Master Thesis in Machine Elements

Agile robotic arm for vertical applications

Evaluation, design and development

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Abstract

Existing pick and place robots are either heavy or have a limited workspace for vertical operations. Since there is no robot today that are both light and have a good vertical workspace, this leads to a gap in the market. With the use of the laws of physics Cognibotics is trying to fill these gaps in the market, by developing new fast and lightweight robots. These new robots are designed to have as much of the total weight as possible close to the base. This will decrease the moment of inertia which will help make the robots faster.

Cognibotics holds a patent with multiple different robotic arms that have the possibility to have a vertical workspace. This thesis will focus on evaluate these robotic arms and develop the robotic arm with the best opportunity to be fast, lightweight and have a vertical workspace. The development will focus on the overall layout of the arm, which includes the rods and joints. The sizes of the rods will be selected and for the joints, bearing type and size will be selected. The development of the joints will also include how the bearings should be mounted.

In the patent, the robotic arm presented in fig. 9 is evaluated to be the best option for further development. This arm is light, has a good weight distribution (most of the weigh is close to the base) and fewer parts than the other arm, which will probably make it cheaper. The original arm presented in the patent do only have three DOF (degrees of freedom). The arm however can be modified to have a fourth actuator at the end effector for the possibility to get the last DOF, which is needed for the application this thesis applies. Based on the selected robotic arm from the patent, two concepts where made. The first concept ”concept 1”, will probably be lighter and have a better weight distribution than the second concept ”concept 2”. Based on this, the conclusion is drawn that ”concept 1” is the best option.

For the selected concept, a CAD model was made. In the CAD model both the rods and the joints are designed in greater detail. A total of five different joints within the CAD model, were needed to be designed and developed. For the development of the joints, a wide arrange of bearings are used. Some of the more common bearings are angular contact ball bearings and tapered roller bearings. In one of the more complex joint, spherical roller bearings are used. For the development of the rods, a reach study was made. The lengths of the inner and outer arms is selected based on this reach study. For a good performance the size and profile of the rods was then investigated. Since one rod is carrying almost the entire weight of the robotic arm, this rod need to be bigger than the rest of the rods.

When the development of the robotic arm was complete, a crude cost analysis of the robot was performed. This includes the total material cost for the robot, which includes the cost for the rods, joints (with bearings), tool mounting platform, motors, gearboxes and control systems.

Acknowledgments

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Contents

1 Introduction

1.1 Background

1.1.1 Pick and place robot

The objective for a pick and place robot is to pick up an object at one place and then position it and drop it of at another location [1]. There are various design of robots that can achieve this and some of the different pick and place robots are described in the following chapter (1.1.2).

In fig. 1 different parts of the robot and their location can be seen. These parts are the ones that are most frequently used during this thesis. The base is where the robotic arm (manipulator) is mounted against the ground. The robotic arm developed in this thesis is divided in to an inner arm and an outer arm. The inner arm and the outer arm is connected by the elbow joint. At the end of the outer arm the tool mounting platform is located, it is on this part the tool will be mounted. The end effector is then the point at the tool mounting platform which can be seen as the end of the robotic arm.

A parallelogram is a quadrilateral where the opposite sides are always parallel against each other [2]. In fig. 1 two of the three parallelograms for the robot is presented, one in green and one in pink.

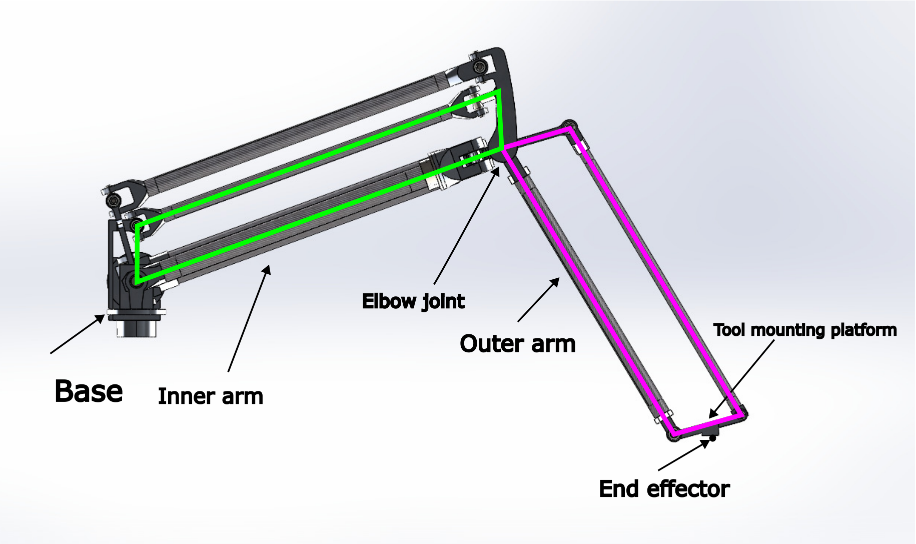


Figure 1: Parts of the robot

1.1.2 Existing pick and place robots robots

Two of the most established pick and place robotics on the market are the Delta robot and the SCARA (Selective Compliance Assembly/Articulated Robot Arm) robot. These two types of robots are both fast and accurate. They do however lack in vertical reach. The definition of the vertical reach for this thesis is the total length the tool can reach normal to the horizontal plane, with other words how deep and high from the horizontal plane the robot can reach. For pick and place applications where vertical reach is an important factor, Articulated robots are often used. These robots are often made of cast iron and are therefore heavier and slower than both the SCARA robot and the Delta robot.

