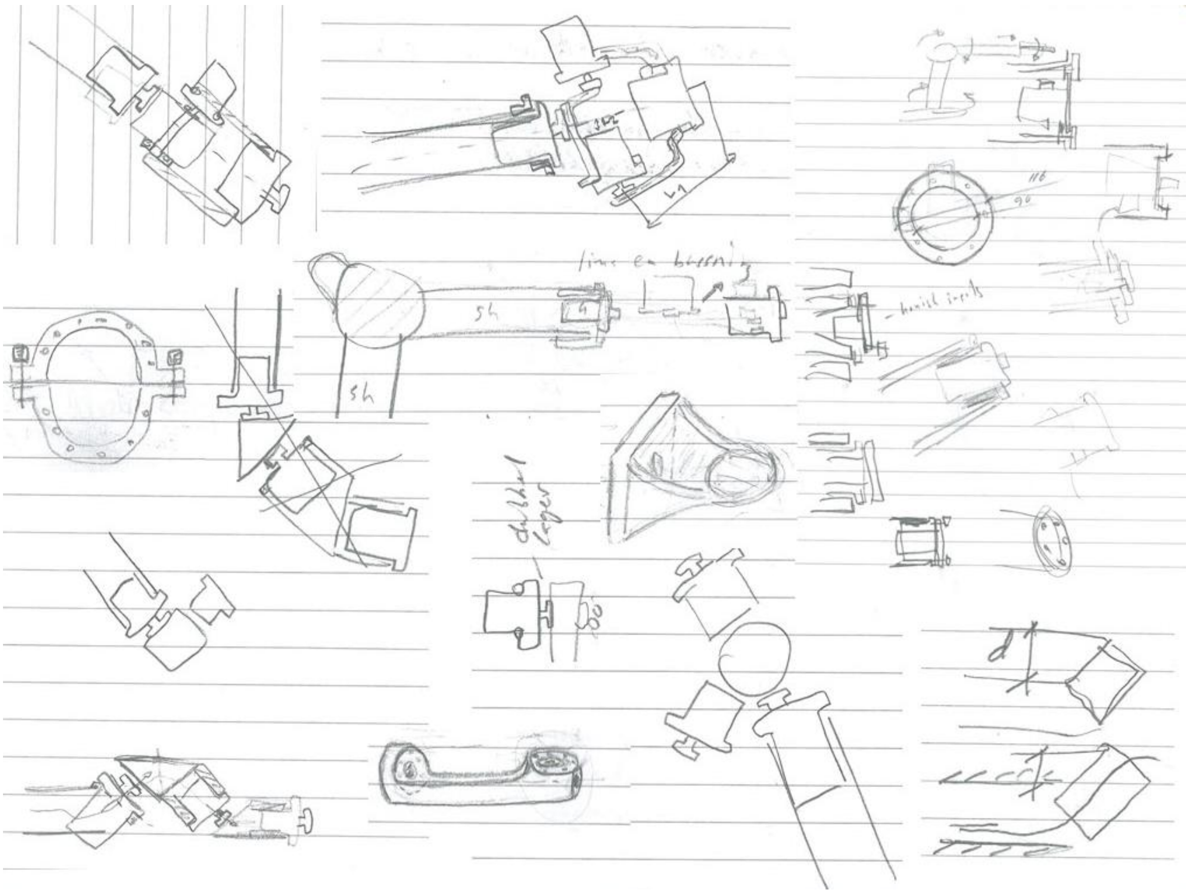


Figure 11: Idea sketches.

These sketches and ideas laid a good foundation for the concept generation. From the brainstorming sessions we could distinguish four different individual leads, from which we created four questions. The concept generation is based on these four questions that are listed below;

- How to connect the carbon fiber tube to the wrist of the robot?
- How to connect motors in axes 4-6 to each other?
- How to position the motors in relation to one and other?
- How to draw the cables through axes 4-6?

With these questions and the previous brainstorming sessions as a basis, concepts were generated and grouped with their individual question. Many ideas were created into concepts, and several of these were filtered out to make it more manageable. When filtering concepts, an elimination process was used by matching the concepts with the questions raised during the problem statement. These questions were, for example;

- Does this concept consist of a lot more components compared to the others?
- Is this concept a lot larger than the average?
- Does the concept need manufacturing methods that are much more expensive than for others?

The remaining concepts that fulfilled and passed these base “requirements” were chosen for further consideration. There were a total of twenty-four concepts chosen. These concepts can be found in appendix 5.

7.6 Evaluation of concepts

After the concept generation phase and after the pre-filtration of ideas, the remaining concepts were systematically evaluated. Since the concepts were divided into four separate categories (A, B, C and D) it resulted in four different evaluations; “Carbon fiber connections”, “Connection between motors”, “Placement of motors” and “Wiring”. One method used for evaluating concepts was the Pugh´s matrix. In addition, the evaluation steps have also been based on my acquired knowledge and through discussions with my tutors and engineers from ABB.

7.6.1 Pugh´s method - Category A

The remaining concepts from category A (Carbon fiber connections) were put into the Pugh´s matrix for evaluation. Some of the requirements used in the Pugh´s matrix were acquired from the QFD. Since this is a new project, the reference used in the Pugh’s matrix was the concept considered the best before evaluation, which was *concept A5 – Inside bushing ver. 2.* The Pugh´s method matrix can be found in appendix 6.

The result acquired in the Pugh´s matrix shows that *concept A4 – Inside bushing* and *concept A9 – Extended aluminum bushing* from “carbon fiber connection concepts” received the highest score. The results are used for aiding in the determining of which concepts that should be chosen for further development. In this case the concepts chosen are concept A4 and A9, which will be reviewed more thoroughly in chapter 7.6.2.

7.6.2 Category B, C and D

For category B, C and D, Pugh´s method was not used because of different reasons that will be stated later on in this chapter.

Category B (Connection between motors)

This part of the evaluation deals with how to connect the actuators to each other. A conclusion made in the filtration stage was that the body of motor 4 will be statically connected to the carbon fiber tube. With this in mind together with the filtration questions, there were only four concepts remaining. Pugh´s method was not to be used, since a decision was made during a discussion to rule out concept B2 and B4. These concepts were connected by motor 5 to the shaft of motor 6, meaning that when axis 6 is rotating it has to move the whole body of motor 6. A lesser payload can therefore be used, because the moving mass will be a lot greater with this extra weight. Therefore, the concepts chosen for further development are *Concept B1 – Shaft-shaft, body-body* and Concept B3 – Shaft-body, shaft- body. All concepts are explained in appendix 5.

Category C (Placement of motors)

The third part of the evaluation deals with the placement of motors in relation to each other. When brainstorming concepts for this part, several concept ideas came up. Most of them were combinations that were too much alike and it was hard to distinguish them from each other. After looking closer at these concepts and after the filtration, four could be separated, having unique traits. *Concept C4 – Snake wrist* was chosen for a side project since it had other application uses than the other concept, and was therefore not compared with the other concepts.[16] The other three concepts were taken to a final evaluation without using the Pugh´s method. Calculations were made on these concepts to estimate the exposed torque on motor 4 and 5 in a static position.[17]

Category D (Wiring)

The wiring variants are based on the concepts chosen in category C "placement of motors", so the concepts that were not applicable on these were filtrated. How to decide which wiring solutions to choose, we used an evaluation process based on three statements;

- Moving wires should be avoided as much as possible
- There should not be any sharp edges where the wiring is drawn
- Wiring should be drawn with fewest sharp "turns" possible

The concepts that came closest to meet these demands and that had a logical passageway between the motors were *Concept D1 – Straight wiring* and *Concept D6 – Around shaft wiring.*

7.6.3 Evaluation of the remaining concepts

In this step of the evaluation, the concepts remaining in each category were taken for further analyzing to decide which of these would together form a single combined concept. This was done by looking at the positive and negative sides of the individual concepts, but the compatibility with the concepts from the other categories also had a great impact in the decision process. In order to understand the painted 2D pictures of the concepts more, different colors have been used to separate certain details. Please note that different parts of the drawing might not be in scale with each other. The color codes are shown below;

- **Blue –** The motor
- **Light grey –** The aluminum bushing (or aluminum)
- **Dark grey –** The carbon fiber tube
- **Yellow –** Fastener between the aluminum and the motor
- **Red –** Connections between motors
- **Purple –** Cabling

In the pictures below when there is more than one motor, the motor the most to the right always has the superior number. We are looking at the wrist so when there are three motors, it is motors 4, 5 and 6 with their corresponding axis starting from the left.

The picture to the right illustrates the different parts of the motor. These will be addressed several times in this chapter.

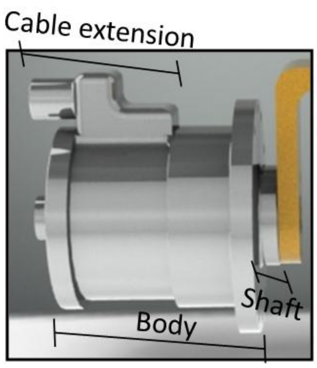


Figure 12: Parts of the motor.

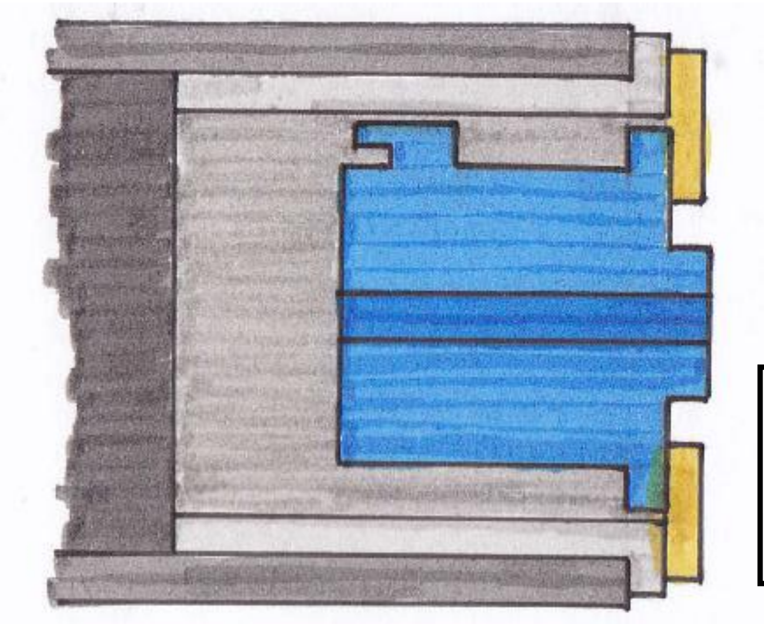
[16] Appendix 9
[17] Appendix 8

7.6.4 Evaluation A – Carbon fiber connections

This part dealt with how to connect the carbon fiber tube to the aluminum bushing. According to the Pugh´s matrix, concept A4 and A9 was taken for further analyzing, before deciding which of the two concepts to develop further.

Concept A4: Inside bushing

This concept is focused on putting the motor and the aluminum bushing inside of the carbon fiber tube, to make the wrist look like it is shortened and give the upper arm a cleaner look. The concept would also be easy to manufacture, since the aluminum bushing, and the aluminum fastener part have uniform and simple shapes. The concept did partly emerge from the ambition to make it easy to assemble.



Blue – The motor
Light grey – The aluminum bushing
Dark grey – The carbon fiber tube
Yellow – Fastener between the aluminum and the motor

Figure 13: Concept A4 – Inside bushing.

The pros (advantages) and cons (disadvantages) that we could find for this concept have been put into words below;

Pros

- The aluminum parts are both uniform with simple shapes, making them easy to manufacture.
- Since the motor doesn't need to fit into special compartments, and the motor is screwed together with the fastener before placed on top of the aluminum bushing makes it easy to assemble.
- The simple aluminum parts are easy to manufacture which lowers costs.
- The wrist will be durable because of simple shapes, and because there are no compartments cut out of any part.

Cons

- Many screws are needed.
- The size of the carbon fiber tube carries most of the weight in these concepts, and because this concept has the largest tube, this concept is also the heaviest.

- The concept needs a large carbon fiber tube and will therefore have a thicker upper arm.
- Maintenance is difficult, since the rest of the wrist is mounted directly on this motor, and needs to be disassembled in order to reach motor 4.

Concept A9: Extended aluminum bushing

This concept emerged from the need to achieve a thinner carbon fiber tube. Since this is a lightweight version of an IRB 2400 and IRB 2600, it should give the impression of being thinner than the original. By reducing the diameter of the tube, the weight of the upper arm could also be significantly decreased. Another problem that needed attention was that there were no good solutions for making maintenance easy for motor 4. This is why the motor was placed on the outside, to make it easily accessed by removing the other part of the aluminum without any other disassembly.

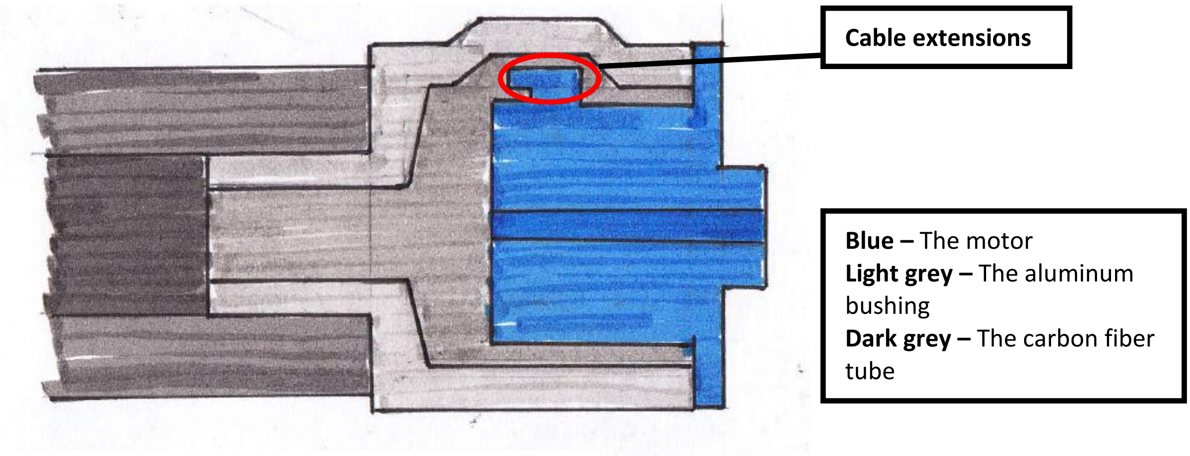


Figure 14: Concept A9 - Extended aluminum bushing.

The pros and cons for this concept are described below;

Pros

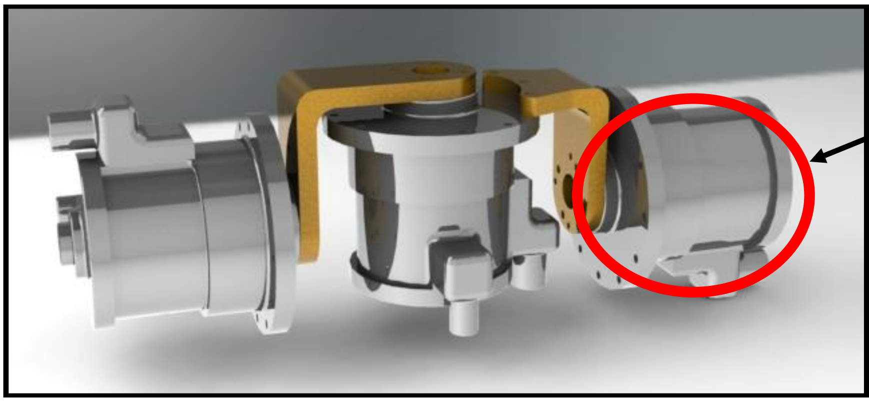
- Easy to maintain both motor and cables by removing the aluminum plate, without any other disassembly necessary.
- Lower costs since this concept has a very thin carbon fiber tube.
- Splitting the aluminum into two parts makes assembly a lot easier.
- By not making any cuts in the carbon fiber or aluminum for cable extensions, makes the concept more durable.
- The arm will be thinner because of the smaller carbon fiber tube.
- Fewer components are needed.
- This concept has a low weight because of the small carbon fiber tube.

Cons

- Both the aluminum parts will be more difficult to manufacture because of their shapes.
- Higher manufacturing costs for the aluminum parts, since they have more complex curvature.

7.6.5 Evaluation B – Connection between motors

This part deals with how to connect the actuators to each other. This was partly conducted to decide the moving mass when an axis rotates before any additional payload has been added. Since motor 4 is statically connected with the carbon fiber tube, four combinations are available. A decision was made to rule out concept B2 and B4. These concepts were connected to the shaft of motor 6, meaning that when axis six is rotating, the body of motor 6 is moving. This would impact the capacity of the robot allowing it to carry a lesser payload because of the already large moving mass.



When rotating axis 6, the whole motor steals a lot of the weight from the payload.

Figure 15: Concept B2 – shaft-shaft, body-shaft (was ruled out due to increased torque when rotating axis 6).

As a result, there are only two concepts left, which were taken directly to a final evaluation. *Concept B1 – shaft-shaft, body-body* and *concept B3 – shaft-body, shaft-body* was further analyzed.

Concept B1: Shaft-shaft, body-body

This concept is connected from the shaft of motor 4 to the shaft of motor 5, which means that when bending axis 5, it needs to move the mass of motor 6 and the body of motor 5. Motor 5 is connected from its body to the body of motor 6, which means the shaft of motor 6 is the only mass moving when rotating axis 6.

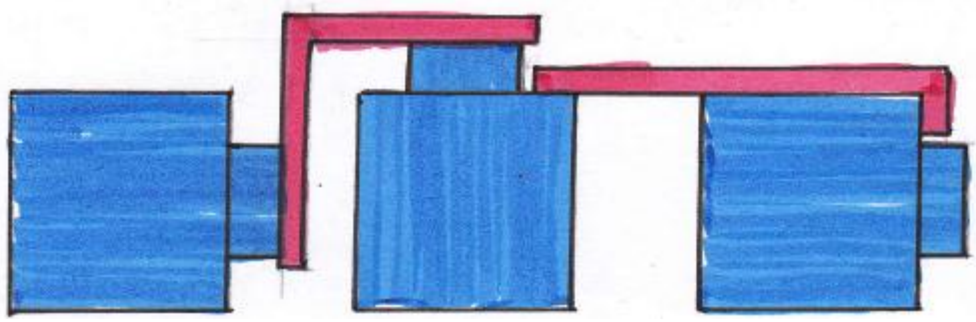


Figure 16: A sketch of concept B1 - shaft-shaft, body-body.

Blue – The motor
Red – Connections between motors

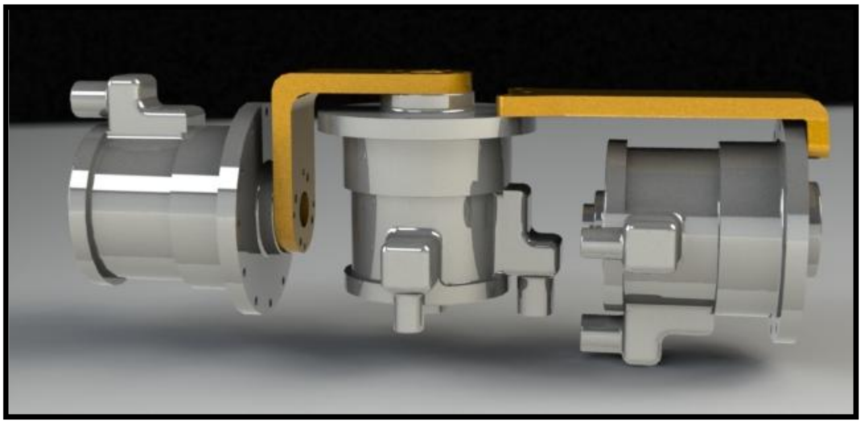


Figure 17: A CAD of concept B1 - shaft-shaft, body-body.

Pros

- Lower moving mass in axis 6, since the shaft of motor 6 is the moving part.
- The surfaces connected by moving parts are smaller, since body of motors 5 and 6 are moving together. The area that needs protection from dirt is between the moving part of the shaft and body of motor 5.
- The body of motor 6 can be closer to the body of motor 5, since they are moving together. Moving them closer to each other reduces torque.
- Moving cables is reduced, and therefore it makes it more durable and able to perform for a longer period of time before maintenance.
- The concept is less costly to manufacture because there are fewer moving cables, and the rotating areas that needs to be protected are smaller.

Cons

- Bending axis 5 creates more moving mass, reducing the applicable payload and increasing torque.

Concept B3: Shaft-body, shaft- body

This concept is connected from shaft to body between motor 4 and 5. When bending axis 5, motor 6 and only the shaft of motor 5 moves. The connection of motor 5 and 6 are between the shaft and body. When rotating axis 6 the shaft of motor 6 is moving.

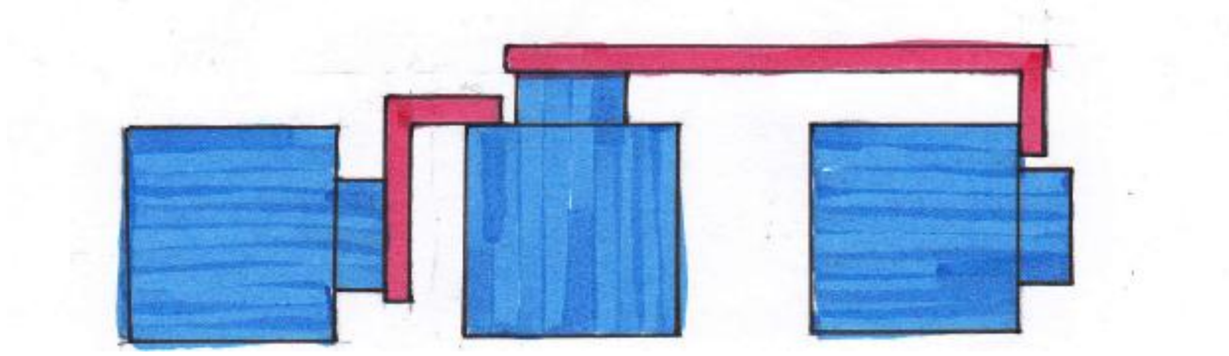


Figure 18: Concept B3 - shaft-body, shaft-body.

Blue – The motor
Red – Connections between motors

Pros

- A low moving mass when rotating axis 6 because the body of motor 6 is static when axis 6 is moving.
- When bending axis 5 there is a low moving mass because the body of motor 5 is static, increasing the payload.

Cons

- The rotating area needs to at least surround most of the body of motor 5
- This large area needs to be protected from dirt.
- The seals between the moving parts need to be changed often due to loss of function which leads to more frequent maintenance.
- More moving cables needs to go through the wrist, which creates more friction and needs more frequent maintenance.
- This concept is expensive to produce because of more moving cables and because there is larger areas that need to be protected against dirt.

7.6.6 Evaluation C – Placement of motors

This part deals with the placement of the three actuators in the wrist. The placement of the motors in relation to each other is very important since it can impact several essential factors, listed below;

- It can affect the thickness of the arm
- It can create a positive or negative effect on torque and resonance frequency
- It can affect wiring
- Programming a robot movement can be made harder or easier
- It can affect the area needed when turning a robot axis

Two of the essential factors to consider are the torque and resonance frequency, these can be determined by deciding the distances L1 and L2 as shown in figure 17.

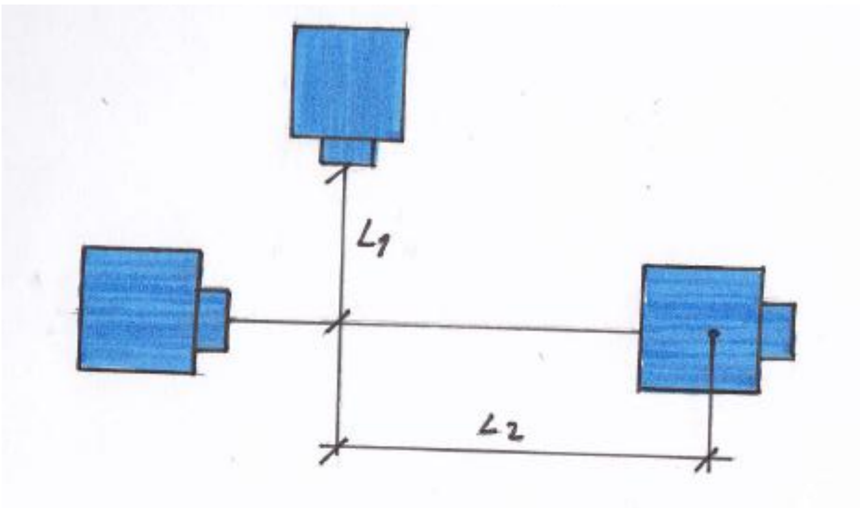


Figure 19: Motor placement factors.