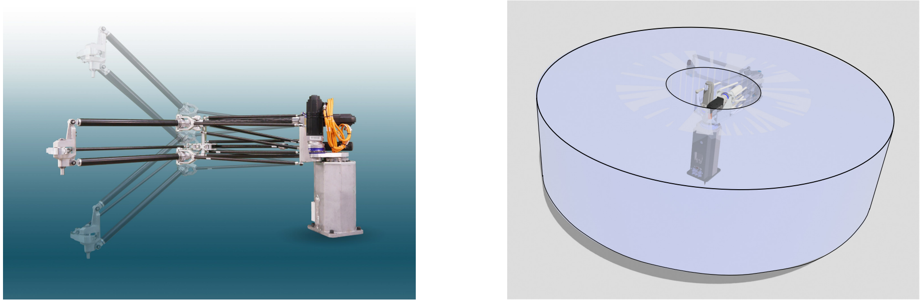
The Delta robot is very fast, but the working area is very limited by its design. The pick up area and drop off area need to be similar in height, since the vertical reach is limited due to its bowl like working space, (fig. 2). The tool is placed under the robot, and therefore it needs to be mounted on a roof or in a cage where it can be hanged. [3]

Figure 2: Delta robot and its workspace [4]

The SCARA robot do also have a fast operating speed, but when it comes to its vertical reach it is limited. This can be seen in fig. 3, which show that the workspace is good when moving objects horizontally. The SCARA robot can be mounted on roofs, walls and on benches, which make it more adaptive than the delta robot. [5, 6]

Figure 3: SCARA robot with its workspace [7]

Both of the robots presented above are fast but has a limited vertical reach. The two robots above do also have a limitation in the horizontal reach, where the reach often is not more than one meter. For horizontal operations where the reach need to be longer Cognibotics is developing a new robot called HKM. This robot have a longer horizontal reach, but as can be seen in fig. 4b its vertical reach is still limited.



(a) HKM [8]

(b) HKM workspace

Figure 4: HKM

For pick and place applications where vertical reach is important, articulated robots are often used. These robots are both larger and heavier than the delta, SCARA and HKM robot presented above. These articulated robots are made of cast iron and are therefore much heavier than all the three robots mentioned above, this do also mean that they are slower than the other robots. E.g of an articulated robot can be seen in fig. 5.

Figure 5: ABBs IRB 660 [9]

It looks like the pick and place robots on the market is either light and fast, but with limited vertical reach. Or they are heavy and slower, but with a good vertical reach. This leaves a possibility for a new robot, one that are combining the lightness and speed of a delta and SCARA robot, with the vertical reach of an articulated robot.

1.2 Purpose

Cognibotic is a relative new robot manufacturer on the market, which are exploring new grounds for robot design and development. They are trying to use these gaps (one is mentioned above) in the market to create new robots that have the possibility to fill these gaps. The main idea for the robots developed by Cognibotics is to minimize mass and inertia to make them faster and to use rods in carbon fibre to make them stiff. Both the acceleration in eq. 1 and the angular acceleration in eq. 2 can be increased, when the force or moment are decreasing due to decreas in mass and/or inertia. Also by decreasing the mass and increasing the stiffness the resonant frequency (eq. 3) will be increased which will benefit control.

$$F = ma \tag{1}$$

$$M = I\ddot{\theta} \tag{2}$$

$$\omega = \sqrt{\frac{k}{m}} \tag{3}$$

To fill this gap mentioned above, Cognibotics have a patent including different robotic arms with all the wanted properties. The arms presented in this patent can have both a better vertical reach than the delta robot, SCARA robot and the HKM, but also be lighter and faster than the heavier articulated robots. The arms presented in the patent do also have the advantage that much of the mass is close to the base, this compared to other pick and place robots where the mass is located further from the base.

The aim for this thesis is to develop one of these robotic arms presented in the patent, with the purpose of having a robot that could load a roll container without the need of any assisting device such as lifting tables, which is needed for the current HKM as can be seen in fig. 6.

Figure 6: The existing HKM operating in a working environment similar to the one for this new robotic arm.

1.3 Objectives

Cognibotic has a patent containing various robot arms, designed to operate with a good vertical reach. This thesis will evaluate and investigate if one of the robot arms included by the patent is suitable to develop for the purpose of being a pick and place robot with a good vertical reach. The robotic arm should be able to fulfil the following requirements:

- Fill a roll container with the dimensions 1800x800x720 mm (without any assisting devices, such as lifting tables)
- Handle a payload of 25 kg
- When fully loaded turn with 1g of acceleration
- Have 4 DOF
  - x-direction
  - y-direction
  - z-direction
  - Rotate payload (around z-axis)

The patented robotic arm that best can fulfil these requirements will be further developed. If none of the robotic arms in the patent can fulfil these requirements, other solutions for a robotic arm will be looked at.

The robotic arm has to be attractive on the market. To achieve this, it needs to be of good quality and operate with enough accuracy to perform its task. At the same time, the robotic arm must also be competitive in price. It is important to consider all of these aspects while developing the robotic arm.

1.4 Limitations

The purpose of the robotic arm is to be used as a pick and place robot and it will be developed for this purpose only.

If a robotic arm from the patent is selected to be further developed, the arm should be developed according to the claims in the patent. Some degree of modification is acceptable as long as the kinematic principles are followed. If none of the robotic arms in the patent is selected to be further developed, the new arm solutions should be developed as close as possible according to the patent.

The patent includes more than 20 robotic arms and mechanisms. It would be very time consuming to evaluate all of them. Therefore, this thesis will only focus on some of the robotic arms, that are considered to be the most prominent ones for the presented task.

The robotic arm needs to be attractive on the market and to achieve this, it need to be price worthy and have a good lifespan. To achieve this, standard and proven parts will be used in as high extent as possible.

Since it would be to great of a task to develop a complete robotic arm with all its parts, the following areas is selected to be further developed in this thesis:

- General design
    - Locations of the rods and joints
    - Location of the actuators
    - Length of the inner and outer arm
- Rods
    - Size of the rods
    - Length of the rods
- Joints
    - Type of bearings
    - Size of the bearings
    - Mounting of the bearings

Since the gearbox and motor will not be developed in this thesis, it will be hard to develop the parts which are in direct connection to the gearbox. Because of this these parts will not be developed either, since they will need to be redevelop in a future stage.

2 Method

The general work flow for the project can be viewed in fig. 7, where the project starts with evaluation of the patent and the robotic arms presented in it. When a robotic arm has been selected concepts will be created and later selected. This will be followed by the development of the selected concept. During the development the rods will be dimensioned and the joints will designed. Designing the joints refers to selection of bearings and their size and how to mount them. When this is done a FEM study will be performed which will show if the bearings and rod sizes are correctly selected. If they are not correctly dimensioned they will be further dimensioned until they are good enough. When all parts can be consider to be correctly dimensioned, the model is complete.

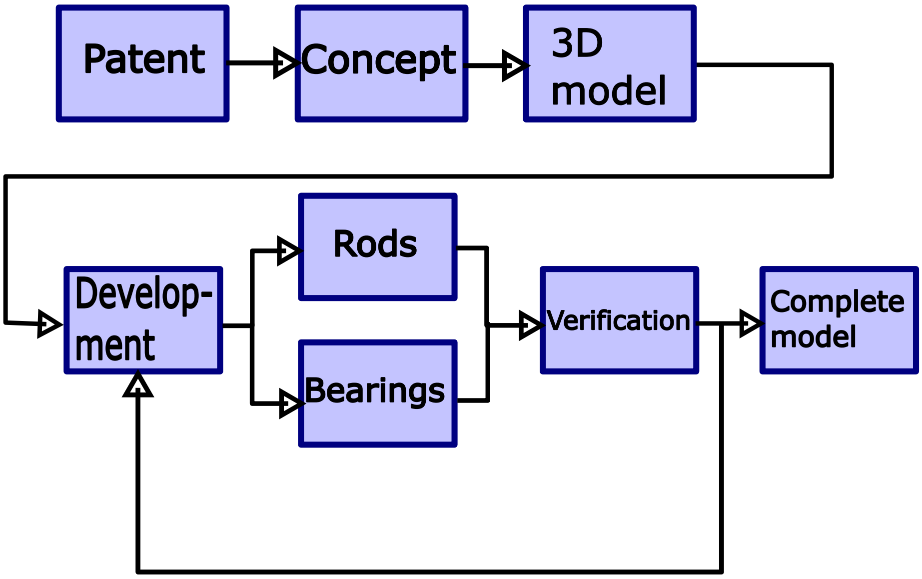


Figure 7: Workflow

2.1 Patent

The first step in the selection of robotic arm is to get a good understanding of its working principles. This includes an understanding of how many DOF (degrees of freedom) it has got and how the DOF are controlled. This will mostly be done by reading and studying the mechanisms of the robotic arms presented in the patent. To keep the project within the frames of the patent, it is also important to know the claims of the patent. This will be done parallel to the study of the mechanisms. To get a further understanding, a meeting will be held with the patent owners. This meeting will help clarify the mechanisms and claims of the patent further.

When the claims and mechanisms of the robotic arms are fully understood, it is possible to have a proper selection process where the best robotic arm is selected. To get a proper selection and evaluation process, some requirements need to be set. These requirements will be based on the purpose and objectives of the robotic arm. To get proper requirements, the objectives need to be defined before it is possible to set the requirements. Once the requirements are set, the robotic arms can be evaluated equally. After the evaluation, the best robotic arm can be selected.

2.2 Concepts

The selected patent will show key features for the robotic arm. These features will show patterns, geometries and location of some objects. In order to develop the patent to a real product a design needs to be created. With multiple designs it is possible to choose the design with best features fit for the purpose of the robotic arm. For the selection of concept to continue with, the pros and cons for the different concepts will be discussed.

2.3 Development

First a model will be made to get an idea of how the robotic arm will look like and to help establish the requirements for the bearings and rods. An initial size of the rods and bearings will be selected. A FEM study will then show the displacement of the robotic arm, the stress in the different parts and what forces will be subjected to the bearings.

The parts in the model will be developed further based on the information provided by the FEM study. The selected bearings and rod sizes will be evaluated and developed further if they not meet the requirements. A new FEM study will be made on the developed robotic arm to verify if the new dimensions of the rods and bearings is good or not. If not they will be developed further until all the bearings and rods have good dimensions.