L1 = Less distance decreases the resonance frequency
L2 = Less distance decreases torque

Concept C1: Open arm

In this concept motor 4 and 6 are concentric with each other by their center axis. This concept was generated for the purpose to give an open space for the main cables to travel. That's why motor 5 is turned with its shaft touching the centre axis of motor 4 and 6. This creates an open space where cabling can pass.

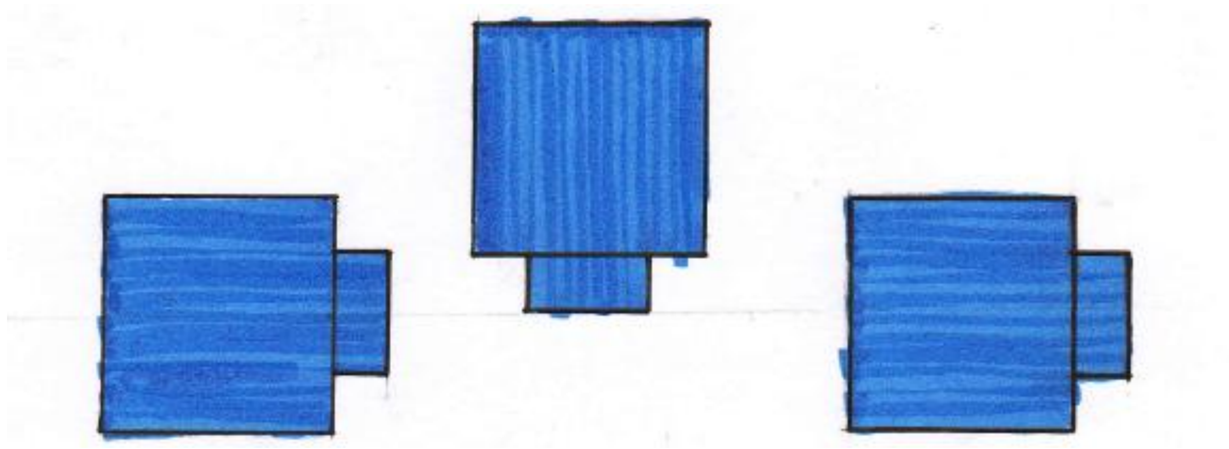


Figure 20: Concept C1 - Open arm.

Pros

- The open space can be used to do wiring, and less sharp turns of the wiring is possible.
- Motor 6 can be moved closer towards motor 5 which reduce torque when bending axis 5.
- Axis 5 is in the centre of motor 6 which reduce the motors resonance frequency to make it more accurate when moving.
- The open space, and easy cabling results in easier assembly.

Cons

- The arm is broader because motor 5 is only going to the center of motor 4 and 6 axel.
- Difficulties to illustrate the arm as lightweight occur when the wrist is broader.

Concept C2: Thin arm

The purpose of this concept was to create the thinnest arm possible, using the chosen motors. In this concept, motor 5 and 6 are concentric by their center axis. Motor 5 had to be turned 90 degrees and then put with its centre (on the length) in the centre of their axes.

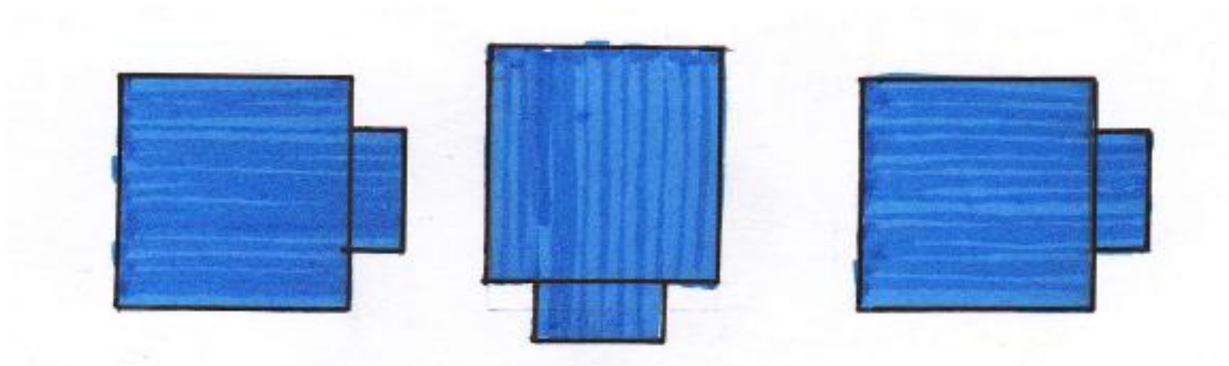


Figure 21: Concept C2 - Thin arm.

Pros

- By putting motor 5 in the middle between motor 4 and 6 makes this concept the smallest with these motors.
- The esthetics of the arm will be easy to transform to radiate the feel of lightweight when the arm is thin.
- The resonance frequency will be quite small by having motor 5 bending axis close to the centerline of motor 4 and 6 axels.

Cons

- A greater distance between motor 5 and 6 is necessary to be able to draw cables.
- There will be many sharp turns for the cabling, so they wear out faster. This means that it reduces the time between maintenance.

Concept C3: Thick arm

This concept came up from the idea to create an as compact arm as possible. This means that motor 6 is below motor 5, and therefore creates a thick arm. The center of motor 5 and 6 is in line with the center axis of motor 4.

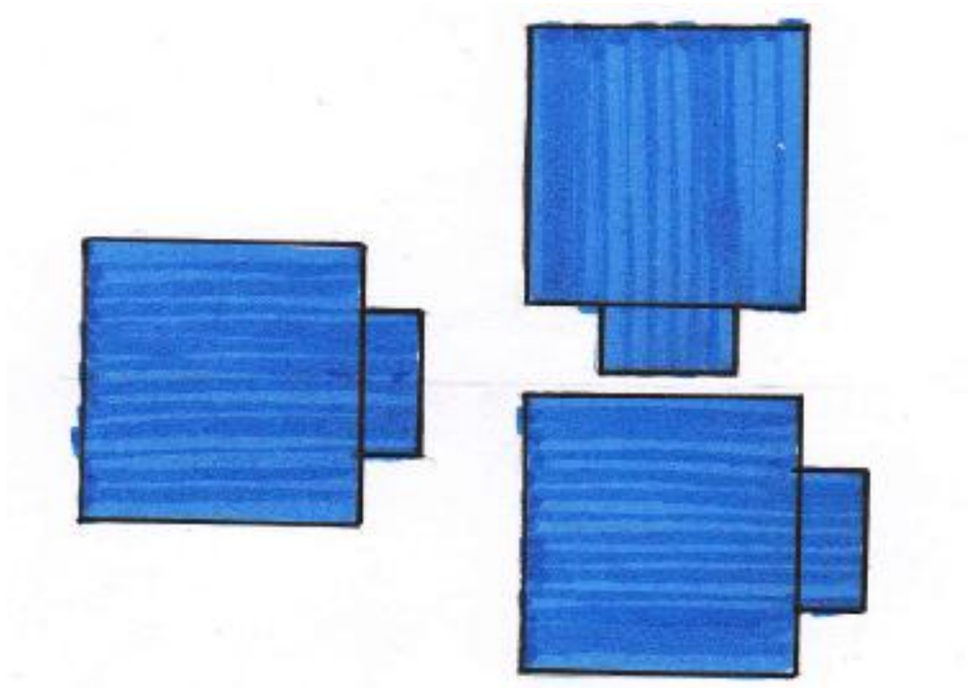


Figure 22: Concept C3 - Thick arm.

Pros

- The wrist is very compact and axis 5 has reduced torque when bending.
- The resonance frequency is small, when having motor 5 close to the centerline of motor 4, increasing the accuracy when moving.

Cons

- The arm is very hard to design to look lightweight because of the thickness of the arm.
- The thick arm makes some work more difficult to carry out, for example when the robot needs to reach through thin areas.

7.6.7 Evaluation D - Wiring

This part deals with how to draw the wires in the wrist. How to draw the wires is very important since it can be very costly and cause a lot of problems if it is done badly. As told in chapter 7.6.2, some of the things that should be avoided when drawing wires are;

- Moving wires
- Sharp edges
- Sharp turns

This is why *Concept D1 – Straight wiring* and *Concept D6 – Around shaft wiring* were chosen since the other concepts could not pass these demands.

Concept D1: Straight wiring

In this concept wiring goes through the center axis of both motor 4 and 6 and below motor 5 in the open space where its shaft is pointing.

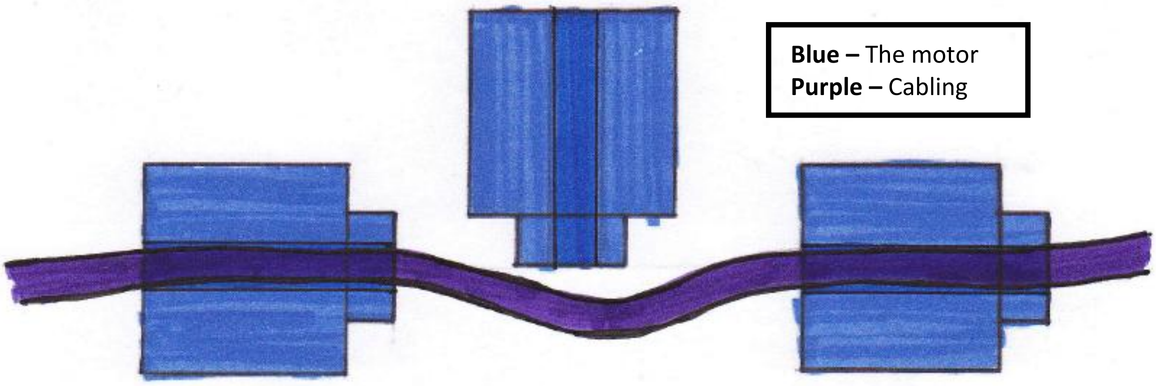


Figure 23: Concept D1 - Straight wiring.

Concept D6: Around shaft wiring

In this concept wiring goes through the center axis of motor 4 and 6 and around the shaft of motor 5.

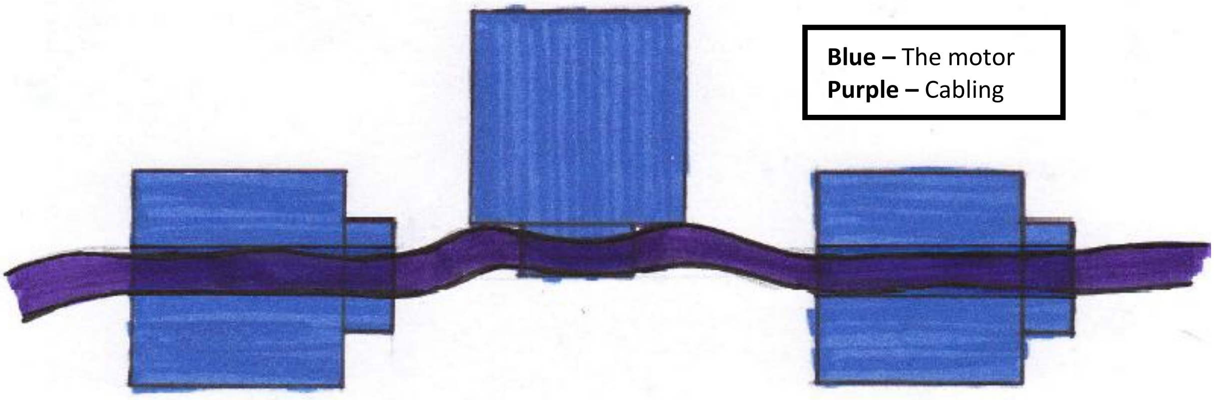


Figure 24: Concept D6 - Around shaft wiring.

7.6.8 Further development

After the final evaluation, a discussion took place to decide which of the concepts should be taken for further development. The concepts were compared with the problem statement, and how well they could respond to our issues.

Carbon fiber connections

After analyzing the two final concepts, and weighing the pros and cons against each other, it showed that concept A9 had significant more advantages than concept A4. Therefore *concept A4 – Inside bushing* was not taken for further development. This ended up with the choice of going further with *concept A9 – extended aluminum bushing*.

Connections between motors

There are three major concerns when deciding how to connect the motors. There should be fewer moving cables, the amount of moving mass should be reduced and the surface where the moving parts are connected should be as small as possible. *Concept B3 – shaft-body, shaft-body* was great in the aspect of reducing the moving mass, but came short with most other demands. Concept B1 – shaft-shaft, body-body were good for both cables and sealing among other things, and was therefore the concept chosen for further development.

Placement of motors

The decision was primarily based on how cables could be drawn. Therefore neither *concept C2 – thin arm* nor *concept C3 – thick arm*, was chosen as the final concept since there would be too much friction on the cables. *Concept C1 – open arm* was chosen for further development because it meant a lot less friction on the cables. Concept C1 was also a good combination between concept C2 and C3, being relatively thin and at the same time able to reduce torque.

Wiring

We could not decide which of the two cable solutions to choose since they had different advantages depending on how the rest of the wrist would be designed. Therefore both *concept D1 – Straight wiring* and *concept D6 – Around shaft wiring* were chosen for further development.

A sketch was made with the combination of the carbon fiber connection, the connection between motors and the placement of motors named concept E, illustrated below;

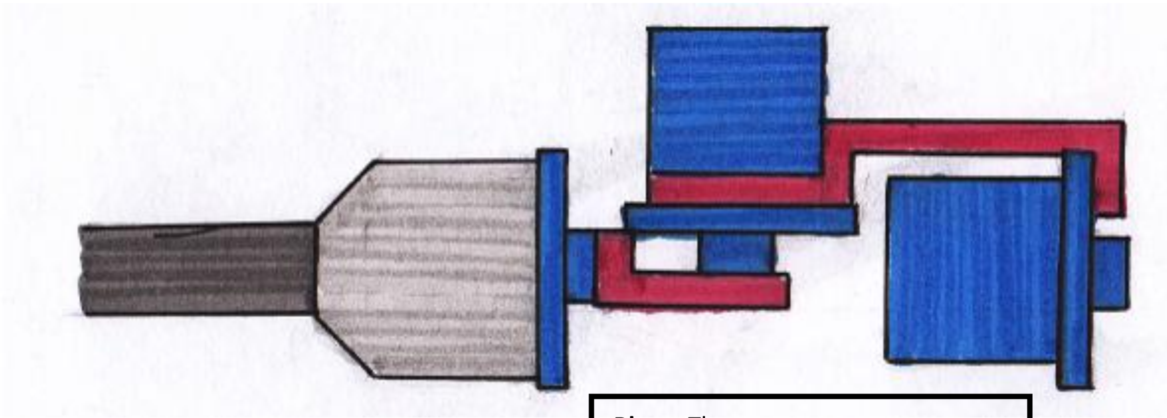


Figure 25: A sketch of the combined concept (concept E).

Blue – The motor
Light grey – The aluminum bushing
Dark grey – The carbon fiber tube
Red – Connections between motors

The concept was then sketched with the two different cable solutions;

Figure 26 shows a sketch of concept E combined with the wiring concept D1. This concept was named concept E1.

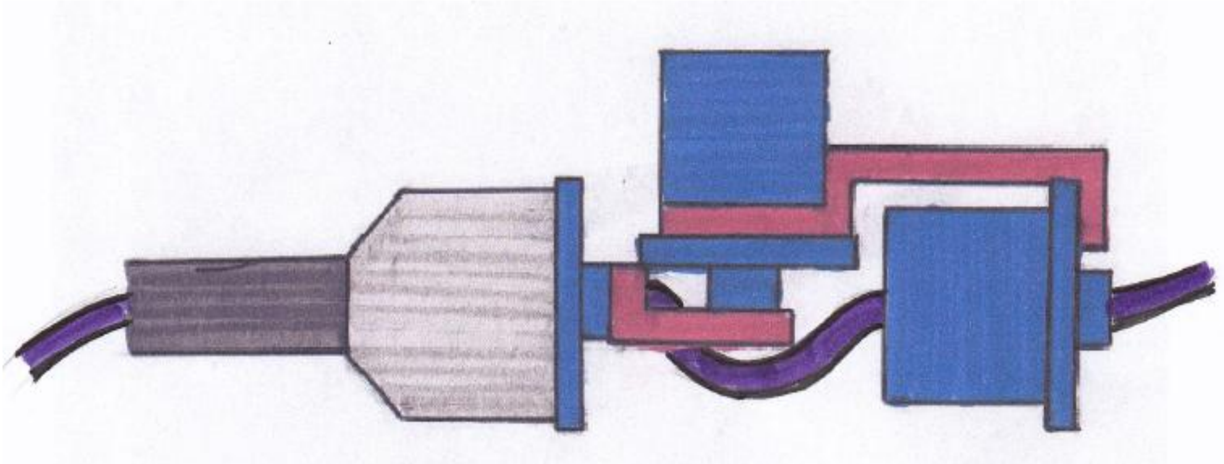


Figure 26: Combined concept with the straight wiring (concept E1).

Blue – The motor
Light grey – The aluminum bushing
Dark grey – The carbon fiber tube
Red – Connections between motors
Purple – Cabling

Figure 27 shows a sketch of concept E combined with the wiring concept D6. This concept was named concept E2.

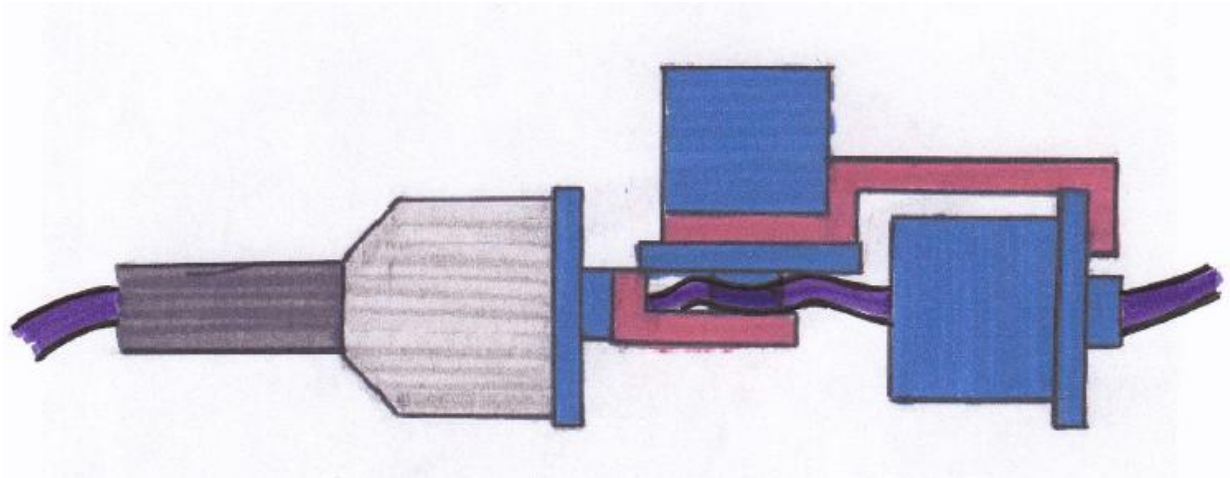


Figure 27: Combined concept with the around shaft wiring (concept E2).

Blue – The motor
Light grey – The aluminum bushing
Dark grey – The carbon fiber tube
Red – Connections between motors
Purple – Cabling

7.7 Developing the chosen concept

The next step was to develop the concept further, which started with enclosing the whole concept package with aluminum. A big issue when enclosing was trying to make moving areas that required as small sealing as possible. That is why I started with developing a seal between motor 5 and 6 with the chosen cable concepts.

7.7.1 Arm seal

The first thing I noticed was that the seal needed to be round to be able to give good protection, a seal with odd shapes are a lot harder to seal and also more expensive. When looking closely at *concept D6 – Around shaft wiring*, it appeared to be very hard to make a sealing for that concept. Therefore *concept D1 – Straight wiring*, was used. The key surface in need of sealing was axis 5 and is shown in figure 28, in yellow color and the wiring in purple.

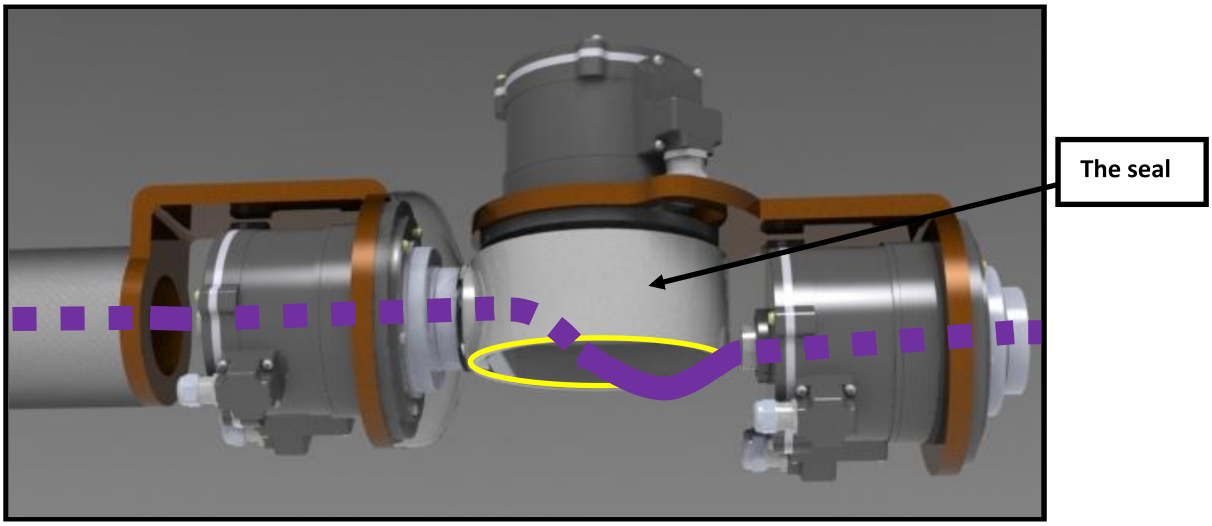


Figure 28: Seal in axis 5.

A plane is going through the middle of the cylinder (the seal) to be able to mount motor 5 on it. An opening was made near the motor 4 shaft to ease the passage for the cables. The opening had a chamfering and fillets to make a smooth transition for the cables.

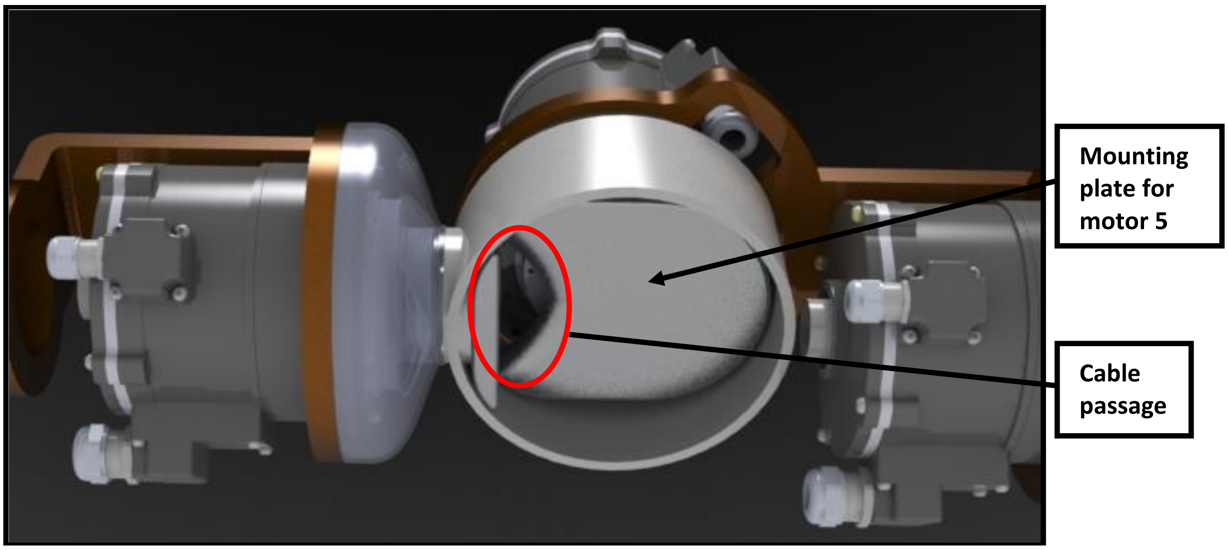


Figure 29: A closer look at the seal, and the mounting plate for motor 5.