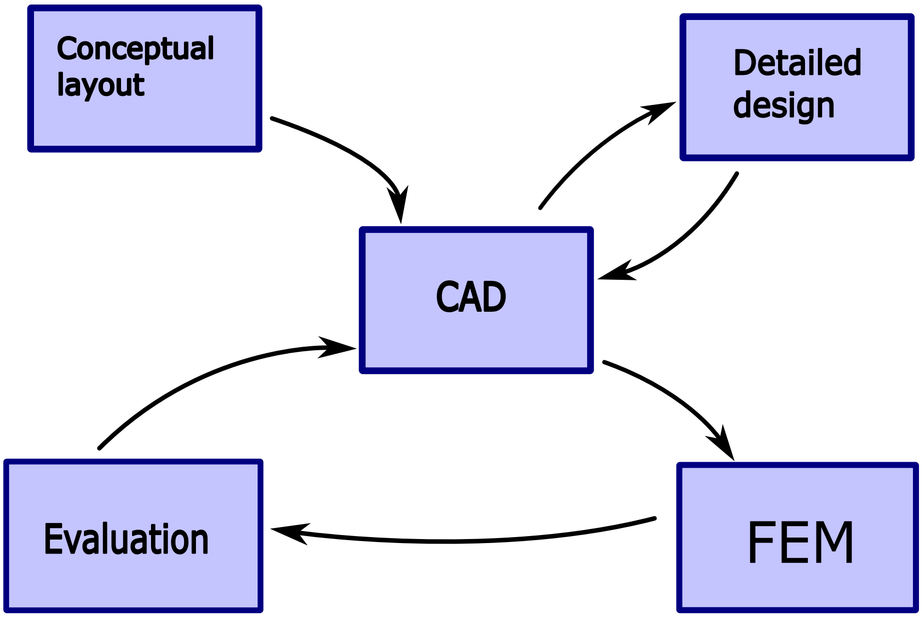


Figure 8: Work flow for the developing of the model

3 Patented robotic arms

As mentioned in chapter 1.4 only a few of the robotic arms presented in the patent will be focused on. The selection of these arms are based on which can be considered to be prominent to fulfil the requirements. Six robotic arms are selected and these arms can be seen in the following figures: 9, 10, 11, 12, 13, 14.

3.1 Requirement selection

The robotic arms need to fulfil all the requirements presented in chapter 1.3. For a better performance the robotic arms should also be evaluated based on weight and weight distribution. Since the robot should be able to place a payload correctly at one place, the accuracy is also one requirement that the robotic arms should be compared on. How the requirements will be evaluated is described in more detail below.

Since the vertical reach is dependant on how long the inner and outer arms are, all of the robotic arm can have potential to fulfil this requirement. Because of this it is not necessary to use this requirement when evaluating the robotic arms.

The robotic arm selected should also have potential to perform good on the market. To compare the robotic arms according to this, cost of the robotic arms will also be included in the evaluation.

After the evaluation each robotic arm will have been give a total score. The robotic arm with the lowest score is the one that can be considered the most prominent one to continue with. After the evaluation a short discussion will determine if the robotic arm that scored best, can fulfil all the requirements needed.

Weight
To compare the potential weight of the robotic arms, the number of parts will be used for evaluation. For simplification all parts will be considered equal in weight. The parts that will be accounted for is the moving parts only.

Weight distribution
To compare the weight distribution of the robotic arms, a score system will be used. This system will score a number between 1-7. What the score represent can be seen in the table 1. For this requirement heavy parts is defined as a motor, gearbox or any other heavier parts such as gears.

Table 1: Score system weight distribution

Score	Requirement
1	No heavy part on either the inner or outer arm
2	One heavy part on the inner arm
3	One heavy part on the outer arm
4	One heavy part on the inner arm and one heavy part on the outer arm
5	Multiple heavy parts on the inner arm
6	Multiple heavy parts on the outer arm
7	Multiple heavy parts on both the inner and outer arms

Accuracy
The number of joints is one factor that will have an impact on the accuracy of the robotic arm. To compare the accuracy of the robotic arms the number of joints will be used. The higher amount of joints, the higher is the risk of play in the arm, which will decrease the accuracy.

DOF
Since it is not only the number of DOF that is important, but also what DOF the robotic arms have, a scoring system similar to the one for the weight distribution will be used. This scoring system will give a score between 1-4. How the score is given is described in 2.

Table 2: Score system DOF

Score	Requirement
1	Have all four wanted DOF and some more DOF
2	Have all four wanted DOF
3	Can have all four DOF with modification
4	Have four DOF but all DOF are not the needed ones

Cost
To compare the cost for the different robotic arms, the total number of parts on the robotic arm will be use to compare them.

3.2 Evaluation

Robotic arm 1
As can be seen in fig. 9 the number of rods between the actuators and the end effector are few and because of this the moving mass is also low. This arm contains three actuators, the green actuator (actuator 1) are in control of raising and lowering the inner arm (the inner arm exists of the green rod (rod 15) and the pink rod (rod 18)). The pink actuator (actuator 3) turning the bevel gear which in turn rotates the pink arm which move the arm sideways. The turquoise actuator (actuator 2) moving the outer arm in and out. The arm is one DOF short since it can not rotate the payload. The robotic arm do have enough space on the tooling platform (rod 41) to mount a fourth actuator. This actuator do not need to be big but it will still increase some of the moving mass. The rotation of this fourth actuator is displayed in fig. 9 by the red line located at the tool platform

From fig. 9 it is also clear that most of the weight is close the base. All of the three big actuators are located on the base, which means they are not included to the moving mass. The moving mass exist by carbon rods, joints and the small actuator located at the end effector. This actuator do not need to be big and it will because of this also be cheaper than a big actuator.

The overall layout of the robotic arm is simple, there is no big chains of rods and joints, which will increase its potential to be accurate. Because the design is easy and simple and the lowest number of rods are used it will also be light weight, the simplicity will probably make this arm easier to manufacturer.

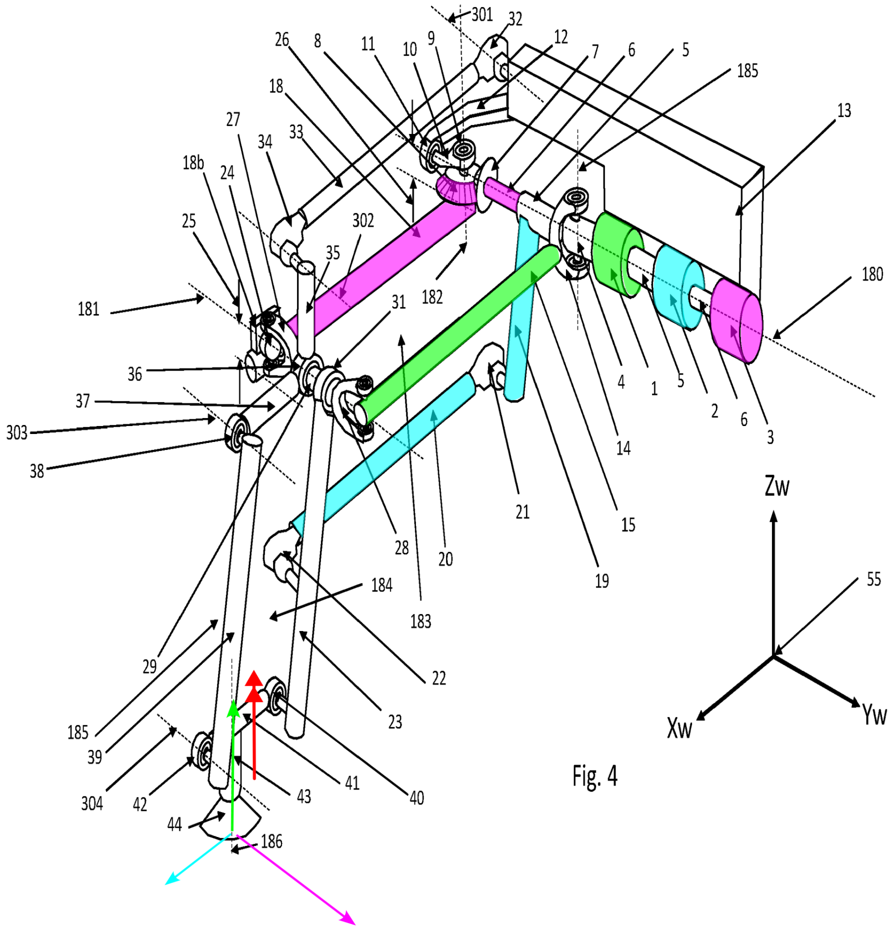


Figure 9: Figure 4 in the patent [10]

Robotic arm 2
This robotic arm has five actuators. The green actuator (actuator 1) is used to raise and lower the inner arm. The turquoise actuator (actuator 2) is used to move the outer arm in and out. The pink actuator (actuator 46) is used to move the inner arm sideways. The dark blue actuator (actuator 3) is used to tilt the tooling platform. The red actuator (actuator 98) is used to rotate the payload. Both the two last movements are made possible by long chains of rods and joints and because of the long rods it may be hard to get a good accuracy from this arm.

This arm is big and has a lot of rods and actuators, which will make it heavier than the rest of the arms. Because of the number of part it will potentially be more expensive. The arm do have all the wanted DOF.

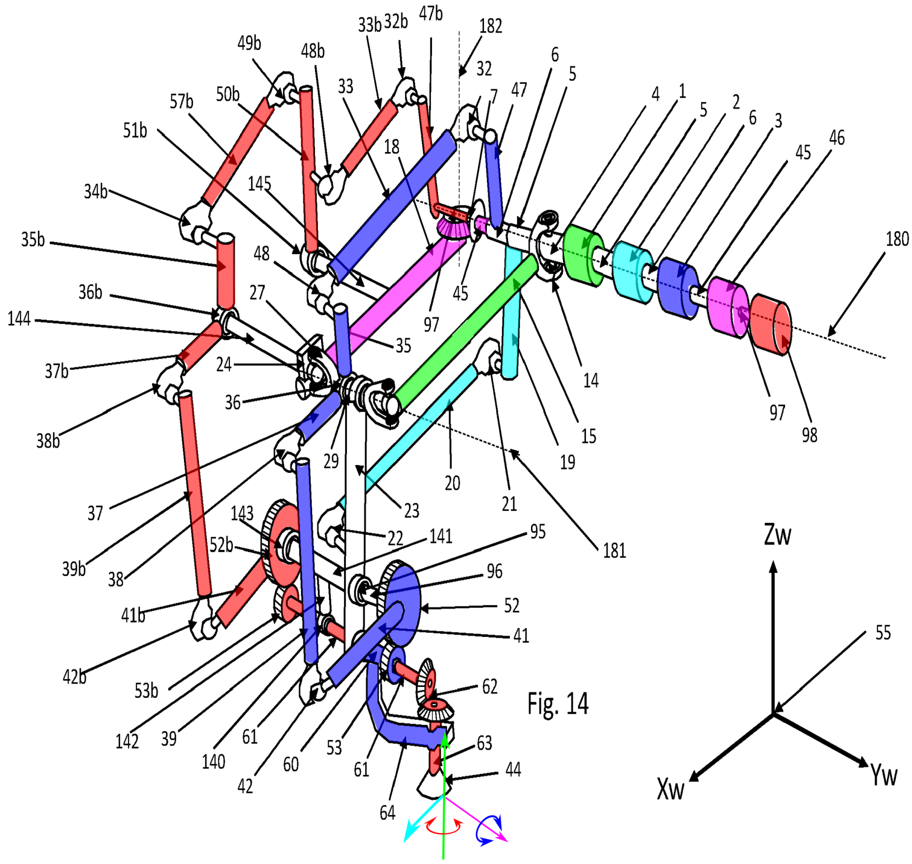


Figure 10: Figure 14 in the patent [10]

Robotic arm 3
This arm have a similar structure of the inner arm as the first robotic arm (fig. 9). The big difference between them is how the side motion (Yw-direction) is accomplished. Here this motion is accomplished through a ball screw (located in red at the top left corner). Fig. 11 do only contain the inner arm, because of the similarities to the first robotic arm the outer can be estimated to be similar to the one presented in fig. 9. A fourth actuator could be mounted on the tooling platform to provide the last DOF which is to rotate the payload.