7.7.2 Enclosed arm

The rest of the arm was closed in to cover all the internal mechanics and electronics. In this stage, there had been no emphasis on the esthetical design, instead it was concentrated to seal up between the different joints.

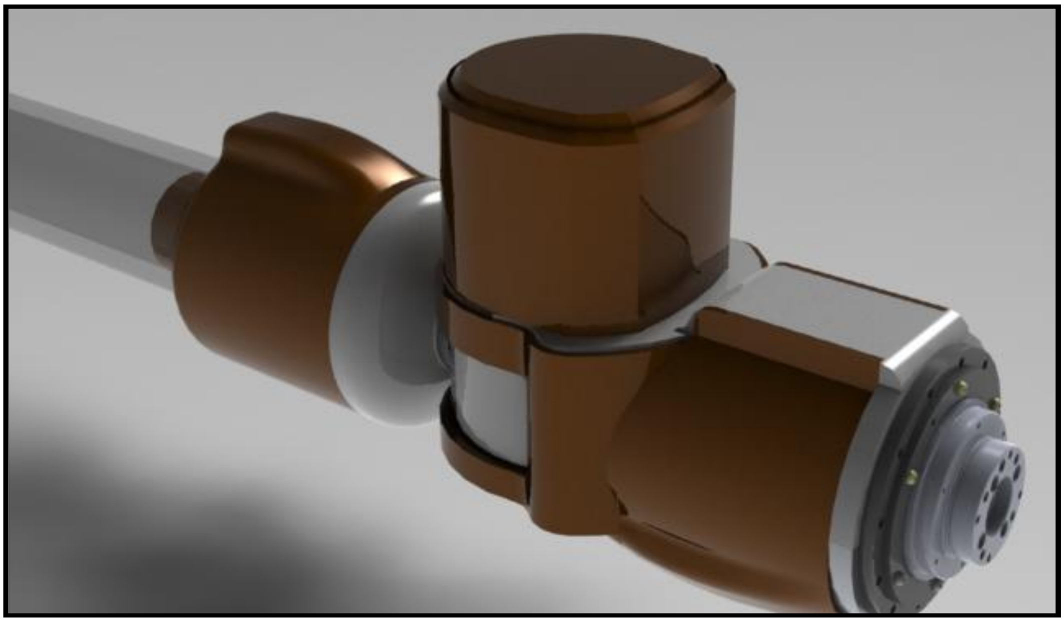


Figure 30: Enclosed arm.

7.7.3 Cable movement

Cables had to be drawn below the seal to reach motor 6. Therefore a gasket was made in the casing for motor 6 where the cables could pass. Since the casing is moving around the seal the cables will always have free space to move around. The casing was also made so cables needed for motor 5 also had enough space to move. This seal was made as a connector between motor 4 and 5 and would therefore be the static part whilst the casting for motor 6 turns around it.

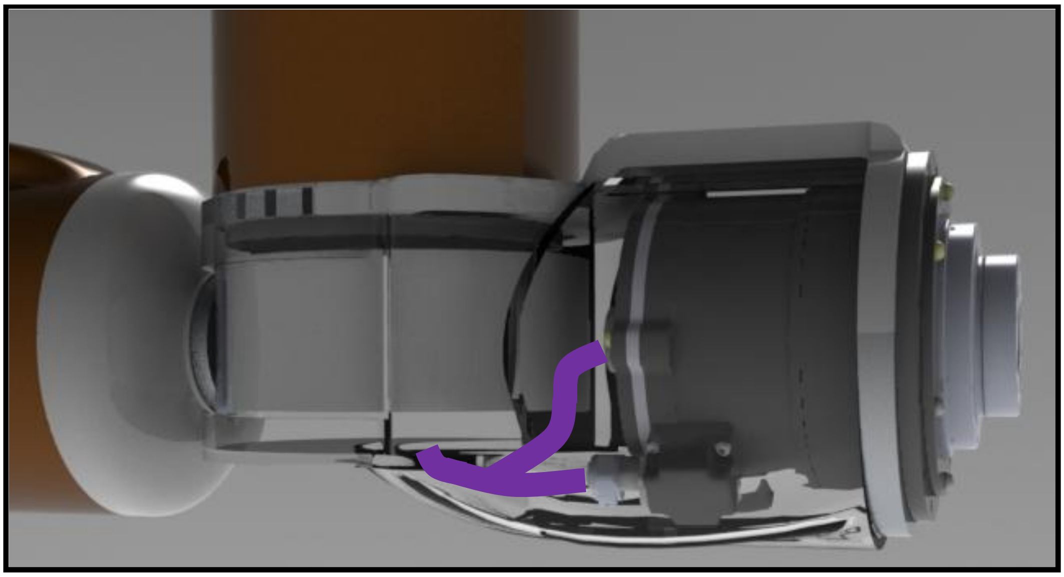


Figure 31: Cable movement, the cast that covers motor 6 is transparent in this figure.

7.7.4 Further consideration

All in all it seemed to be a good concept so far. With some minor alterations and a good esthetical design, it could fill most of the demands set up in the start of the project. A simple FEM analysis was made to test how components would react, when exposed by an external force. In this case the 12 kg payload.[18]

The concept however wasn't satisfactory. The following were needed to put into further consideration;

- The ring used to seal the moving parts was causing disturbance to the main cables running to motor 6. Motor 6 either had to be moved down or offseted forward to make a clean passage.
- The cable extentions from motor 5, meant that a special design was needed. The design hindered some of the movement when bending axis 5.
- There was a really sharp edge, that would create a lot of problems for the cables.
- The seal was still too big, and a smaller solution was necessary.

After further brainstorming, an idea came up to use the concept that was concluded in chapter 7.6.6, but by crossing both the cable solutions. A sketch was drawn, and another discussion took place to see the advantages with the new concept. The new concept would fix most of the problems and was then decided to be used in the final concept of the wrist.

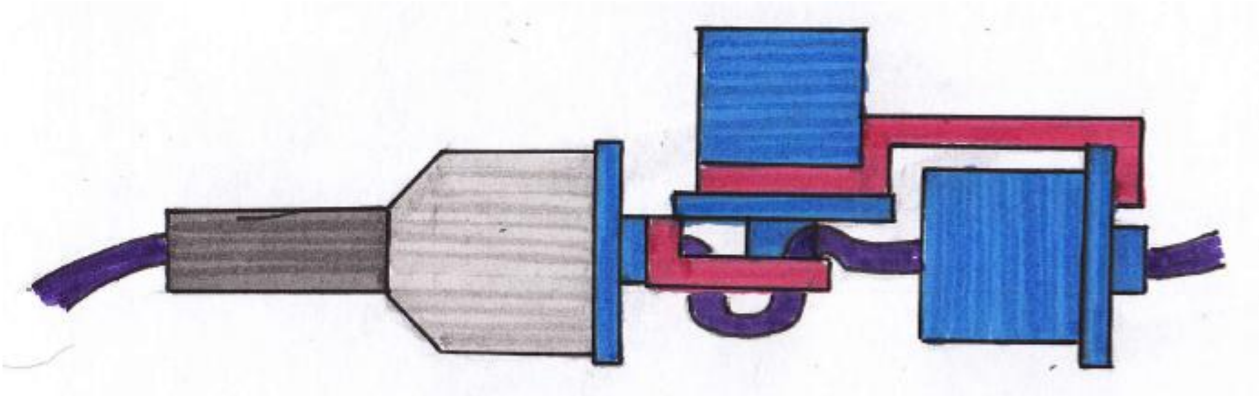


Figure 32: A sketch of the final combined concepts.

Blue – The motor
Light grey – The aluminum bushing
Dark grey – The carbon fiber tube
Red – Connections between motors
Purple – Cabling

[18]Appendix 10

7.7.5 Body design

I was given a few parameters to create a simple body of the robot, with the necessary functions needed to satisfy the project requirements. A few meetings were spent on planning the construction. It was decided to make a hasty version of the body without any tedious evaluation, since it would mostly be used as an underlay for the esthetical design. Still a few functions were decided to be used in the robot; some of them came directly from consumer demands.[19] The functions considered were;

- A tripod foot for the robot, keeping the robot from wobbling.
- Motor 1 vertically placed (with drive shaft upwards) inside of the center of the foot. It is expensive to place the motor on the side, because of the angle gear needed.
- A smaller foot diameter then the reference robots (IRB 2400 and 2600).
- A uniform foot with evenly distributed fasteners around the foot to ease the mounting of the foot.
- An opening big enough for the parallelogram to go through, allowing back bending.

In the pictures below, the basic look of the body has been illustrated, with all the functions above satisfied. The first picture (figure 34) shows the opening needed allowing the robot to back bend, and the placement of motor 2 and 3.The second picture (figure 33) illustrates the rest of the body including the upper arm.

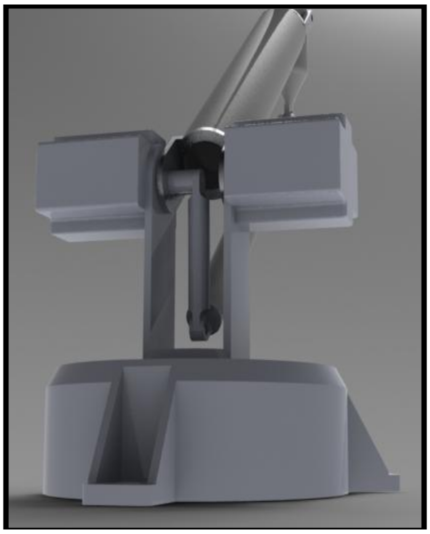


Figure 34: The opening is allowing the robot to back bend.

Figure 33: Basic picture of the robot.

[19] Appendix 7

7.8 Designing the robot

An analysis was made on the brand ABB, to be able to represent their idiom in the concept that was developed.[20] From the analysis, I decided what key elements to include in my design. The work put into the design concepts, and the limitations that came from its construction had given me a good idea of what I wanted the wrist to look like.

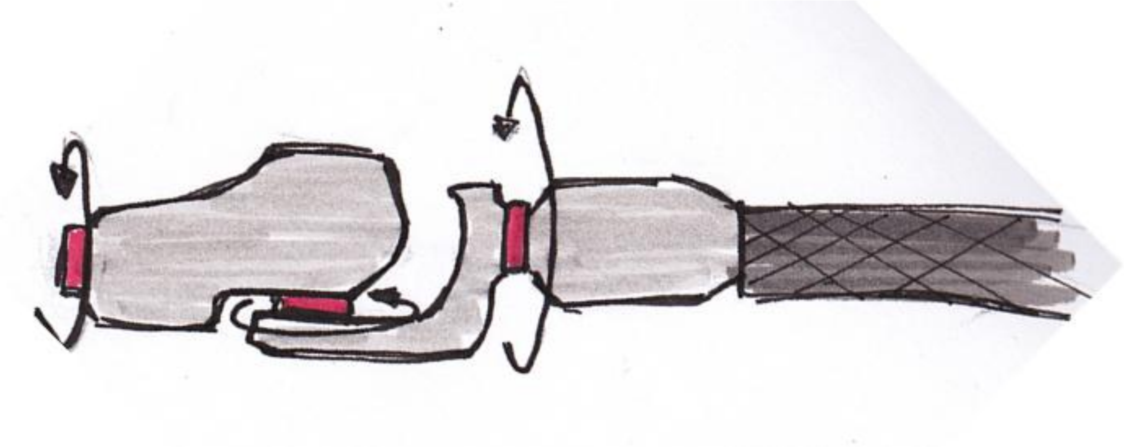


Figure 35: The robot wrist, design proposal.

I wanted to give the casting of motor 4 a clean look, with a gasket made for the motors cable connectors, illustrated below;

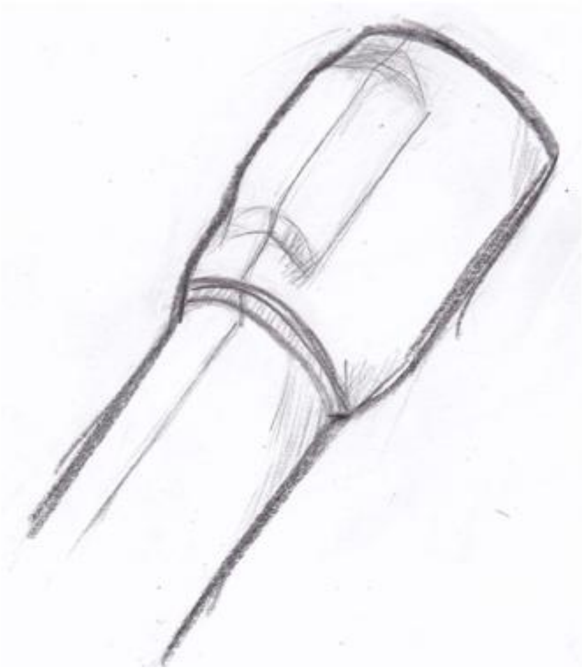


Figure 36: Sketch of casting of motor 4, connected with the carbon fiber tube.

I wanted the arm to be perceived as thin and therefore tried to smooth the transitions from motor 6 up to motor 5. At the same time I wanted the wrist to be robust and create that “ABB feeling”, leading to large exposed bolts above motor 5.

[20]Appendix 12

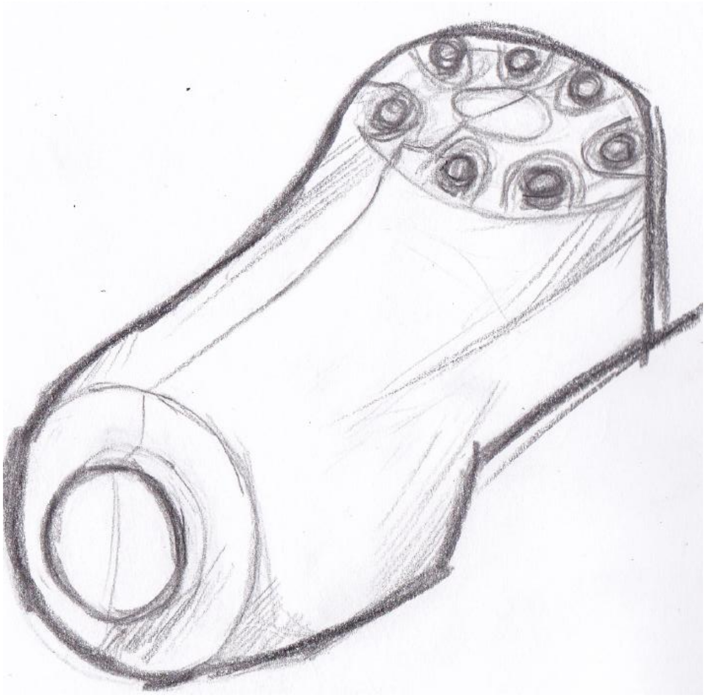


Figure 37: Sketch of casting covering motor 5 and 6.

From the analysis I choose to go with the chamfered foot and for the rest of the body, I made a cross between the IRB 2400 and IRB 2600. A simple sketch of the whole robot design is illustrated below;

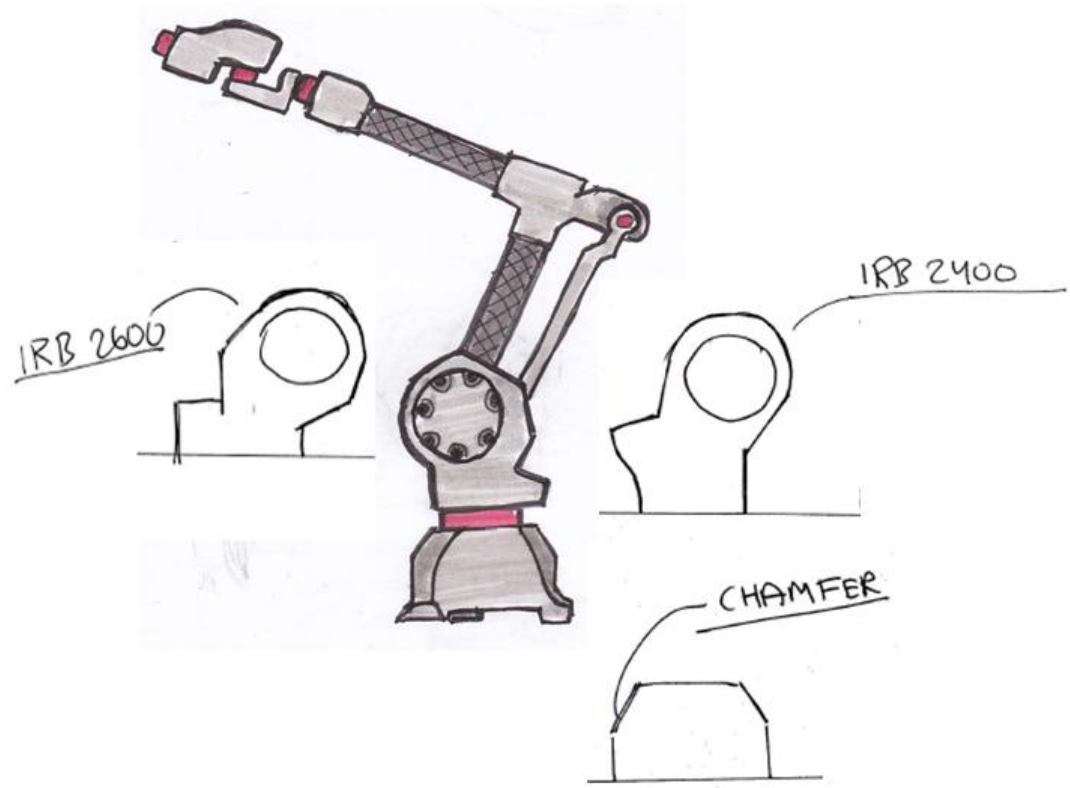


Figure 38: Simple sketch of the whole robot design.

A CAD with the ABB design was created. It possesses a lot of the traits that would define an ABB robot. It looks like a lighter version of an IRB 2400 and an IRB 2600. Below are some pictures that illustrate the design.

Figure 39: Draft of the robot design.

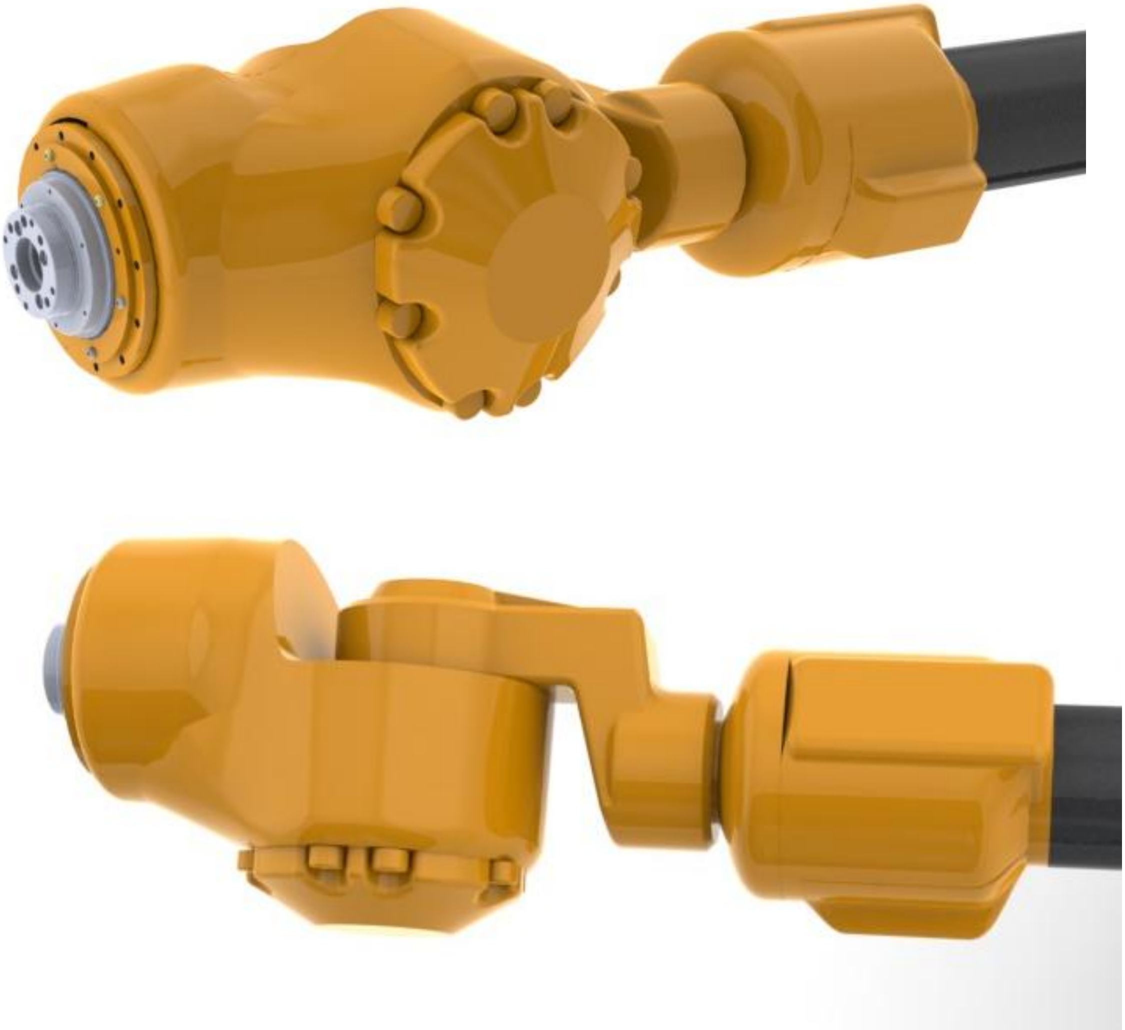


Figure 40: Draft of the robot wrist.

Figure 41: Draft of robot foot.

Figure 42: Draft of the robot body.

Figure 43: Draft of the robot elbow.

The draft of the robot design looked like it could be an ABB robot and therefore partly gave a satisfying result of the design. However it lacked a design that would appeal to the user. A light weight robot in this size is fairly innovative and should therefore express this in the design. For the final concept, I therefore gave the robot a new esthetical design based on this draft.

7.9 FMEA

An FMEA were conducted to identify potential failures in the design, and the effects that follow. The FMEA, presented in Appendix 11, shows some of the failures that might occur. The FMEA also illustrates which components are more likely to fail, showing that castings are more likely to break than other parts. Bellow follows actions recommended for components with high risk of failure;

- Castings break because of defects in material – Recurring quality controls should be performed to investigate the functions and qualities of components.
- Castings break because they have been wrongly calculated – Calculations should be reviewed and FEM analysis evaluations should be reassessed.
- Castings break due to collisions – Castings needs to be analyzed with FEM analysis and experience crash tests.

8. Results

The project resulted in a lightweight robot design, developed to solve the problem of constructing a light and durable wrist that at the same time will keep the manufacturing costs and the time between maintenance to a minimum. This was made possible by using a servo actuator prototype, which is both light in weight and keeps a high performance. The final design of the robot is a lightweight version of the ABB robots IRB 2400 and IRB 2600, made from lightweight materials such as aluminum and carbon fiber.

Figure 44: Final robot design.

8.1 Wrist construction

The robotic wrist design has been constructed with the use of the servo actuator prototype and aluminum castings. In figure 46, castings have been made transparent to display the positions of the three motors in the wrist. The connection of the elbow to the wrist is done with a standard carbon fiber tube.