The overall layout of this robotic arm is slightly more advance and complex than the first robotic arm, this due to the big joint located on the red chain. This joint connects the ball screw to the red rod (rod 18). The cost is fairly similar to the first robotic arm.

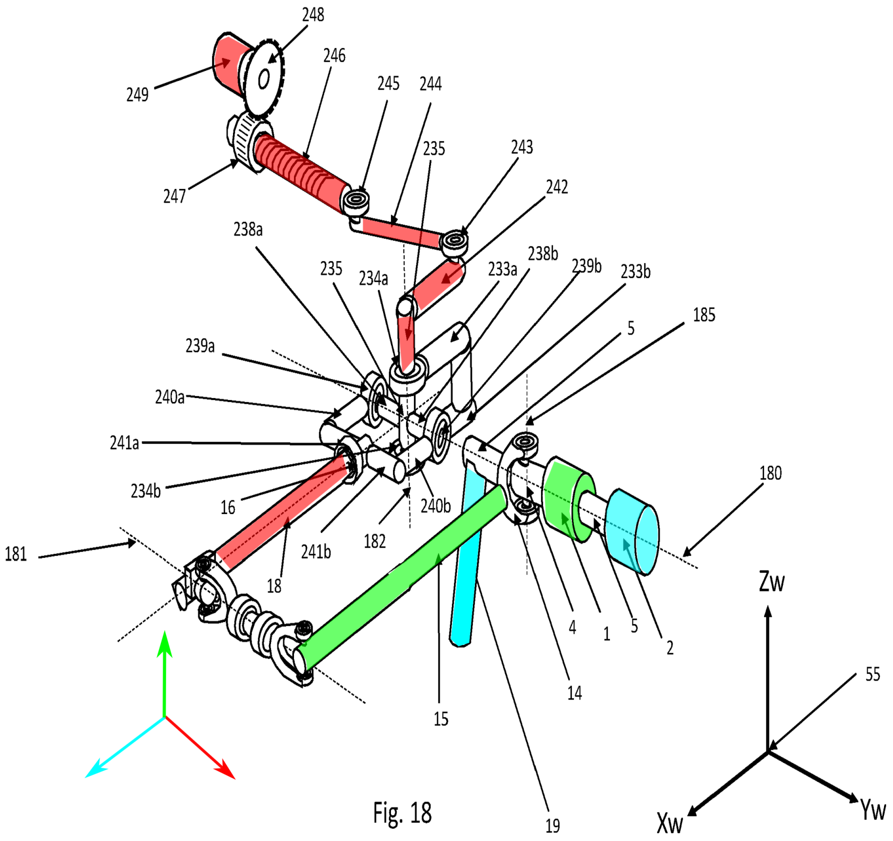


Figure 11: Figure 18 in the patent [10]

Robotic arm 4

The robotic arm in fig. 12 is almost identical to the one above (fig. 11) and because of this it will have the same properties. The main different is the design of the joint which connects the ball screw to the red rod (rod 18). This joint is less complex in this arm compared to the robotic arm above.

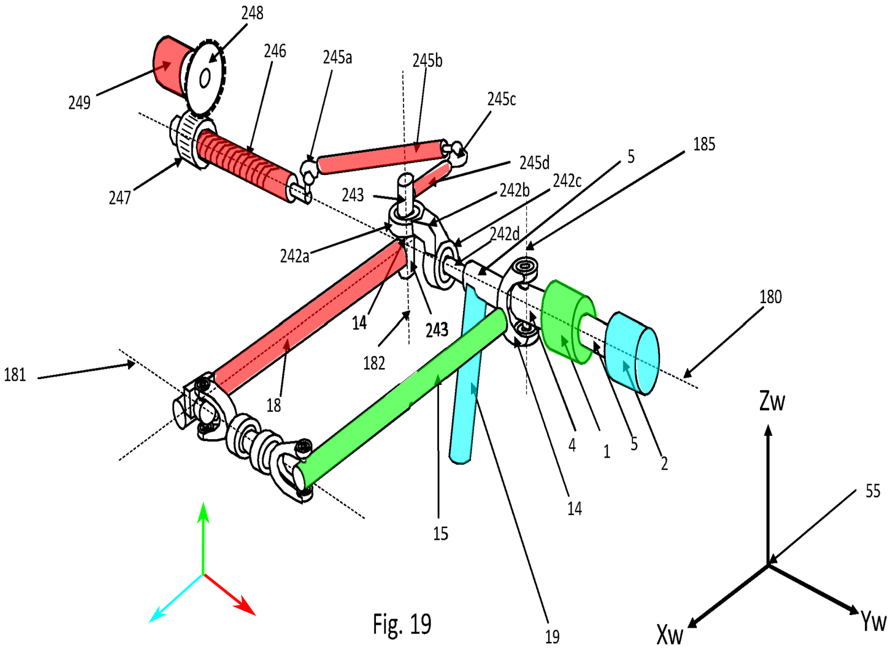


Figure 12: Figure 19 in the patent [10]

Robotic arm 5

This robotic arm has three actuators and one ball screw. The green actuator (actuator 1) is used to raise and lower the inner arm (Zw-direction). The pink actuator (actuator 3) is used to move the arm sideways (Yw-direction). This actuator is also placed directly on the green actuator and because of this it will move together with the arm when the arm is raised or lowered. The turquoise actuator (actuator 2) is used to move the outer arm in and out (Xw-direction). The ball screw which are represented in dark blue is controlling the last DOF which is the tilting function. The robotic arm can not rotate the payload and because of the gears located at the end of the outer arm it may be hard to mount a fifth actuator. The tilting function could not be modified to achieve the rotating motion since it would then loose the control of the horizontal position of the tool platform.