The carbon fiber is connected to the aluminum bushing that has been extended to cover half of motor 4. The other half of the aluminum casting encloses motor 4. A separate casting is then made between motor 4 and 5 in which the cables run. At the tip of the robot there is a casting constructed to hold both motor 5 and 6. This casting only covers half of the motors. Two other aluminum castings close in each of the motors. The final weight of the upper arm, including the wrist with its actuators and the connected carbon fiber tube was 11,9 kg. This has been verified by the FEM analysis in appendix 10.

Figure 45: Final wrist design.

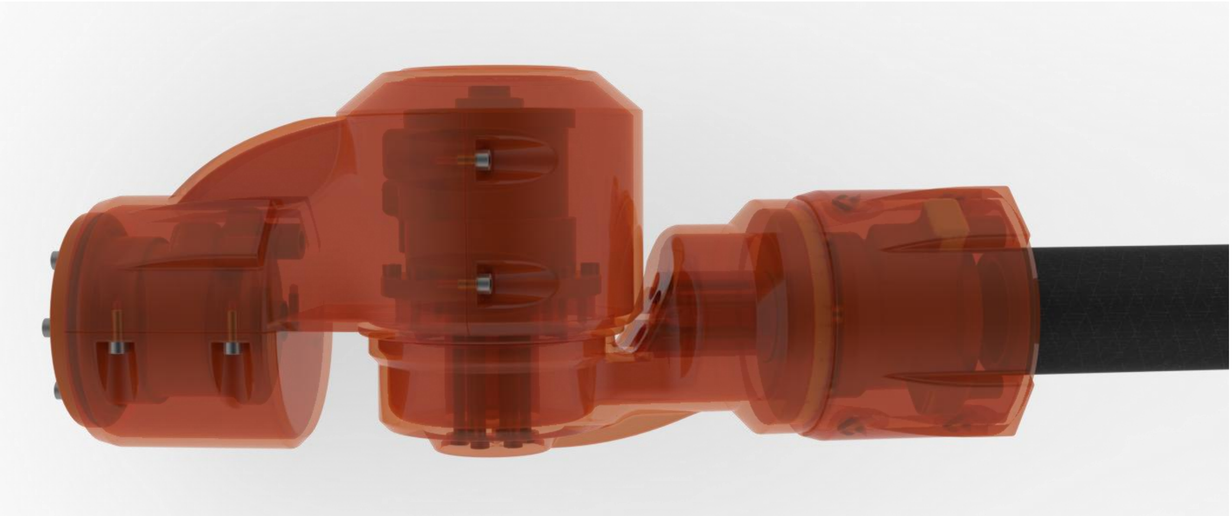


Figure 46: Actuator positions in the wrist.

8.2 Cabling

On the wrist construction, consideration has been taken into account on how the cables can be drawn through the inside of the robot. The robot is designed to reduce moving cables as much as possible. Smooth transitions have been made where the cables turn, and extra space and sharp edges have been softened on parts that comes in direct contact with the cables.

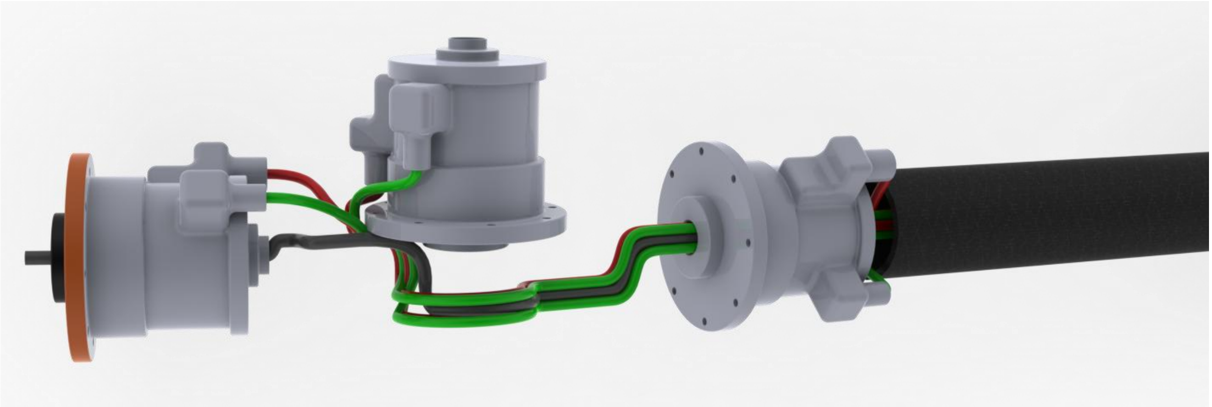


Figure 47: Cabling.

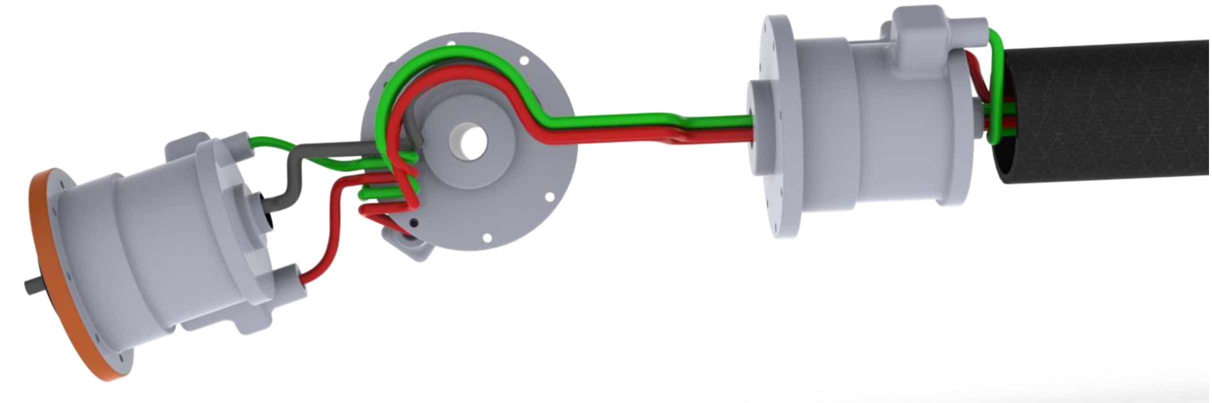


Figure 48: Cabling from another perspective.

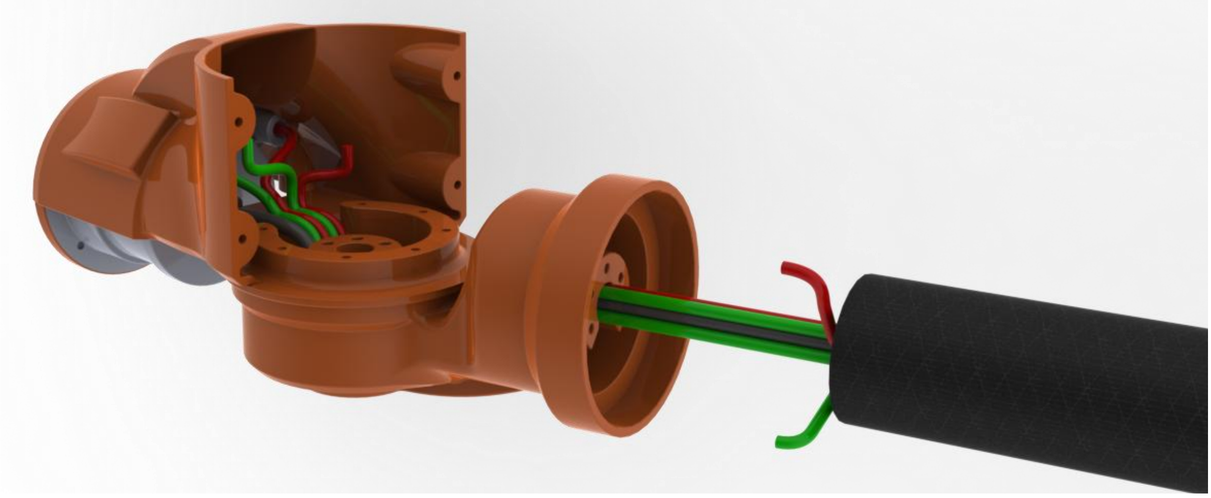


Figure 49: Cable passage through castings.

Figure 50: Cabling with transparent castings.

8.3 Esthetical design

When creating the external appearance of the robot, IRB 2400 and IRB 2600 in particular, have been examined.

The robot was designed from the bottom up, starting with the foot and ending with the tip of the wrist, trying to keep the design consistent and smooth.

The foot is similar to the foot from IRB 2600 but with a larger chamfer which is one of the key elements that characterize an ABB robot. Motor 1 is integrated inside the foot, and the fasteners are evenly distributed around the foot.

Figure 51: Design of the robot foot.

The body of the robot is a mix of the IRB 2400 and the IRB 2600. What really characterize an ABB robot in this part are the large bolts that give the robust feeling, which makes you think about an ABB robot.

Figure 52: Design of the robot body.

The elbow of the robot reminds us of the IRB 2400 elbow. A big difference is that a large portion has been cut out in the upper right corner of the picture below. This part was used to hold motors that are now located in the wrist and the open space is a good area to connect extra equipment. The embossed circles at the rotating points are characteristic for ABB. The carbon fiber tubes that connect the wrist to the elbow and the elbow to the body give the robot a clean and slim look.

Figure 53: Design of the robot elbow.

The robot arm is designed to have the slimmest look possible. The large bolts are exposed to create a robust feeling as in an ABB robot, and the embossed circle and chamfer also gives the robot an ABB look. I have kept the "ABB orange color" for the robot, but instead of making the whole robot orange I also kept the natural black color of the carbon fiber. It gives the robot a more modern look; the black makes the robot look thinner and together with the patterns from the carbon fiber it exudes the sensation of being light weight.

Figure 54: Design details of the wrist.

Figure 55: More wrist details.

9. Analysis

In this chapter the results are analyzed to see how well they fulfill the specification of requirements and the problem statement.

9.1 Problem statement

From the problem statement; how can light and composite materials be used effectively to create a light weight robot concept? How to position the actuators to reduce torque and the thickness of the wrist? How to draw cables on the inside of the arm through axes 4, 5 and 6? How to make the arm applicable on several robot models? How to create an idiom that appeal to users and that follows esthetics of ABB?

The final concept in this thesis includes the solutions to the problems stated above. The new robotic arm is made out of composite materials and has a low weight. It uses the chosen servo actuators that are placed to make the arm small and reduce torque. It is also constructed to be able to draw cables through the axes 4, 5 and 6 on the inside of the arm. An esthetical design was given to the arm, to represent the idiom of the company ABB.

9.2 Comparing with the specification of requirements

The comparison has been categorized into three areas, “general”, “technical” and “desirable”, as listed below;

9.2.1 General

- Mounting: Floor, wall, shelf, tilted, inverted
  The robot foot has been designed to make it easier to mount it in several ways by having evenly distributed fasteners.

- The robot should use lightweight materials
  The upper arm of the robot is built from carbon fiber tubes and aluminum castings.

- The robot wrist will be constructed using the newly developed servo actuator
  The servo actuator have been used in the robot wrist

- The robotic wrist should be designed to be as thin as possible, reduce torque and resonance frequency
  The motors have been placed to create a synergy between the thickness of the arm, torque and the resonance frequency.

- The concept must be applicable on several robot models
  It is possible to use the upper arm on existing robot models (it can be used as a module), if an elbow is designed to fit the desired robot type. This could increase the reach of the arm without needing to buy a bigger robot.

- Cabling needs to go through the inside of the robotic wrist (axes 4- 6)
  The wrist has been designed to allow for all cables to go on the inside.

- Outer robot dimensions should not be larger than IRB 2400 and 2600, preferably thinner in some parts

The thickness of the arm in the concept is smaller than both IRB 2400 and 2600

- The robot should be able to back bend
  The body has been constructed to be able to backbend

9.2.2 Technical

Features

- Reach 1,65 m
  The concept has been designed to make sure that the arm has the ability to reach the expected area of 1,65 meter radius from the center of axis 1.

- Payload 12 kg
  The concept has been tested in a static position and is able to withstand the payload of 24 kg or a force of 240 Newton. The weight of 24 kg represents the actual 12 kg payload while in motion.

- Number of axes: 6
  The robot has been designed to have six axes, three bending axes and three turning axes.

Physical

- Upper arm weight: Max 15 kg
  The upper arm (the wrist with motors and the connected carbon fiber tube) ended up with a weight of 11,9 kg. Screws, sealing's, cables and some bearings have not been accounted for. These will add some extra weight and the total (final) weight cannot be decided until further tests have been made.

Movement

- The axes of the robot have been tested and are able to turn and bend within its desirable demands.

- It has the same movement area as an IRB 2400.

9.2.3 Desirable

- Esthetics
  The concept has been designed to express the quality and sensation associated with the brand ABB.

- Manufacturing cost
  Standard carbon fiber tubes are used, and aluminum parts have been designed to keep manufacturing costs down.

- Nr. Of components
  By using smart solutions and good designing, the number of components has been kept down.

10. Conclusions and recommendations

From the result and analysis, conclusions and recommendations for further work is presented below.

10.1 Conclusions

The aim of this thesis was to develop a concept for a lightweight industrial robot, with a wrist design that would be thin, using lightweight material and at the same time keeping the same performance as an IRB 2600 robot. The robot should also inherit the idiom from the local company ABB.

The newly developed servo actuator has been used in axes 4, 5 and 6 to ensure the performance and lightweight of the upper arm. A carbon fiber tube is used to connect the robot wrist to the elbow, and aluminum castings have been used in the wrist. The servo actuators, carbon fiber and aluminum make the upper arm lightweight. With the 11,9 kg of weight, it is stated that the robot lands well within its weight limit.

The aluminum castings that cover half of motor 4, 5 and 6 can be used as a service hatch, allowing easy access to motors and cabling without any other necessary disassembling.

A separate aluminum casting was made to connect motor 4 and 5, reducing moving areas that are needed to be sealed from dirt, and is hollow for the cables to run through. This does not only reduce costs since sealing is expensive and the cost rises with the area needed to be sealed, but it also reduces the time between maintenance.

The use of the extended aluminum concept allowed for the use of a thinner carbon fiber tube, making the robot look slimmer. Together with the ABB design integrated in the robot, a lightweight robot that expresses the idiom of ABB has been created.

The wrist is constructed to reduce the amount and ease the passage of moving cables, decreasing the inflicted friction when rotating axes. This will reduce costs for cabling and also the time between maintenance.

A gap between motor 4 and 5 was made, to allow axis 5 to bend 120 degrees in both directions, and the length of the opening below motor 2 and 3 allows the robot to backbend.

The robot is applicable for several robot models, by using the wrist concept, with different lengths of the carbon fiber tube.

Motor 1 is integrated inside the foot to make it smaller and also uniform. This helps when the whole robot is moved into tighter spaces, and because the fasteners are evenly distributed around the foot, it is easier to create wholes if there is a need to rotate the whole robot. The foot uses three legs keeping the robot from wobbling.

Most of the specifications set for this project have been satisfactory. With continued testing and developing, I believe that this concept has a lot of potential as a working industrial robot and with discovering further uses of lightweight robotics.

10.2 Recommendations

For the continued work and further development of this concept I recommend;

- Building of a first mechanical prototype to test the design and movements of the robot upper arm. The servo actuator also needs to be tested in a real life environment.
- The upper arm needs to be further developed, and also a more thorough design is needed on the rest of the body, to understand the potential weight of the whole robot.
- Cost calculations should be made to see if the project has any selling potential.
- Investigate how to integrate the robotic arm with an already existing robot. What changes are needed and are they economically sustainable enough.
- Further testing of the parts, more thorough FEM analysis and stress calculations should be made.
- Material testing on carbon fiber tubes and aluminum castings to test durability over time. To see if the material is durable enough to hold for collisions and if it will be vibrating in motion.
- Need to investigate further about the possibilities of lightweight robots, how it effects costs, the environment and the use of robots in general.
- The cabling wears over time due to friction. Rigs should be set up to test cabling over time to see where the critical points are and what can be done to reduce abrasion. Either by redesigning parts or by reinforcing the areas of the cables that are exposed to friction.

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Söderbäck, Olle. Production Engineer Sjölanders

13. Appendices

1. Gantt chart
2. Function analysis
3. Quality Function Deployment (QFD)
4. Specifications of requirements
5. Generated concepts
6. Pugh´s Method
7. Results from interviews
8. Calculations
9. Snake wrist
10. FEM analysis
11. FMEA
12. Designing the robot

Appendix 1 – Gantt chart

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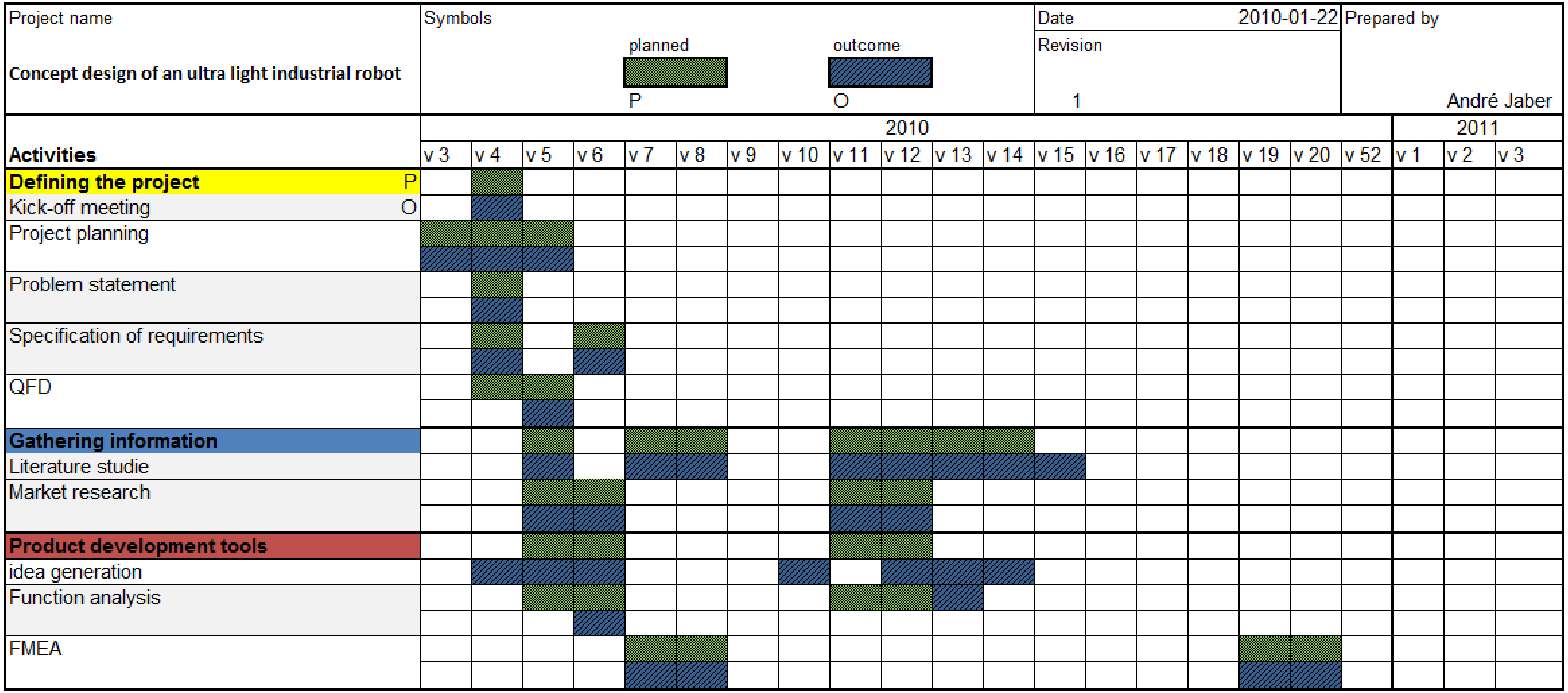
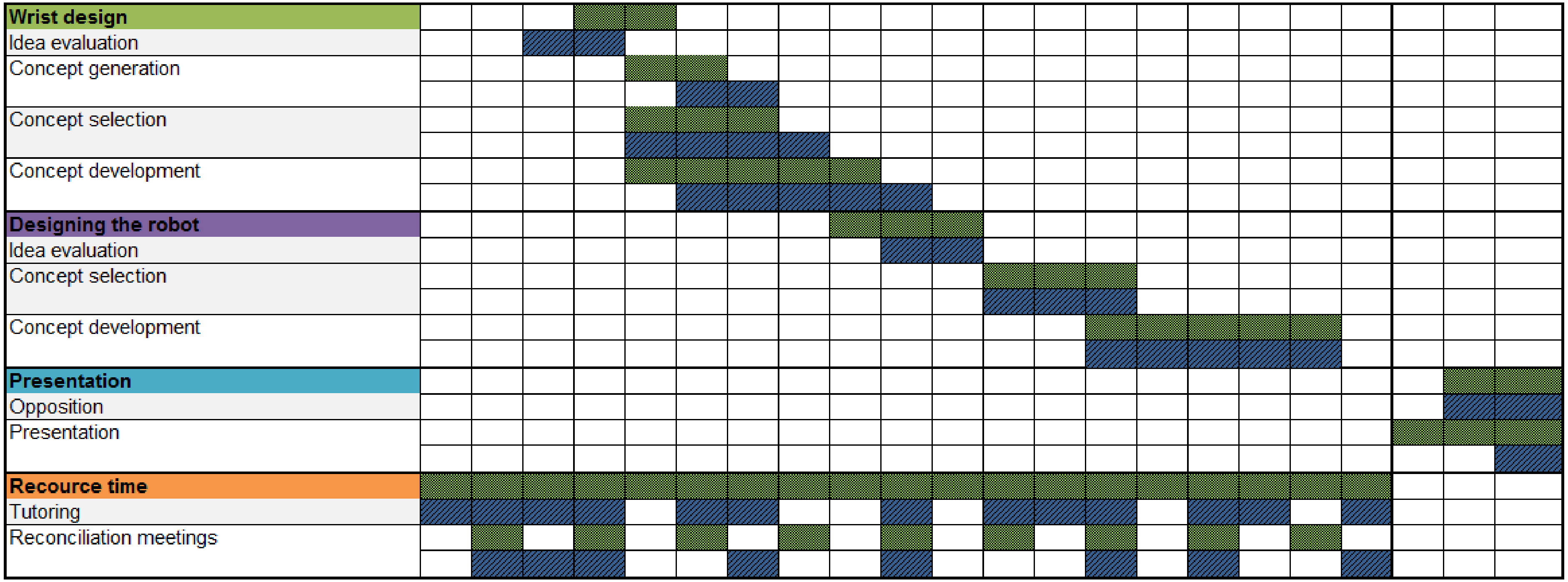


Appendix 1 – Gantt chart
(Page 2/2)



The Gantt chart is a project plan that illustrates the project activities (left side). It is divided into seven areas: *Defining the project, gathering information, product development tools, wrist design, designing the robot, presentation* and *resource time.*
The green staples shows the planned time, and the blue represent the outcome.

Appendix 2 - Function analysis
(Page 1/2)

Function analysis for light weight robots

Main function: Be able to move an object to a point in space
The robot takes an object from a specific place and carries it to another, perhaps with a certain orientation.

Sub function: Allow movement
Flexible movement and further reach is attained by having six degrees of freedom and also allowing back bending. The robot's low weight allows faster acceleration.

Sub function: Allow lifting
The need for lifting and displacing objects is attained by being able to attach the correct tool for the job.

Sub function: Allow grabbing
The need for grabbing different objects is fulfilled by the use of different kinds of grippers.

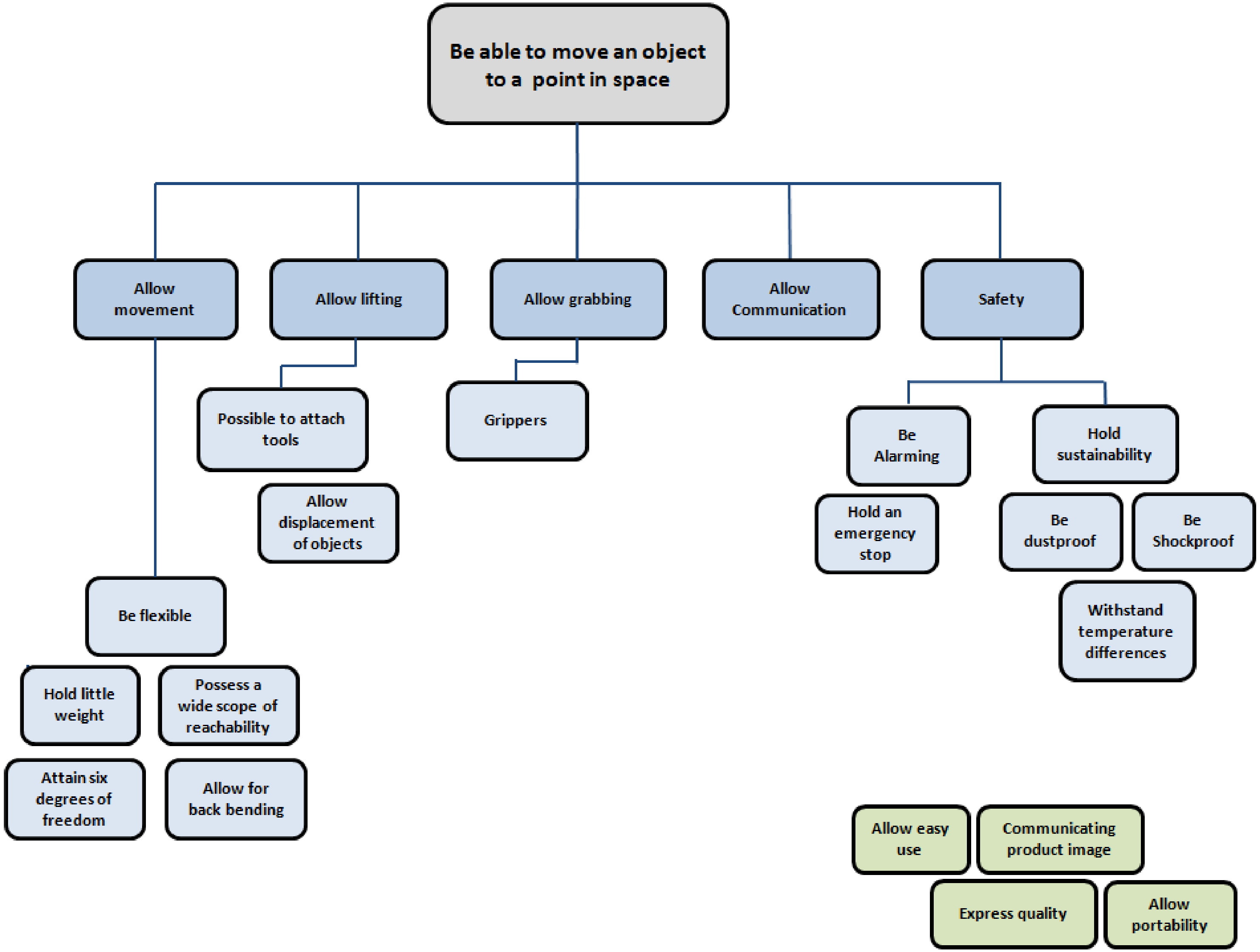
Sub function: Allow communication
The robot needs to be able to communicate with itself and other auxiliary equipment that is either attached or is in the robots surroundings.

Sub function: Safety
A robot is a heavy machine that can accelerate and move very fast and therefore becomes a safety issue. It has to be equipped with an alarm, a hold and an emergency stop. The robot also has to be sustainable, dustproof, shockproof and withstand different temperature and humidity levels.

Desired functions

- The robot should be easy to maneuver and user friendly to the end user when programming different movements.
- The robot should be communicating the brand and product, expressed through quality.
- Portability – the robot could easily be moved from one location in the factory to another.

Appendix 2 - Function analysis (Page 2/2)



Appendix 3 – Quality Function Deployment (QFD) (Page 1/3)

	Product attributes (How?) / Customer demands (What?)	Requirement weight	Choice of material	Dimensioning	Idiom & industrial design	Manufacturing cost	Nr. of components	Nr. of materials	Dustproof	Motor choice & placement	Engagement time
Assembly & Maintainance	Easy maintenance	4	1				3		9		3
	Easy to manufacture	3	9	1	9			3			3
	Easy assembly	3	1		1		1				3
	Long time between service	3	3				3		9		
Function	Able to lift objects	5	3	3						9	
	Durable	5	9	9			3		3		
	Long reach	3		9							
	Low power consumption	1		3						9	
	Easy to relocate (low weight)	2	9	9		3					
	Easy to control	4								9	9
General	Low cost	5	9		9	9	9	9		3	
	Safe	5		9		3				3	
	Robust & suitable design	4			9	9					
	Importance of attribute		**166**	**156**	111	102	84	54	78	**120**	66

The QFD is used to identify the demands and requirements from the customer. To rate the importance of the demands and requirements, they will be graded with a scale from 1 to 5 (requirement weight). Proper product properties that can satisfy the market demands will be identified, and the magnitude of the relation between the demands and product properties will be graded. A grade, 1, 3 or 9 will be given and a 9 is used if there is a strong relation and 1 if it is a weak. If there is no relation at all there will be a blank space or 0. Then this grade is multiplied with the requirement weight and the weight total is used to understand which product parameters are more important. These will then be used as a foundation when building the specification of requirements.

Appendix 3 – Quality Function Deployment (QFD) (Page 2/3)

Explanations of parameters from QFD

The customer demands and product features used in the QFD matrix are described below. Customer requirements are divided into three categories; Assembly and maintenance, function and general.

Assembly and maintenance

Easy maintenance – It should be easy to disassemble parts of the robot to reach components that are worn out over time and need to be changed, such as cables and sealing.

Easy to manufacture – The parts should not have complex curves and shapes to attain as few steps in the manufacturing process as possible, and to avoid more expensive processes.

Easy assembly – The components should be designed to make it impossible to assemble the parts in the wrong way and to make it easier and ergonomic to assemble.

Long time between services – A reliable robot that doesn't need frequent service or maintenance.

Function

Lifting objects – The robot must be able to lift objects.

Durable – The robot must be durable to withstand hits without breaking if it would crash into other objects at high speed.

Long reach – Long reach is needed for a robot that needs a great scope.

Low power consumption – A desire to keep the power consumption down, especially when environmental friendly products have become more important.

Easy to relocate (low weight) – The demand for a robot that is flexible and light, that can be relocated to work with small batches.

Easy to control – The robot should be easy to jog (manually move the robot axes) without difficulties in understanding axial movements.

Appendix 3 – Quality Function Deployment (QFD) (Page 3/3)

General

Low cost – A parameter aiming for low costs.

Safe – The need for a robot that is safe.

Robust and suitable design – A technical design where the parts are dimensioned and tested to endure the inflicted torque and forces.

An external design that is sustainable, reflecting the environment it will be used in.

Product attributes

Material – The choice of materials to be used for the robot.

Dimensioning – This parameter decides whether the size of the robot or different parts of it will affect other demands.

Idiom and industrial design (esthetics) – Designing the robot, giving it the right expression by looking at different shapes and esthetics.

Manufacturing cost – The cost for manufacturing the product.

Number of components – The number of components used in the robot.

Number of materials – The number of different materials used in the robot.

Dustproof – The need to limit the amount of dust entering the links between different axes.

Motor choice and placing – Which motor to choose and how to place them.

Engagement time – The time you need to understand what to do.

Appendix 4: Specification of requirements

(Page 1/2)

The requirements will be more thoroughly explained in this document.

General

Lightweight materials for the robot – The materials used for the robot should be of lightweight materials, such as aluminum, magnesium and carbon fiber. Exceptions are allowed when necessary.

The robot wrist will be constructed using the newly developed servo actuator – A particular servo actuator have been chosen for this project though its degree of efficiency is great towards its size and weight.

The wrist concept needs to be applicable on several robot models – The robotic wrist should be designed as a separate module, making it independent from the rest of the arm. Then it can be applicable on several robots by changing the length of the upper arm.

Cabling needs to go through the inside of the robotic wrist (axes 4- 6) – Wiring should run through axes 4-6 on the inside. This keeps the cables from external damages and not getting in the way. Another problem that can come up is when programming the robot “offline”, because if the cables run on the outside, they do not show up during the programming and can become a later problem. Wiring on the inside might also cause some damage over time since the moving cables are exposed to friction.

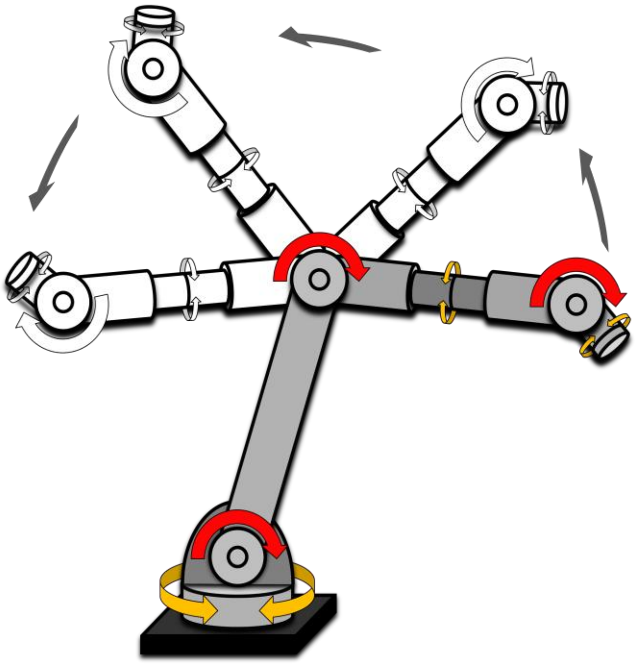
Protection standard IP67 – The Ingress Protection (IP) standard has been developed by the European Committee for Electro Technical Standardization. It specifies what environmental protection that is provided by the enclosure. In this case the first number (6) says it has to be “totally protected against dust, and the second number (7) states the protection against liquids, which is “protected against the effect of immersion between 15 cm and 1 m.”

The concept should be able to Back bend – Back bending is when the upper arm of the robot is turned over the elbow or axis 3. This means that in some scenarios were you usually would turn your robot around to do something right behind where you are currently working; it would instead reach back on its own to do the job. This can be useful in situations when it could cut lead time or just when there is not enough space for the robot to turn. The amount of back bending will depend on the construction of the robot.

Appendix 4: Specification of requirements

(Page 2/2)

The picture below illustrates a robot that is back bending;



Technical

Reach – The reach of the arm means the distance it can reach when the arm is stretched.

Payload – The payload of the arm means the load that the robot can carry in axis 6.

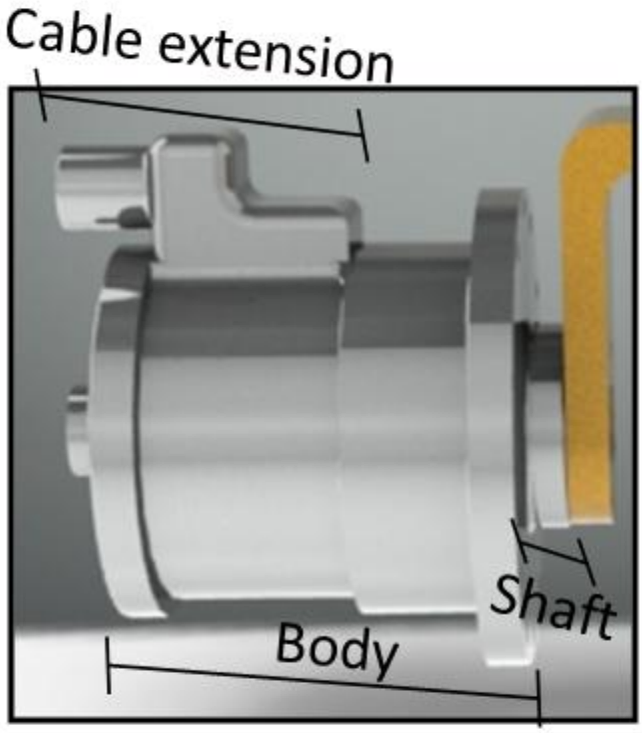
Armload – Armload refers to the load that can be carried on the upper arm.

Appendix 5 – Generated concepts
(Page 1/13)

All concepts that were not ruled out in a first sorting will be presented here. Four different types of concepts will be presented according to the questions that came up;

- How to connect the carbon fiber tube to the wrist of the robot
- How to connect motors in axes 4-6 to each other
- How to position the motors in relation to one another
- How to draw the cables through axes 4-6

When describing the concepts, the word shaft, body and cable extension is used. The picture below illustrates the different parts of a motor. Motor is also mentioned frequently, when speaking about motor 4, 5 and 6, it means the motor that bends or rotates in the corresponding axis; motor 6 is the motor that rotates axis 6.



A color code has been used to describe different parts in the concepts;

- **Blue –** The motor
- **Light grey –** The aluminum bushing (or aluminum)
- **Dark grey –** The carbon fiber tube
- **Yellow –** Fastener between the aluminum and the motor
- **Red –** Connections between motors
- **Purple –** Cabling

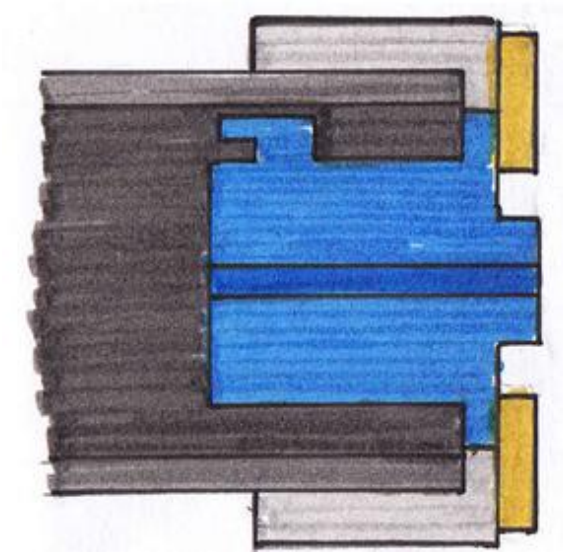
Appendix 5 – Generated concepts
(Page 2/13)

A concepts - Carbon fiber connections

The concepts here are different solutions on how to connect the carbon fiber tube to an aluminum bushing in which motor 4 is located. These concepts have been cross-sectioned in the middle. The lighter parts are the crossed areas.

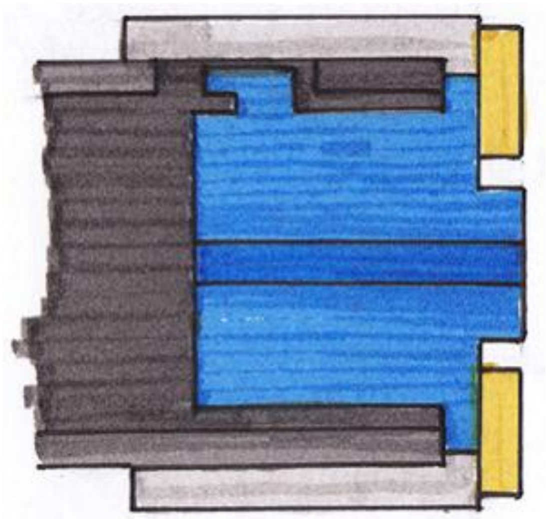
Concept A1: Outside bushing

The aluminum bushing goes on the outside of the carbon fiber tube. The tube is glued together with the inside of the aluminum bushing. The body of the motor is fitted freely inside of the carbon fiber. A fastener that is connected to the aluminum bushing and the motor keeps the motor in place.



Concept A2: Outside bushing ver. 2

This concept has an outside aluminum bushing as the previous concept and is connected with a fastener between the aluminum and the motor. The difference is that the aluminum and the carbon fiber have a smaller diameter and a cut out was made for the cable extensions.



Appendix 5 – Generated concepts
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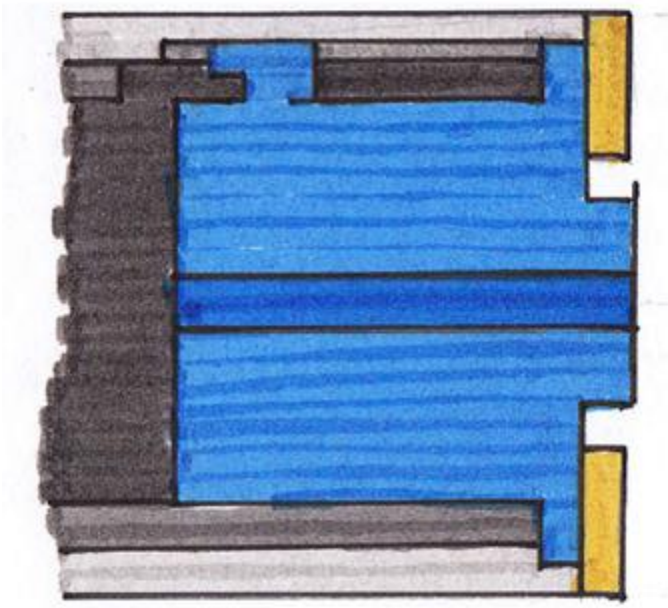
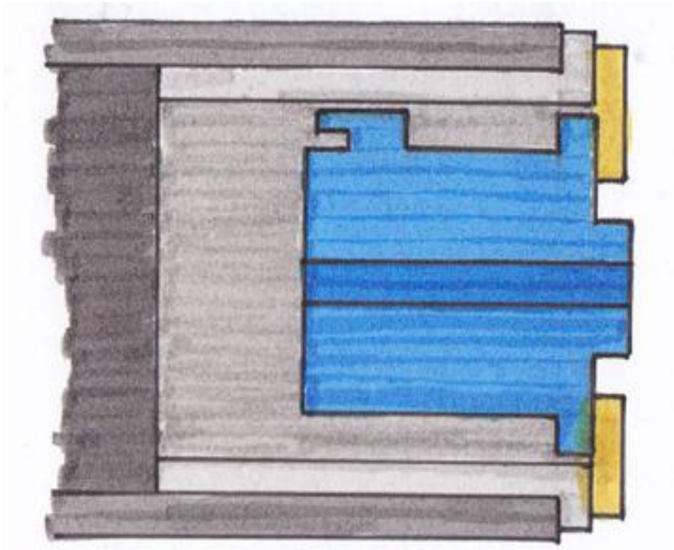
Concept A3: Outside bushing ver. 3

This concept also has an outside aluminum bushing. The carbon fiber tube and the aluminum bushing have a smaller diameter than the previous version. In this version there is an area cut out in both the carbon fiber tube and the aluminum bushing.



Concept A4: Inside bushing

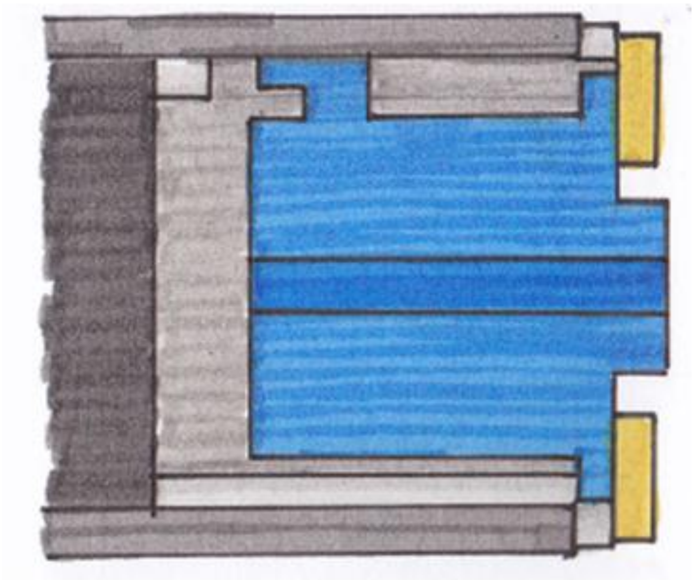
This solution has the aluminum bushing glued on the inside of the carbon fiber. The motor fits on the inside of the aluminum. The motor is connected to the aluminum with fasteners that also keeps the motor in a static position, allowing movement from the shaft.



Appendix 5 – Generated concepts
(Page 4/13)

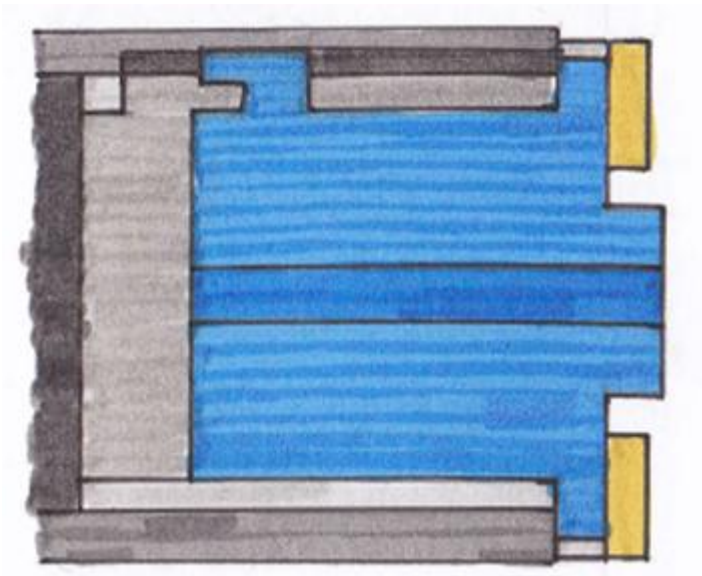
Concept A5: Inside bushing ver. 2

This solution also has the aluminum bushing on the inside of the carbon fiber tube, but the difference is that the carbon fiber tube and the aluminum have a smaller diameter. Therefore, has an area been cut out in the aluminum to have enough room for the motors cable extensions.



Concept A6: Inside bushing ver. 3

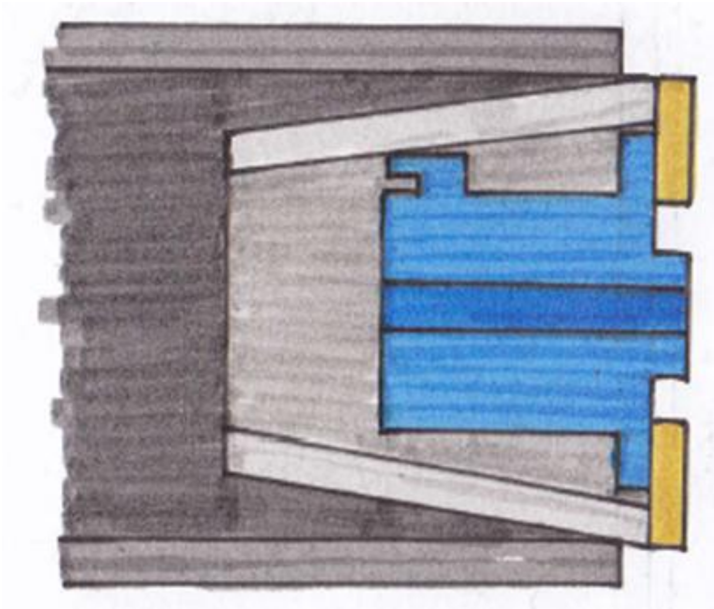
Concept 6 is another version where the aluminum bushing is glued on the inside of the carbon fiber tube. The diameter of both carbon fiber and the aluminum is smaller than concept 5 and there is an area cut out in both parts to fit the cable extension of the motor.



Appendix 5 – Generated concepts
(Page 5/13)

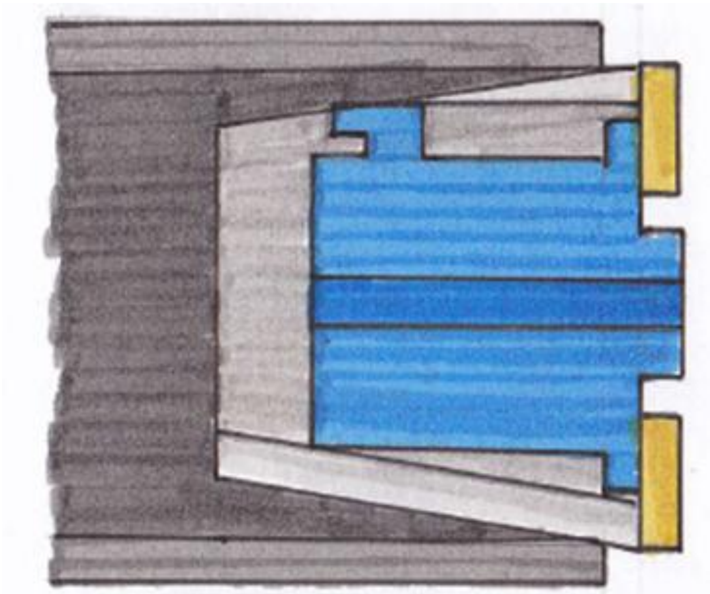
Concept A7: Conical bushing

In this concept a conical aluminum bushing is used. This means that the bushing will have a slope degree so when pressed in to the carbon fiber tube it will stay in place because of the pressure against the carbon fiber walls. Glue is also used as an extra fastener. The motor is fitted inside the bushing and is fastened externally to the aluminum.