The overall layout of this robotic arm is the second biggest and because of the long rod chain it may be hard to produce this arm in a competitive and good way for the given application. Because of the number of rods it will also be more expensive.

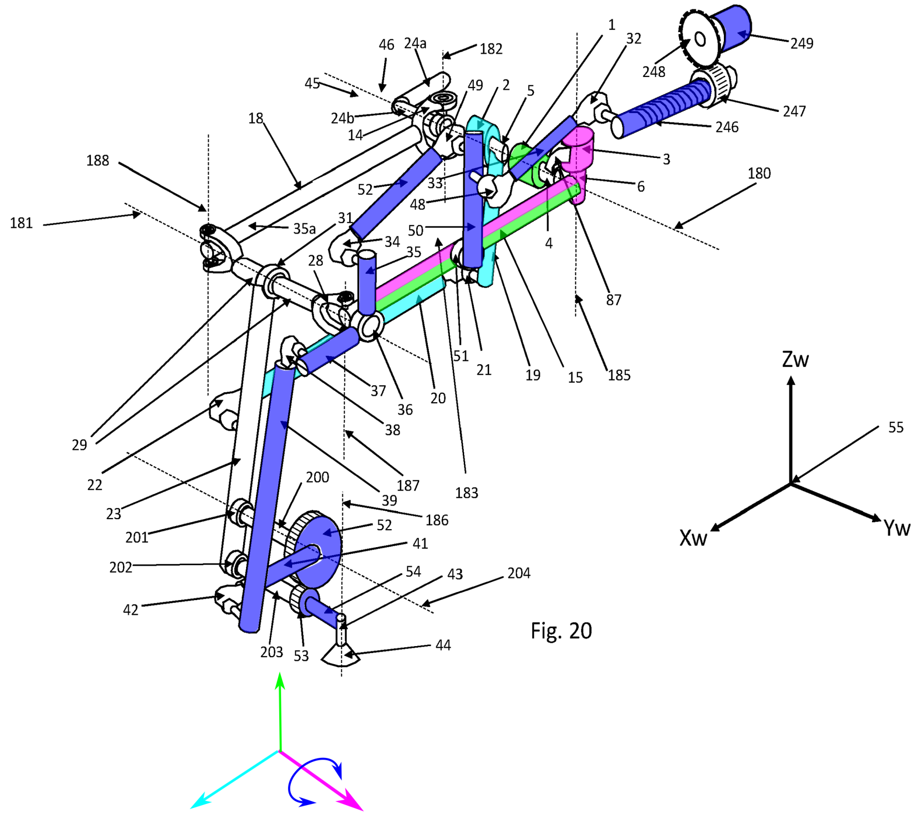


Figure 13: Figure 20 in the patent [10]

Robotic arm 6

This robotic arm is almost the same as the first robotic arm, fig. 9. The difference between them is how some motions are controlled. The green and turquoise actuator in fig. 9 have been replaced with balls screws. To achieve these changes some new joints for the green chain was made.

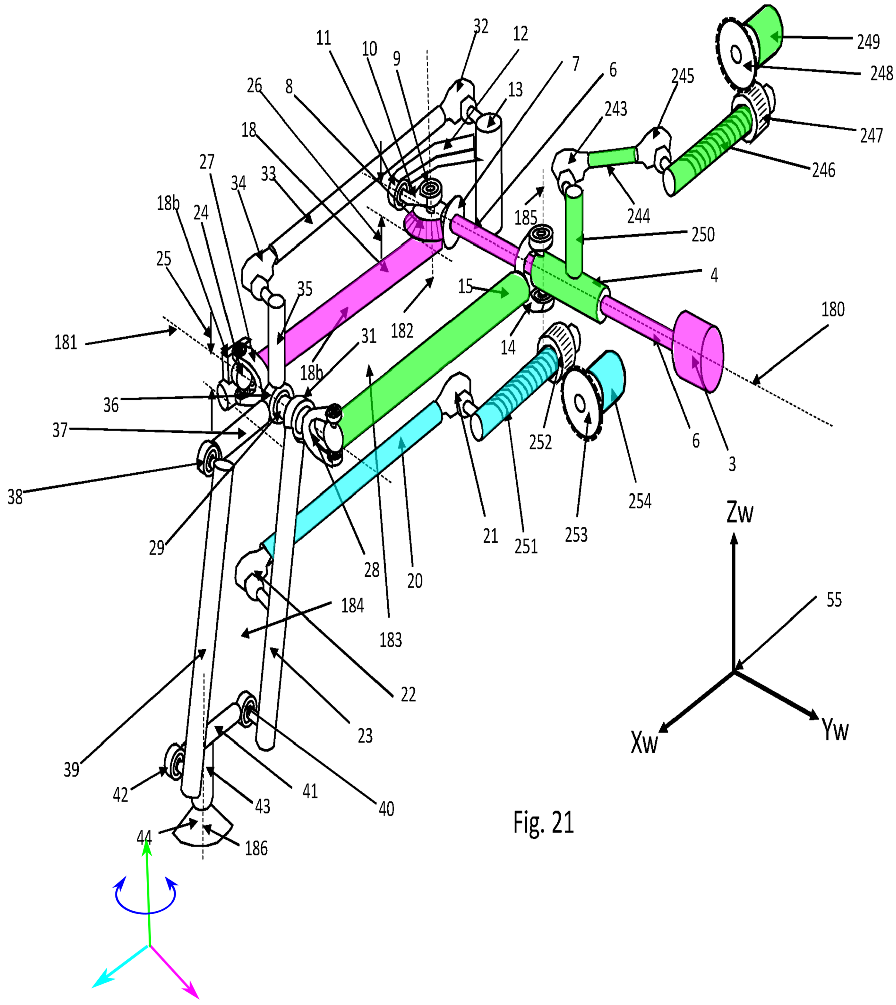


Figure 14: Figure 21 in the patent [10]

The score for the robotic arms can be seen in the table 3. For this score system a lower score is better than than a higher score.