Concept A8: Conical bushing ver. 2

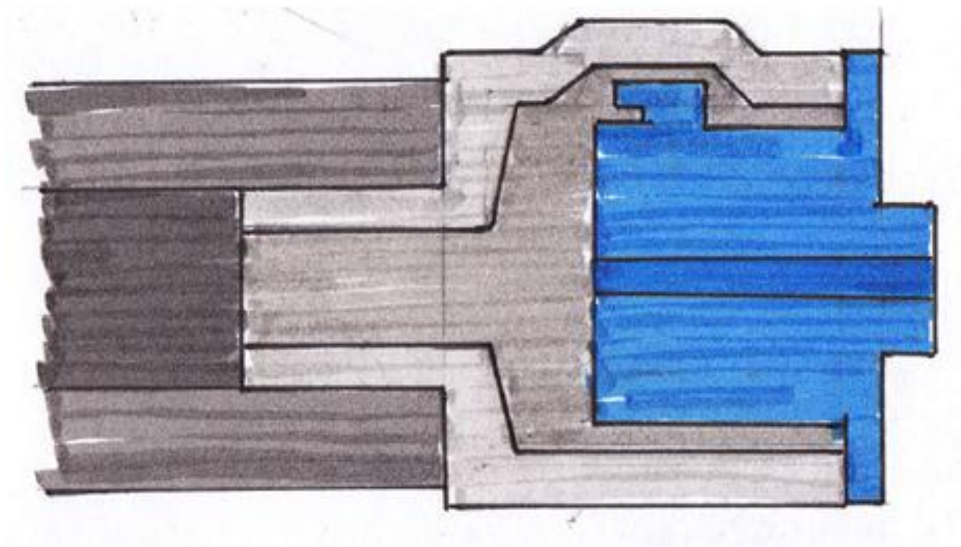
This solution is similar to the previous concept. It also uses a conical bushing that is fastened on the inside of the carbon fiber tube. The difference is that the diameter of both the carbon fiber and the aluminum is smaller. There is also an area cut out in the aluminum to fit the cable extension of the motor.



Appendix 5 – Generated concepts
(Page 6/13)

Concept A9: Extended aluminum bushing

In this solution the carbon fiber tube will be glued on the outside of the aluminum bushing. The thin diameter of the carbon fiber and the aluminum bushing doesn't make it possible for the motor to fit inside. Therefore, an extension is made of the aluminum outside the carbon fiber, where the motor is fitted. The aluminum is made in two pieces and the motor can therefore be directly fastened to the casting.



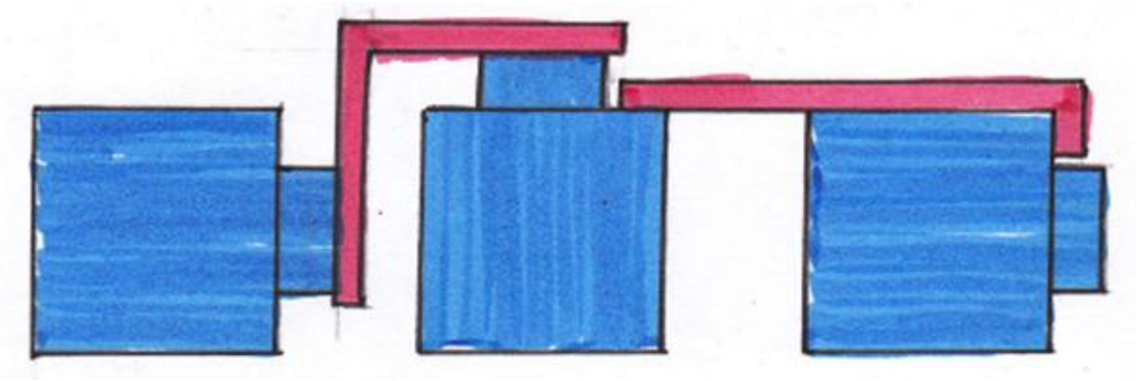
Appendix 5 – Generated concepts
(Page 7/13)

B concepts - Motor connections

In this section, solutions on how to connect motors with each other are described. Since a motor can only be connected in the “neck” of the body and on the shaft, there is a very limited number of options. It has been decided (in the report) that motor 4 will be statically connected to the carbon fiber tube, which leaves us with 4 motor connection concepts. The name of the concepts is inherited from the way the motors are connected.

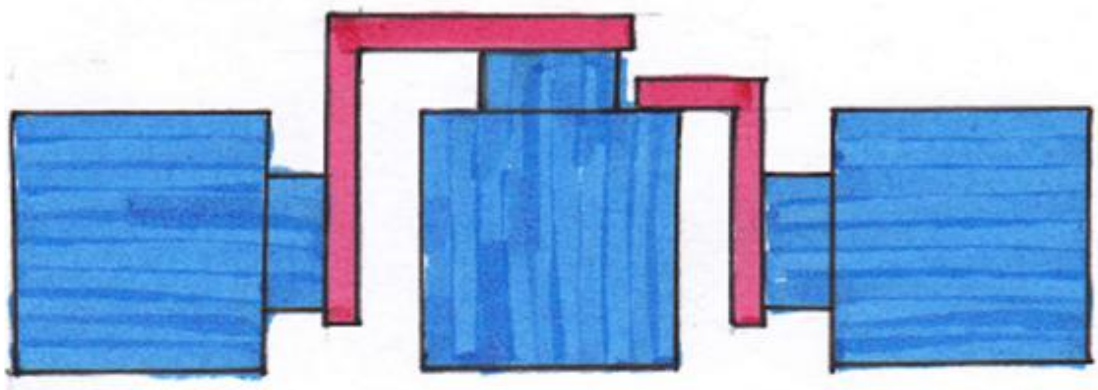
Concept B1: Shaft-shaft, body-body

In this concept the shaft of motor 4 is connected with the shaft of motor 5, this means that when motor 5 needs to move the whole of its body when it is bending. Motor 5 is connected body to body with motor 6 which leave the rotation of axis 6 only in the shaft.



Concept B2: Shaft-shaft, body-shaft

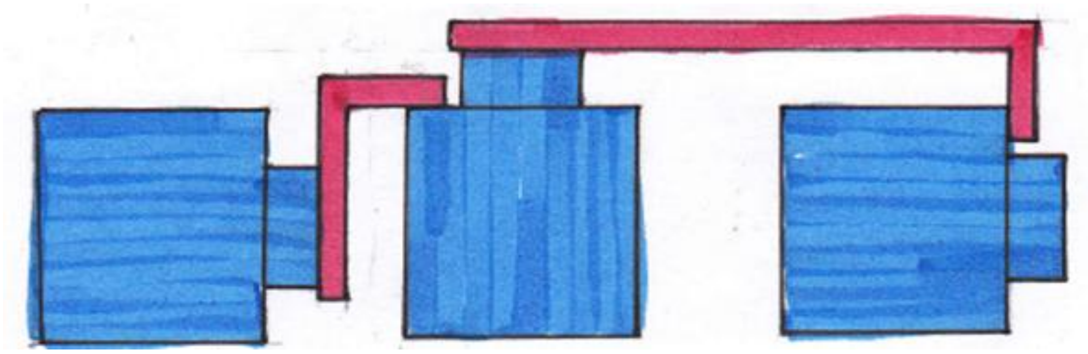
This concept has the same connection between motors 4 and 5. The difference is that motors 5 and 6 are connected body to shaft. This means that the whole body is moving when rotating axis 6.



Appendix 5 – Generated concepts
(Page 8/13)

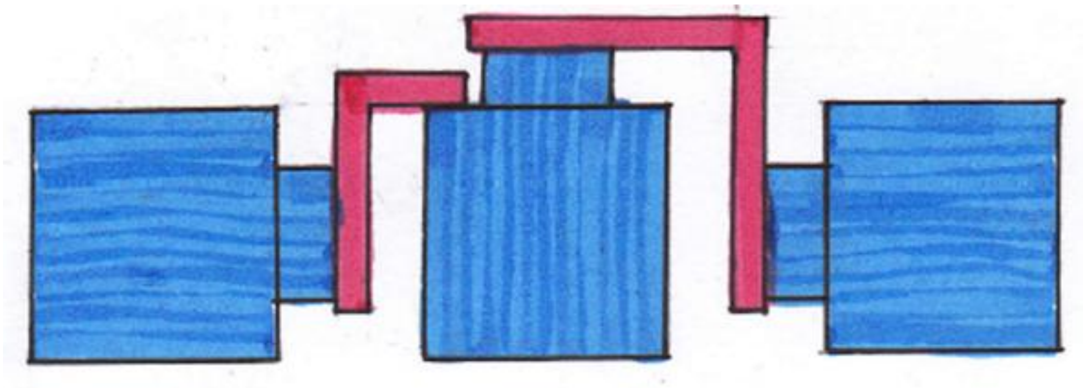
Concept B3: Shaft-body, shaft-body

This concept is connected from the shaft of motor 4 to the body of motor 5. Motor 5 is connected to motor 6 (shaft to body), which means that bending axis 5 moves the shaft of motor 5 and the motor 6. Rotating axis 6 means that only the shaft of motor 6 is moving.



Concept B4: Shaft – body, shaft – shaft

The connection between motor 4 and 5 is the same as in concept B3. Motor 5 is connected through the shaft, to the shaft of motor 6. This means that when bending axis 5, the shaft will be moved from motor 5 including the whole of motor 6. When moving axis 6, the body of motor 6 rotates.



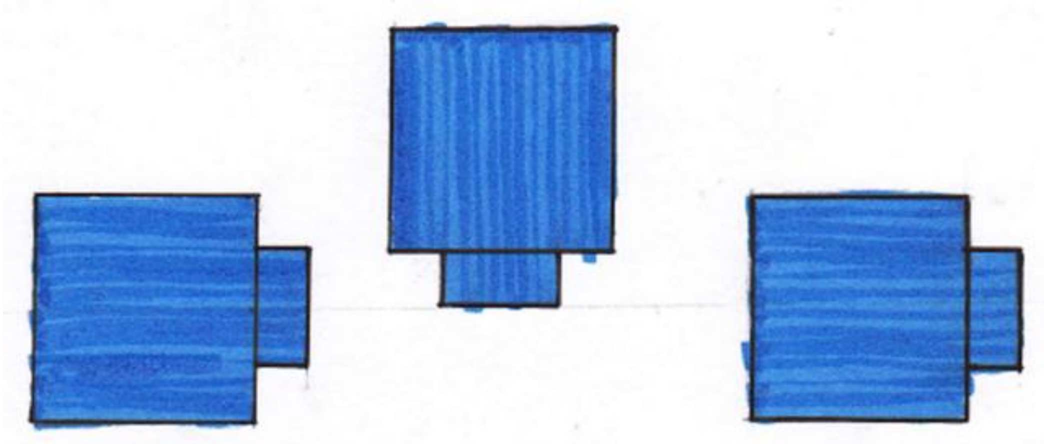
Appendix 5 – Generated concepts
(Page 9/13)

C concepts - Motor positions

Motors can only be connected in a few ways, but they can be positioned in several combinations. From all the possible combinations, four concepts were distinguished to have functions that could be investigated further.

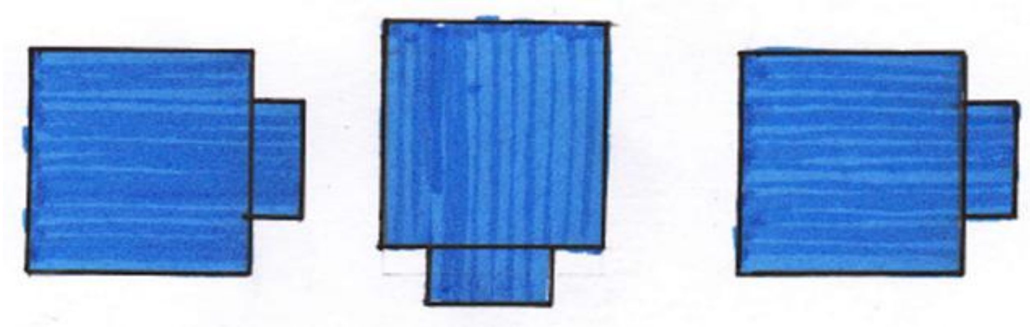
Concept C1: Open wrist

In concept 1 motor 4 and 6 is concentric with each other by their centre axes, which creates a centerline. The shaft of motor 5 is touching the centerline with its body pointing out of the arm. Since the motor is only going to the centerline, an open space is available below it for the use of drawing cables.



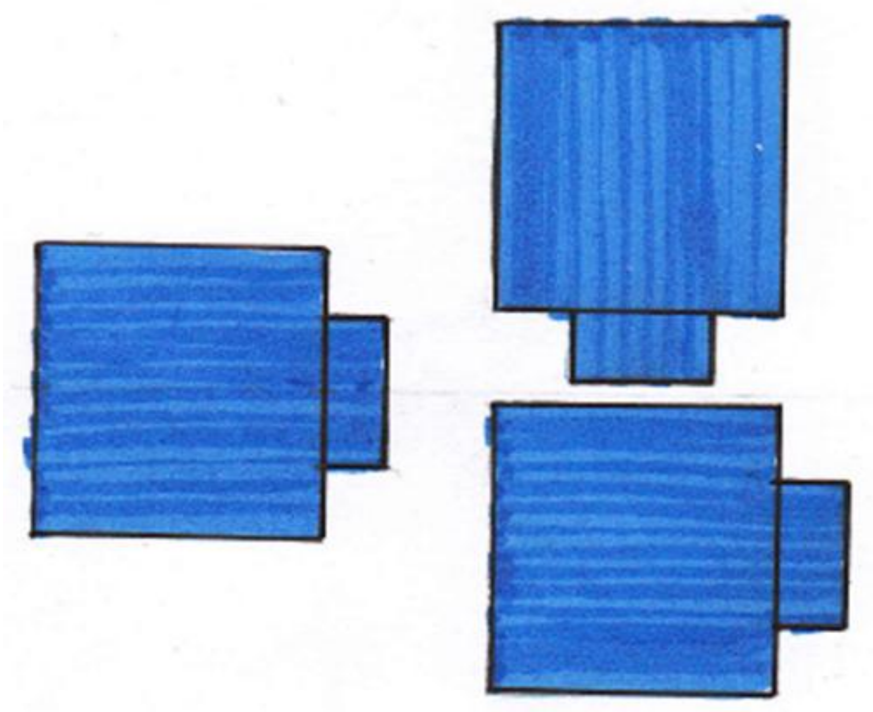
Concept C2: Small wrist

In concept 2 motors 4 and 6 are located as in concept 1. Motor 5 is located in between standing in a 90 degree angle from the other motors. The center of the length of motor 5 is centered on the centerline created by motor 4 and 6, making this arm the smallest possible.

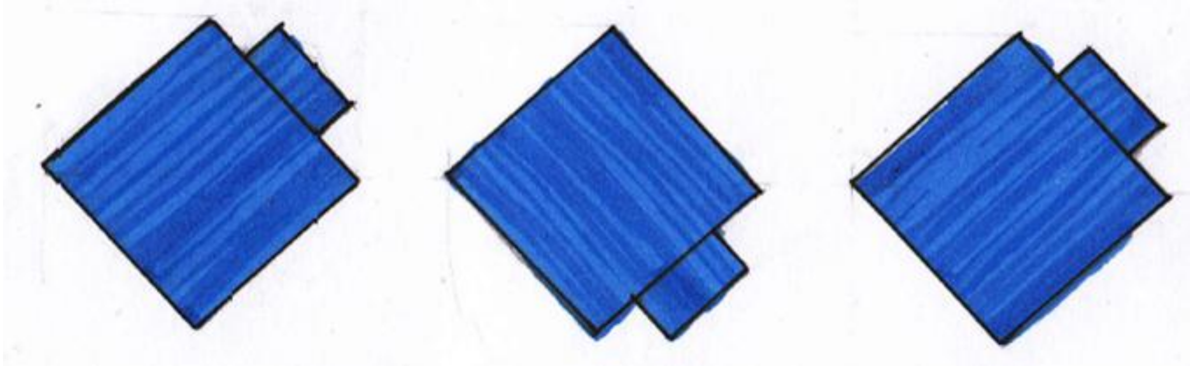


Appendix 5 – Generated concepts
(Page 10/13)

Concept C3: Thick wrist
Concept 3 is the thickest on the end side (motor 5 and 6), but it is very compact on the length, making it the shortest wrist. Motor 4 and 5 are placed as in concept 1, but with motor 6 placed directly below motor 5.



Concept 4: Snake wrist
When the axes are in relation to each other as described below, it is called a snake wrist. Motor 4 starts with a 45 degree angle. Motor 5 is perpendicular or 90 degrees from motor 4 and motor 6 is 90 degrees from motor 5.



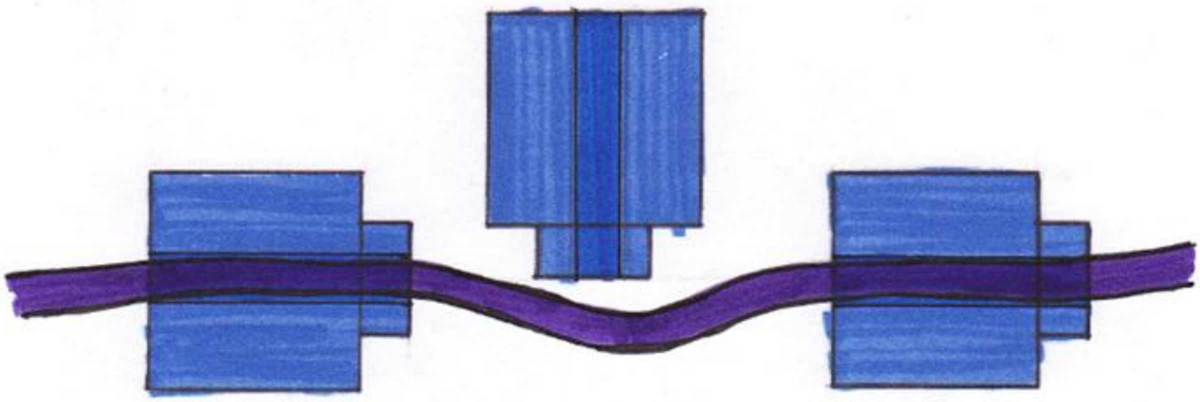
Appendix 5 – Generated concepts
(Page 11/13)

D concepts - Wiring

This part deals with the solutions on how to draw the main cables through axes 4, 5 and 6. A decision was made to choose the solution *concept C1: open arm* on how to position the motor. The solutions described below will therefore only be on how to draw cables to that concept. A concept on how to draw cables for a snake wrist will also be included.

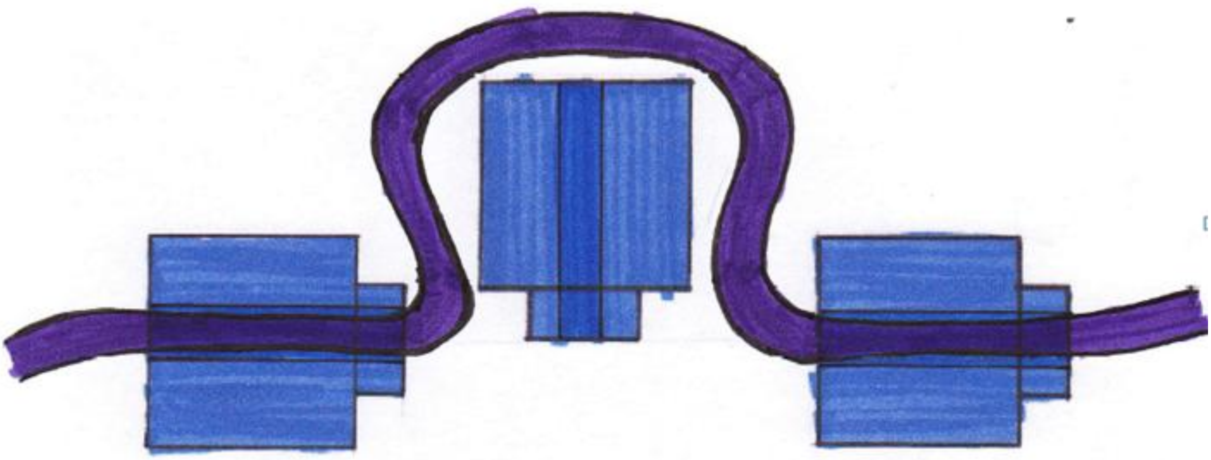
Concept D1: Straight wiring

In this concept, wiring is going through the center of both motor 4 and 6, and will go around motor 5 in the direction of where its shaft is pointing.



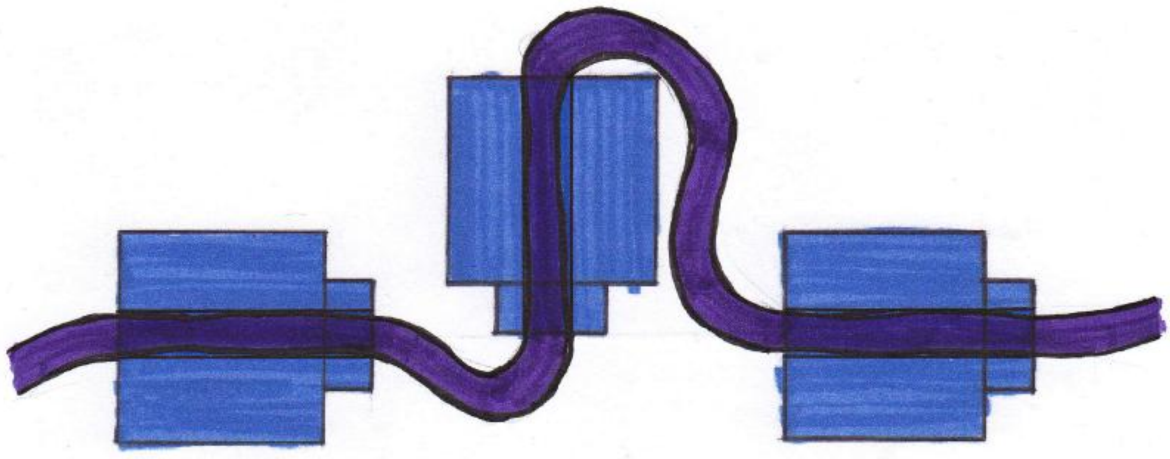
Concept D2: Wiring above motor 4

In this concept the wiring goes through the center of both motor 4 and 6, and around motor 5 in the direction of where its body is pointing.

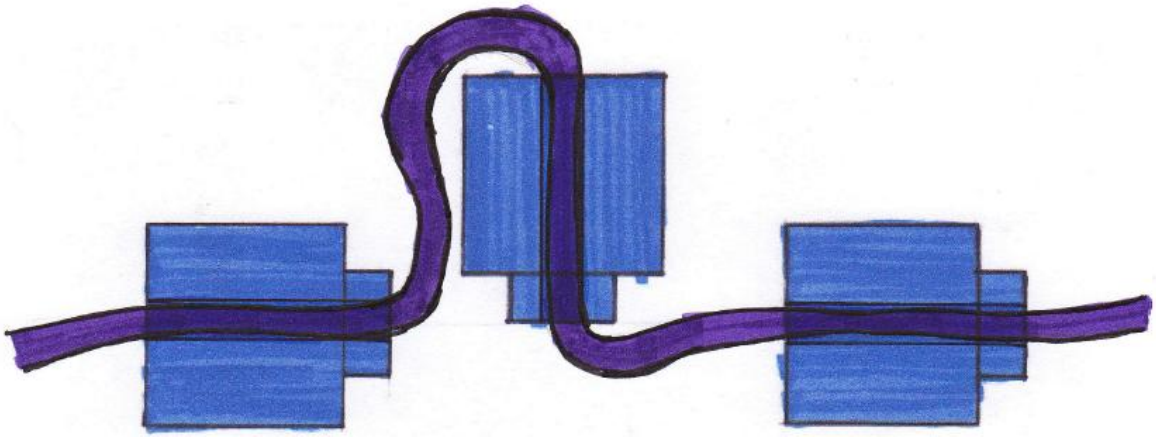


Appendix 5 – Generated concepts
(Page 12/13)

Concept D3: Centre shaft wiring
In this concept wiring goes through the center of motor 4, 5 and 6, and enters motor 5 from the shaft.

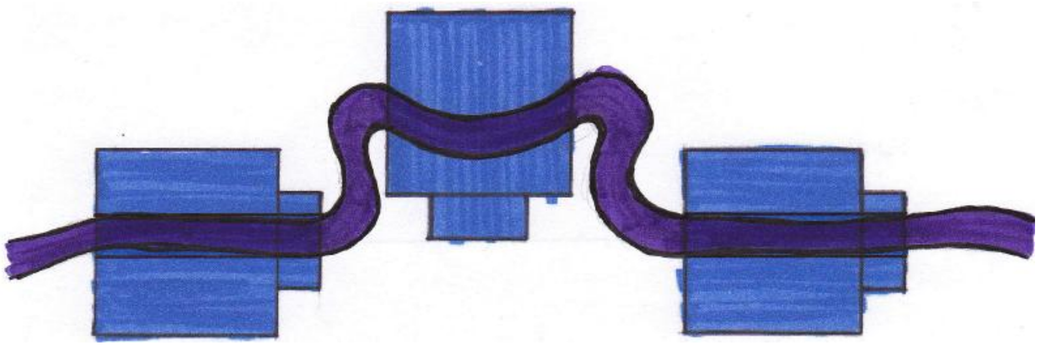


Concept D4: Centre body wiring
In this concept wiring goes through the center of motor 4, 5 and 6 and enters motor 5 from the body.

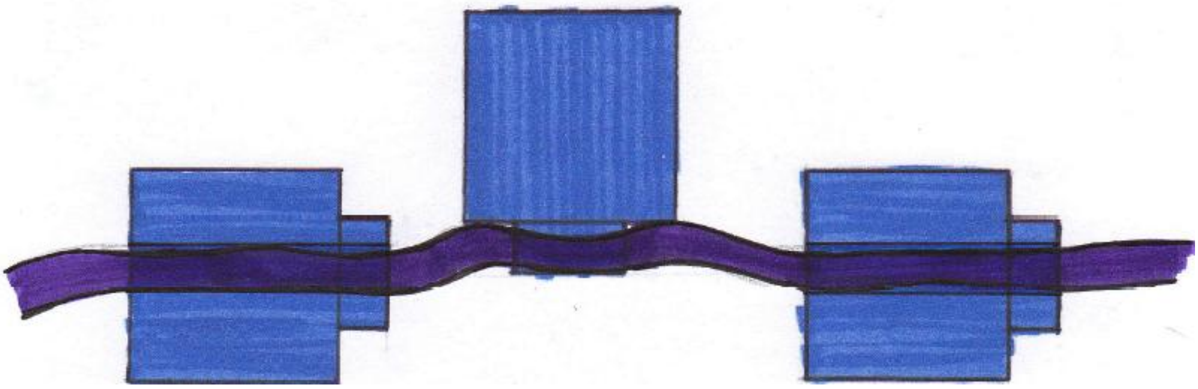


Appendix 5 – Generated concepts
(Page 13/13)

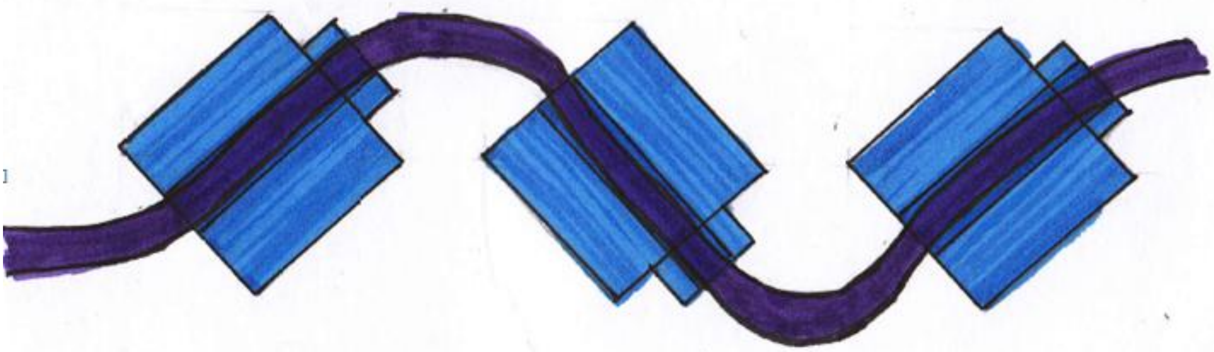
Concept D5: Around body wiring
In this concept wiring goes through the center of motor 4 and 6 and around the outside of the body of motor 5.



Concept D6: Around shaft wiring
In this concept wiring goes through the center of motor 4 and 6 and around the outside of the shaft of motor 5.



Concept D7: Centre wiring (snake wrist)
In this concept wiring goes through the center of motor 4, 5 and 6.



Appendix 6 – Pugh´s Method

Concept evaluation - Carbon fiber connections										
		Concepts								
Requirements	Weight	Ref - Concept 5: Inside bushing ver. 2	**Concept 1: Outside bushing**	**Concept 2: Outside bushing ver. 2**	**Concept 3: Outside bushing ver. 3**	**Concept 4: Inside bushing**	**Concept 6: Inside bushing ver. 3**	**Concept 7: Conical bushing**	**Concept 8: Conical bushing ver. 2**	**Concept 9: Extended aluminum bushing**
Nr of components	3	0	0	0	0	0	0	0	0	+1
Low weight	5	0	-1	0	+1	-1	+1	-1	0	+2
Dimensioning	5	0	-1	+1	+2	-1	+2	-1	0	+2
Durable	4	0	+2	-2	-2	+2	-2	+1	0	+1
Low cost	4	0	+1	-1	-2	+1	-2	-1	-1	-2
Easy assembly	3	0	+1	0	-2	+1	-2	-1	-1	+2
Robust & suitable design	3	0	-1	-1	-1	0	0	0	0	+2
Wiring	4	0	+1	0	-1	+1	-1	+1	0	0
Easy maintenance	2	0	+1	0	0	+1	0	-1	-1	+2
Easy to manufacture	3	0	+1	-1	-2	+1	-2	0	0	-1
Sum +		0	6	1	2	6	2	2	0	7
Sum -		0	3	4	6	2	5	5	3	2
Total sum		0	4	-4	-7	5	-6	-3	-3	9
Weighted sum		0	11	-13	-20	**14**	-17	-11	-9	**32**

A Pugh´s matrix is used to compare concepts by how well they fulfill functional requirements. They are compared by a reference concept, which is either an existing product or the concept considered the best. When comparing, a -2, -1, 0, +1, +2 is used to state whether a concept is better or worse than the reference for a particular requirement. If it is better a +1 or +2 is used, if worse a -1 or -2, and if equal, 0.

These are then multiplied with the requirement weight, the significance of that requirement. The fields are then summarized. The concept with the highest sum is the concept that could best fulfill the requirements.

Appendix 7: Result from interviews

During the work on the thesis, a few companies were visited, and interviews were carried out with the staff. Gathered information is presented below. Only information relevant to this thesis is mentioned below. The companies I visited were “Sjölanders”, ANDON Automation, HDD, and ABB Robotics.

Sjölanders

- A need for a flexible, mobile robot that could be moved to a position for a day or less to do monotonous work
- External cables complicate “offline programming” when it is not shown in the program. External cables damages easily.

ANDON Automation

- When a robot with longer reach is needed, they have to buy a larger robot.
- A smaller foot is needed to fit into small compartments.
- The foot should be symmetrical, and have symmetrical fasteners.
- When the robot is hanging from a beam, ANDON estimated that if the robot only weights 50% of its weight, the price of beams could go down 25%.
- A lighter robot fastened in beams will decrease the resonance frequency.

HDD

- It is possible to develop an even smaller servo actuator with 10 poles and with a diameter of 60 instead of 90mm. This could be used in axis 6.
- The cable extensions on the servo actuator can be rotated to point 180 degrees in the other direction.
- The small servo actuators used in the wrist can use 220V, which will decrease the energy consumption.
- The sensor system can handle approximately 125 degrees Celsius, and the stator can handle about 140.

ABB Robotics

- It costs around 50 million Swedish kronor to develop a robot.
- Approximately 4000-5000 of IRB1600, IRB2600, IRB4600 robots are sold each/year.

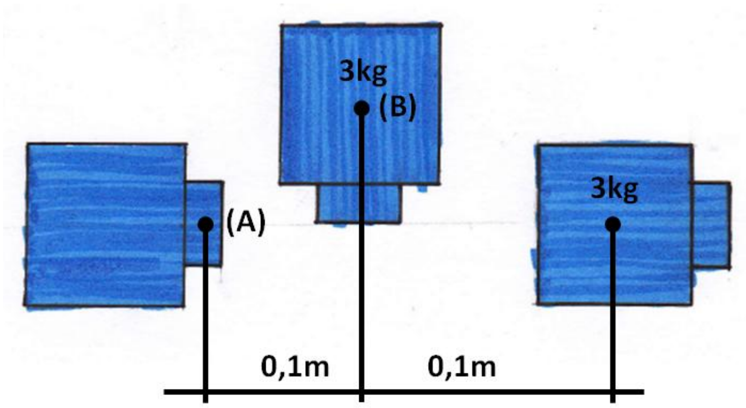
Appendix 8 – Calculations
(Page 1/3)

Calculations were made to understand the force put on the wrist in axes 4 and 5 when the arm is standing in a static horizontal position.

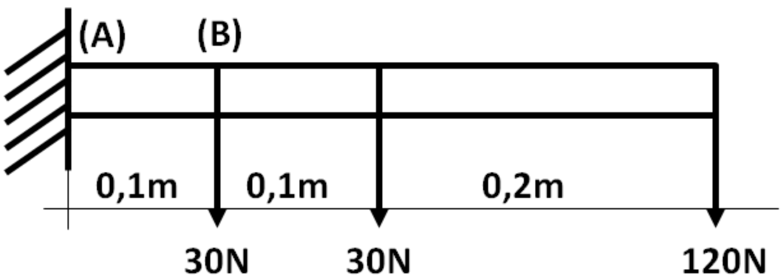
Distances between motors and their body weight (with casing) have been estimated to try to reflect their actual values.

Weight in kg has been converted to Newton, and the lengths are measured in meters.
1kg = 10N (9.81N)
A weight of 12kg which represents the payload is placed with its center of mass 0, 2 meters from motor 6.

Concept 1: Open arm



Simplified image:



Torque around A: 0, 1*30 + 0, 2*30 + 0, 4*120

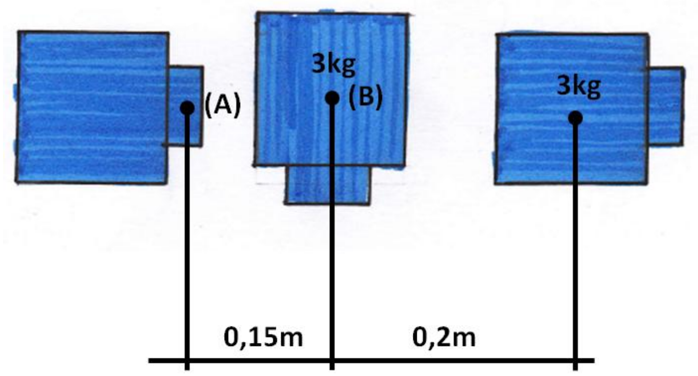
= 3 + 6 + 48 = **57 Nm**

Torque around B: 0, 1*30 + 0, 3*120

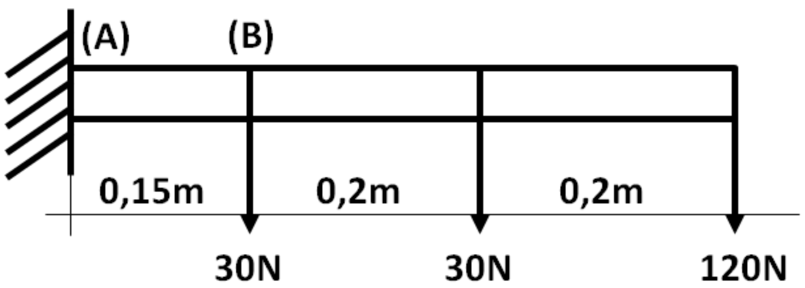
= 3 + 36 = **39 Nm**

Appendix 8 – Calculations
(Page 2/3)

Concept 2: Thin arm



Simplified image:



Torque around A: 0, 15*30 + 0, 35*30 + 0, 55*120

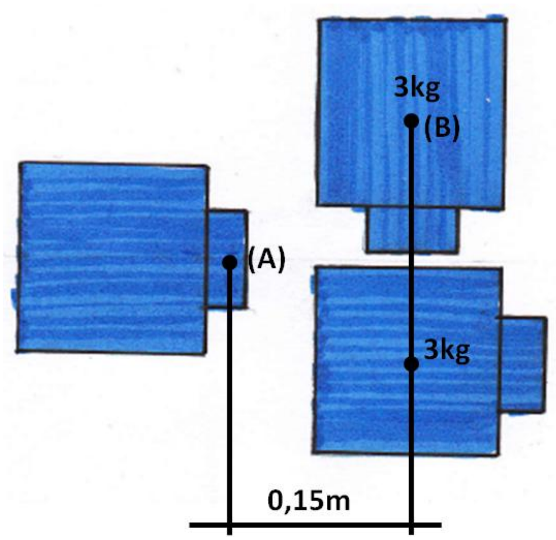
= 4, 5 + 10, 5 + 66 = **<u>81 Nm</u>**

Torque around B: 0, 2*30 + 0, 4*120

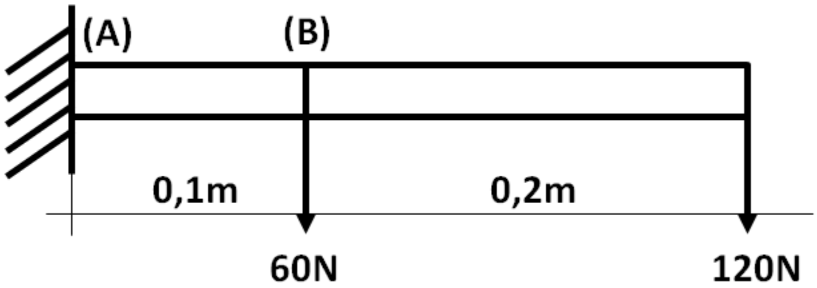
= 6 + 48 = **<u>54 Nm</u>**

Appendix 8 – Calculations
(Page 3/3)

Concept 2: Thick arm



Simplified image:



Torque around A: 0, 1*60 + 0, 3*120

= 6 + 36 = **42 Nm**

Torque around B: 0, 2*120

= **24 Nm**

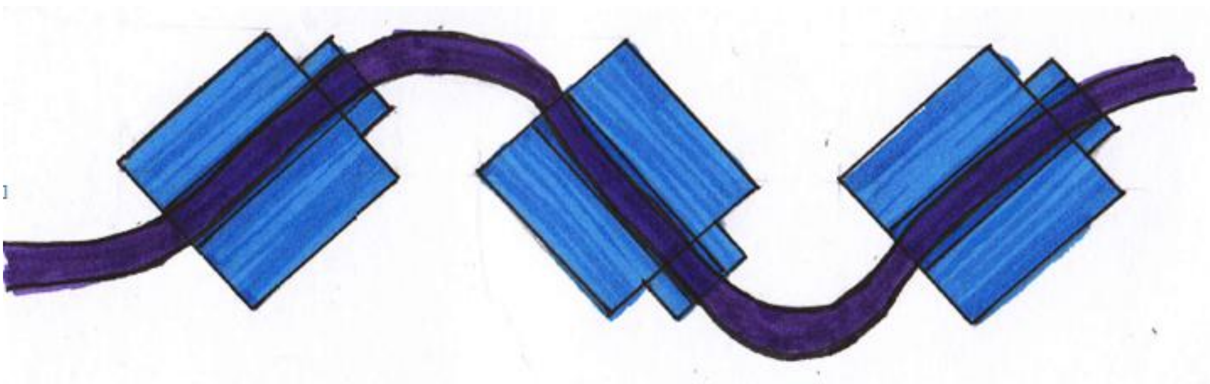
Appendix 9 – Snake wrist

(Page 1/2)

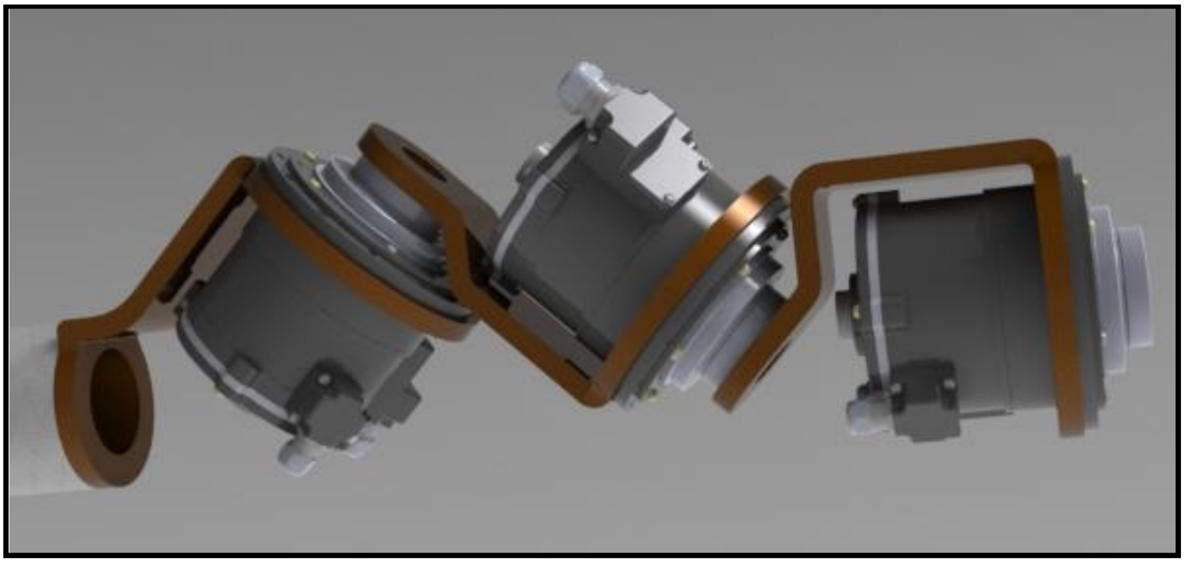
The snake wrist concept was separately developed since it has other application uses than the wrist developed in this thesis. The snake wrist had plenty of good qualities that were interesting and was therefore worth taken a closer look at. It was rapidly designed without any concerns for its construction, just to get an idea of how it could look like.

The concept is the only with angled motors, which is particularly good for painting, because it can point the motors against the robot body, making it easier to get under and behind components that needs to be painted. To achieve this, motor 4 is placed with a 45degree angle, motor 5 is then perpendicular from that, and motor 6 is perpendicular to motor 5. Because of the motor angles, relative straight cabling can be drawn through all center axes.

Snake wrist concept:



The snake wrist concept illustrated in CAD:



I connected the snake wrist concept with the *extended aluminum bushing*, and the motor connection concept *shaft-body, shaft*-body, which seemed most logical.

The concept was evaluated, and a list of pros and cons was set up;

Appendix 9 – Snake wrist

(Page 2/2)

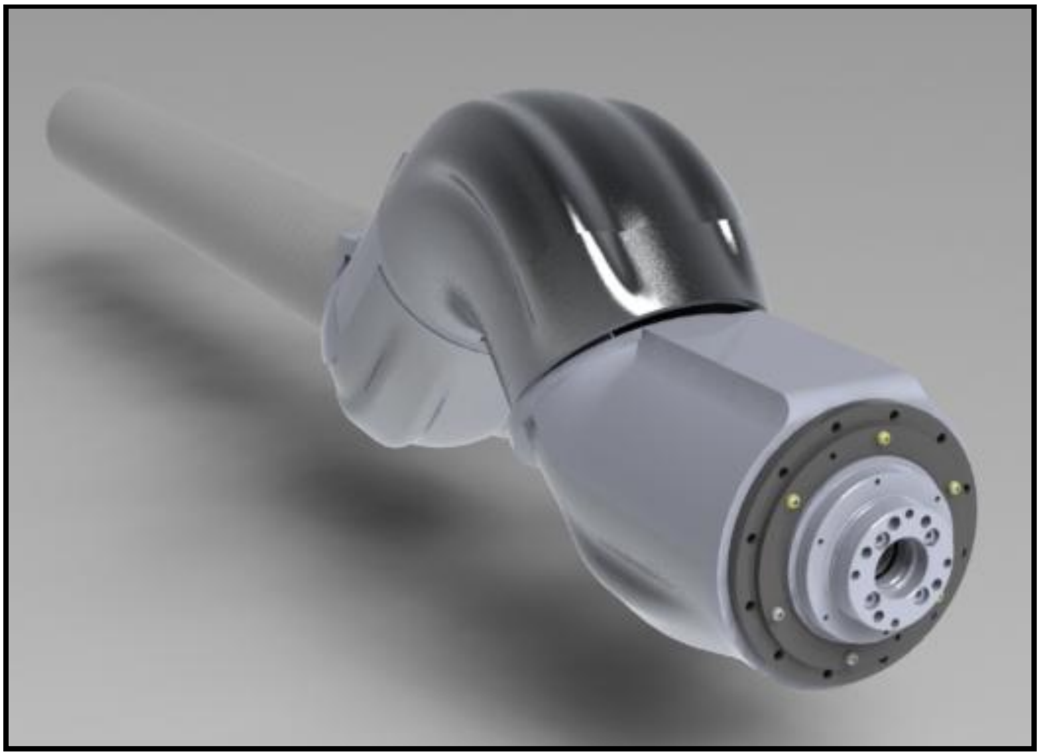
Pros

- Easily maintained - the use of the extended aluminum bushing and covering plates for all motors, make them easily accessible without any other disassembly.
- The thin carbon fiber tube used, keeps weight down.
- Lower cost on the carbon fiber tube because of its small diameter.
- Cablings have smooth transitions between motors; they will not be exposed with too much friction which prolongs the time between maintenance.
- Easy to seal, and keep the area down between moving parts.

Cons

- The aluminum castings are constructed with complex shapes, making it costly to manufacture.
- It is harder to maneuver the wrist manually.

The snake wrist were closed in and designed:



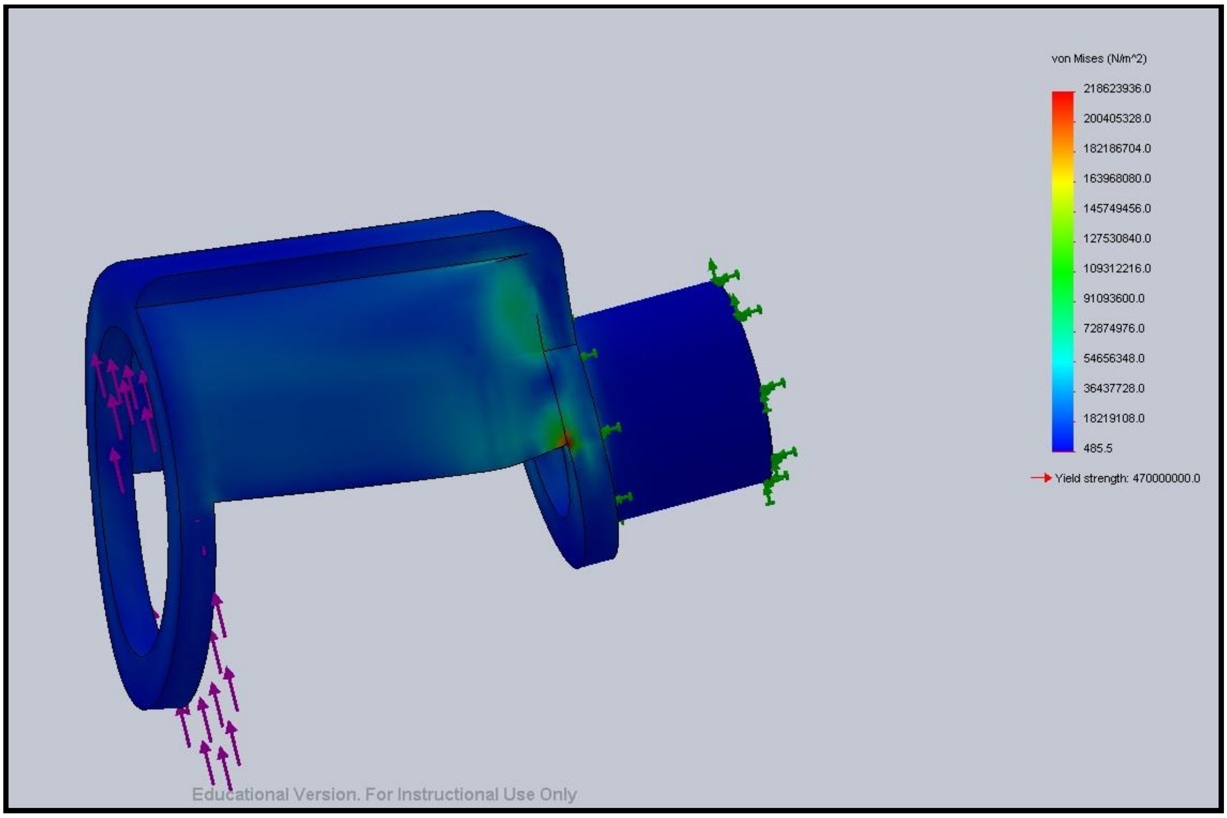
Appendix 10: FEM Analysis

(Page 1/4)

A simple analysis was carried out on an early component using a standard aluminum material. The use of the analysis was to observe how well the component would react when it was exposed to an external force. By doing that I could get an understanding whether the construction would last when subjected with a load and also If I was on the right track. The weight of the payload is 12 kg, which was then multiplied by 2 to get a rough estimation of an accelerated load, which gives 24 kg or a force of about 240 Newton.

As seen in the picture below, some deformation did occur, and the weaker spots have been marked out in red and green.

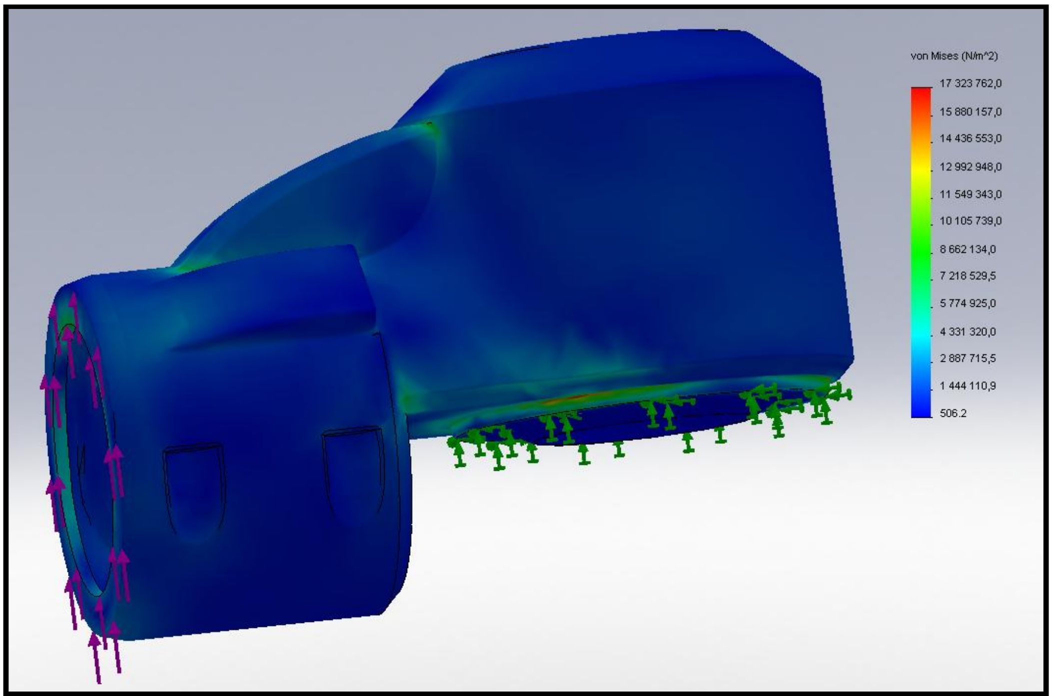
This gave me a good idea of the durability of the component and what I need to change to make it better. This component is going to be connected with an opposing aluminum part, and a motor is going to be placed in between these components which will further support the structure and significantly increase its durability.

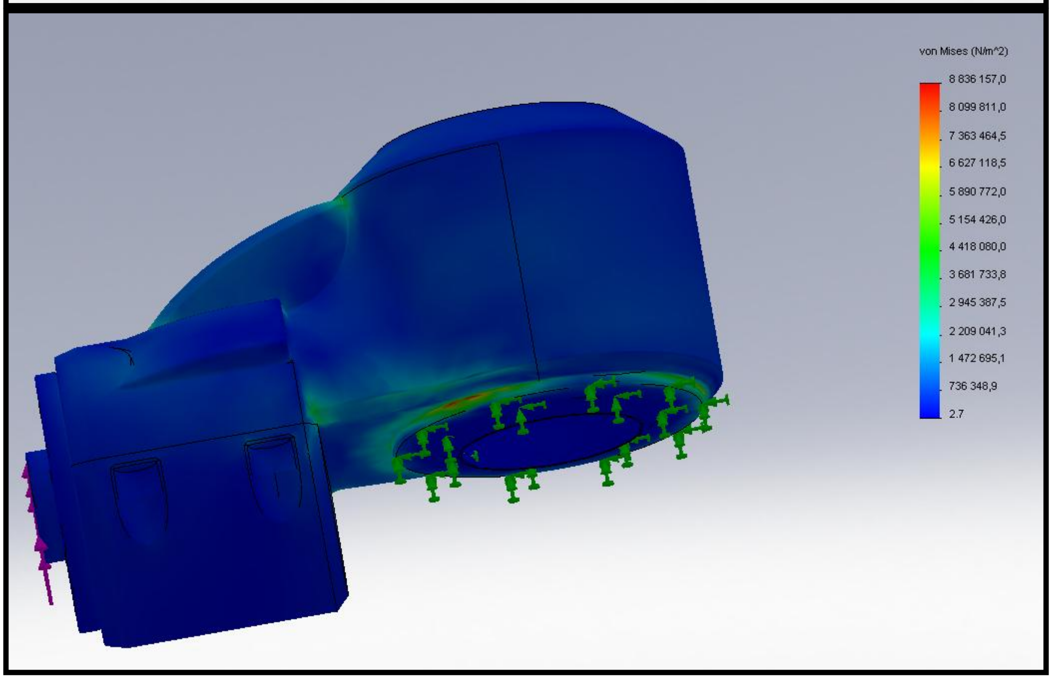


Appendix 10: FEM Analysis

(Page 2/4)

Before I could determine the final design, an analysis was made to make sure it would be durable. The first picture is an analysis of the “shell” of body 5 and 6 treated as one solid. In the second picture I have added motor 6 to show how much it affects the result.

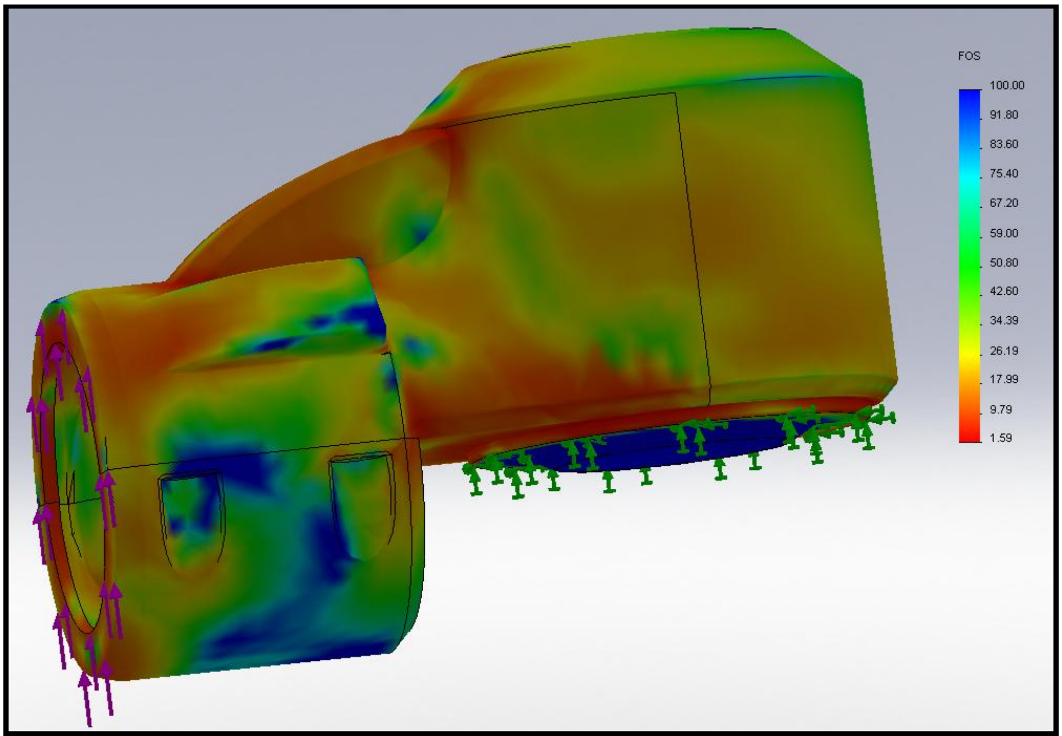


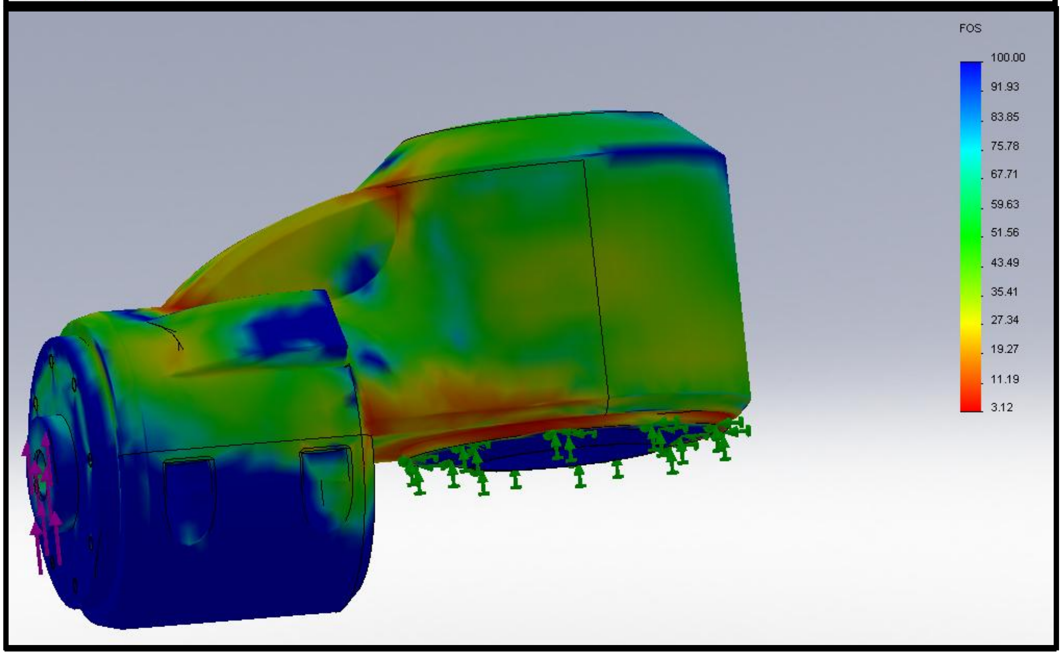


Appendix 10: FEM Analysis

(Page 3/4)

These two pictures show the FOS (factor of safety) with a standard aluminum. Both components correspond with the two images on the previous page. The images show us that the casing without any motors have the smallest FOS at 1.59. With motor 6 the smallest FOS is 3.12. This tells us that the design is very sturdy with a motor (motor 6) and would be even sturdier when motor 5 is in place.

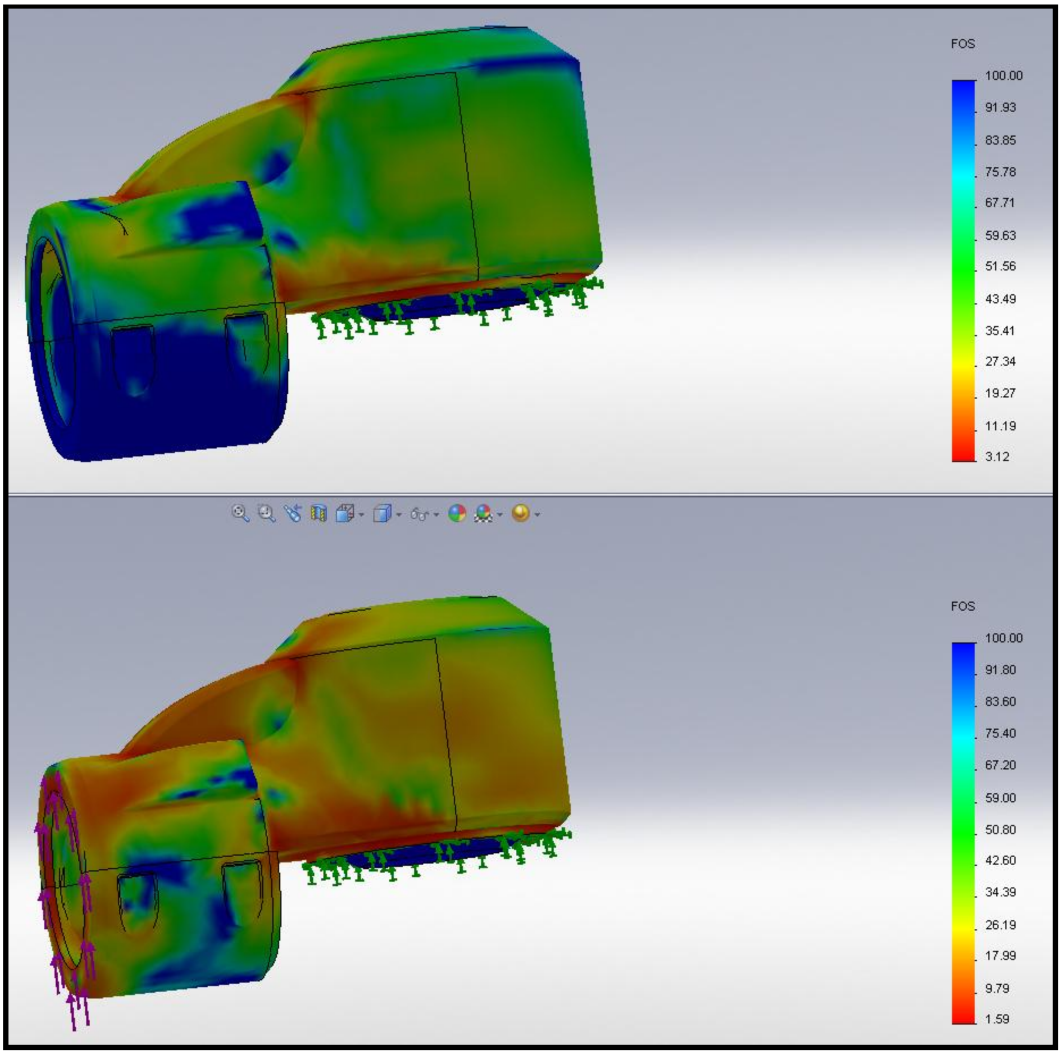




Appendix 10: FEM Analysis

(Page 4/4)

Here is the shell of body 5 and 6 compared with two different aluminum alloys. The bottom picture shows the part with the same alloy as before and has the smallest FOS at 1.59. In the top picture another alloy, with the same density but higher tensile – and yield strength has been used. Therefore the smallest FOS is higher and in this case 3.12.



This analysis shows that the design seems reliable after some smaller alterations by strengthening the design in some areas, and possibly reducing the sturdiness and also weight in areas where it is not material effective.

Appendix 11 – System FMEA

No	Function/ Component	Failure mode	Failure effects	Potential causes	Risk analysis				Actions recommended
					Freq.	Sev.	Det.	RPN	
1	Cabling	No power, no signal	Robot stops	Broken cable	2	9	4	72	
				Bad connection	4	4	7	112	
				Twisted cable	5	4	6	120	
2	Castings	Castings break		**Defects in material**	6	5	8	**240**	Quality controls
				Wrong material	2	6	3	36	
				Wrongly calculated	4	6	9	**216**	Review calculations
				Collision	7	5	10	**350**	Crash tests
		Loose screws	Component falls off	No washer	3	4	8	96	
				Wrong dimension	3	3	8	72	
				Threads too soft	2	3	9	54	
				Wrongly tightened	4	4	9	144	
3	Motors	No signal	Robot stops	Broken motor	1	9	3	27	
				Overheated	5	5	2	50	
				Bad connection	2	4	6	48	

Comments: The FMEA is furher discussed in chapter 7.8 in the report.

Criterium for evaluation of frequency	Scale	**Criterium for evaluation of severity**	Scale	**Criterium for evaluation of detection**	Scale
Unlikely for error to occur	1	No risk of accident or product damage	1	Errors alw ays detected	1
Very small probability of occurence	2 - 3	No risk of accident or function failure	2 - 3	Errors likely to be detected	2 - 4
Small probability of occurence	4 - 5	Small risk for personal damage, some risk for function failure	4 - 6	Some probability of detection	5 - 7
Some probability of occurence	6 - 7	Small risk for personal damage, high risk for function failure	7 - 9	Small probability fo detection	8 - 9
High probability of occurence	8 - 9	Considerable risk for personal and functional damage	10	Not likely to be detected	10
Very high probability of occurence	10				

Appendix 12 – Designing the robot
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To design the exterior of the robot, I studied the IRB 2400 and IRB 2600 to understand the idiom that ABB use. I could distinguish some traits that define an ABB robot. One of the first things that are noticed about an ABB robot is the orange color. Another thing is the feeling of robustness, which manifests in the large bolts showing in the pictures. Chamfering is also commonly used. I looked a little closer at some of the parts that I felt were included throughout the IRB robot series. In the picture below the IRB 2600 (to the left) and IRB 2400 (to the right) are shown.

The first part I looked at was the sides of the IRB 2400 body, where the large bolts are exposed.

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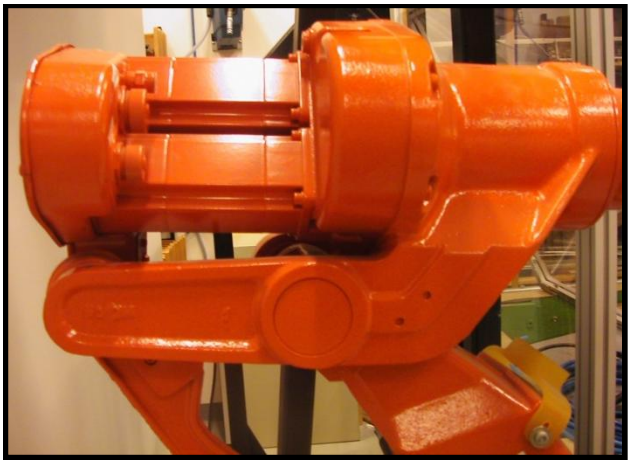
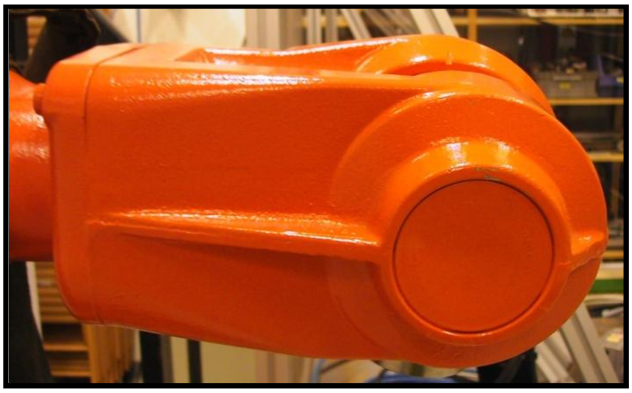
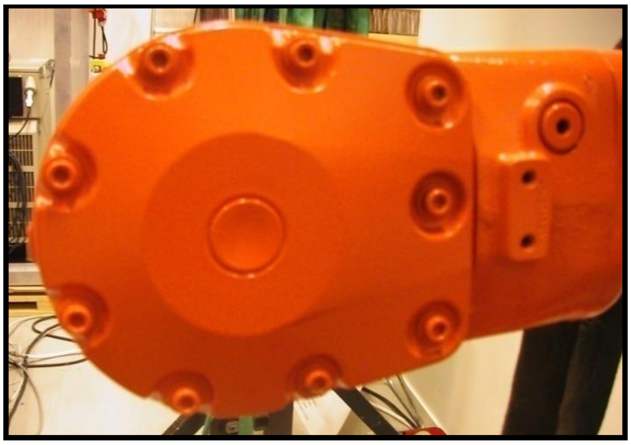
The elbow of IRB 2400 also had some common traits, which is the embossed circle that shows where the lower arm is rotating.



In this wrist, the embossed circle is exposed yet again, with the use of a rib structure that is used in some of the ABB models.



On the other side of the robot wrist, the large bolts are used. And the transition from a larger circular plane to a smaller is a reoccurring trait of the ABB robots.



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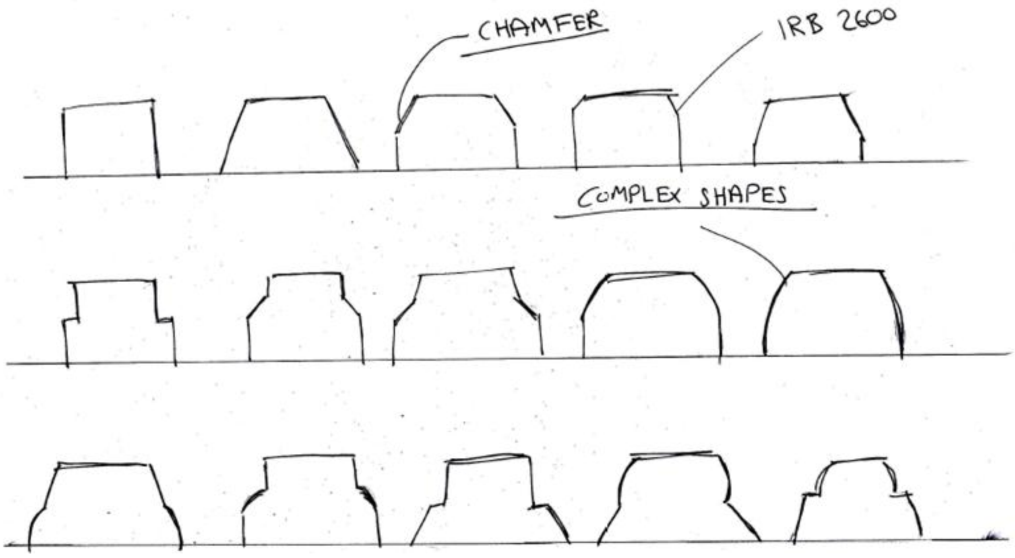
I then looked at different shapes for the body. A few variants were drawn to understand different shapes that can be used. Since it was already decided that the body should be uniform, numerous shapes were excluded. Some of the shapes are displayed below.



Different shapes were also drawn for the rest of the body, since there were no need for this part to be uniform plenty more sketches were made, illustrated below;