Table 3: Score for the robotic arms; $*$ *Since outer arm not included, 13 parts is therefore added. This number is based on the number of parts for outer arm in fig. 9*; $**$ *Since outer arm not included, 7 joints is therefore added. This is based on thenumber of joints for the outer arm in fig. 9*

Arm nr.	1	2	3	4	5	6
Weight	20	51	22*	21*	31	19
Weight distribution	3	6	3	3	6	3
Accuracy	13	25	17**	16**	17	16
DOF	3	1	3	3	4	3
Cost	30	64	36	35	42	32
Total	72	147	81	78	100	73

3.3 Conclusions

From table 3 it is possible to draw the conclusion that the first robotic arm is the best option to continue develop. Since this robotic arm can have the needed vertical reach and with some modification can it have all the wanted DOF. Based on this, it can be concluded that the development should be based on this robotic arm.

From table 3 it can also be noticed that this robotic arm have the best score on almost every requirement used for the comparison. It can also be noticed that the robotic arm nr. 1 and nr. 6 have similar results, this is because they are almost identical in shape.

4 Design concept

The robotic arm selected above display kinematic properties for how the robotic arm should work. To develop the robotic arm further different concepts was created. These concepts give different ideas for for how all the parts will be connected to each other and give a first outline of how the parts will look.

The concept that is thought to have the best properties will be used as a base for the rest of the development of the robotic arm. Since different concept bring different ideas for how things should look and be connected, parts can be used from different concepts when developing the final robotic arm.

4.1 Design concept 1

The main idea for this concept is to have everything centred around one rod of the inner arm. This selected rod from the inner arm will take the weight from the payload and from the robotic arm, this rod is marked with nr. 1 in fig. 15. This rod will need to be big since it will handle high loads. Between rod nr.1 and the elbow joint there is a joint marked with nr. 2. This part will allow the arm to turn sideways.

The elbow joint will in this concept be thin, since it is only directly connected to rod nr. 1. This joint will connect the parts nr. 2, nr. 6, nr. 7 and nr. 8.

For this concept there is 4 actuators, three of them are located at the base and one at the end effector. The actuator at the end effector is not included in fig. 15. The actuator marked with nr. A1 (green) is used to lift the inner arm up and down. Since the joints at the ends of rod nr. 1 will allow it to move freely around the z-axis it can not take any bending moment around this axis. It will take bending moment around the y-axis since the motor will rotate it around this axis. Rod nr. 1 will also take some rotational moment around the x-axis. This is because the outer arm will swing up when the arm is accelerated in the y-direction. The actuator nr. A2 is used to move the robotic arm in the y-direction and because it is connected to rod nr. 4, this rod will take bending moment around the z-axis. Since the joints connected to rod nr. 4 will allow it to rotate freely around the y-axis, this rod can not take any bending moment around the y-axis. The third actuator nr. A3 is used to move the outer arm in and out. For this concept the rod controlling the outer arm nr. 9.

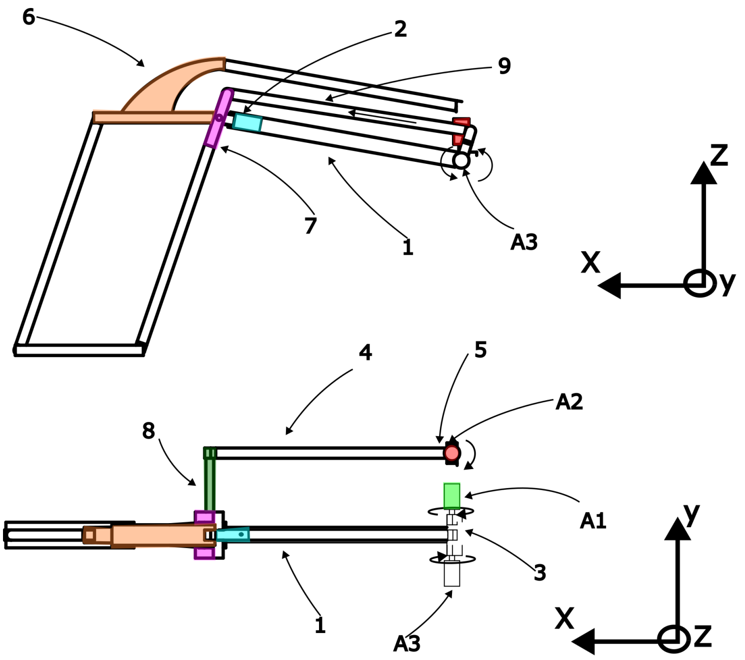


Figure 15: Concept 1

4.2 Design concept 2

The idea for this concept is to distribute the bending moment around both the y- and z-axis equally between the two inner rods, 1L and 1R in fig. 16. To accomplish this there are five actuators in this concept. The first actuator is marked with A1, this actuator is lifting the rods 1R and 1L up and down. To turn the arm sideways the actuators A2L and A2R are used. Since both rods at the inner arm is controlled both around y- and z-axis they will both take bending moment around these axes. The fourth actuator A3 is used to move the outer arm in and out. The fifth and last actuator is located at the end effector, but are not marked in the figure.

The elbow joint is in this concept directly connected to both rods at the inner arm. This do however probably mean that part nr. 2 will be heavier than its equivalence in concept 1 (part nr. 6 in fig. 15).

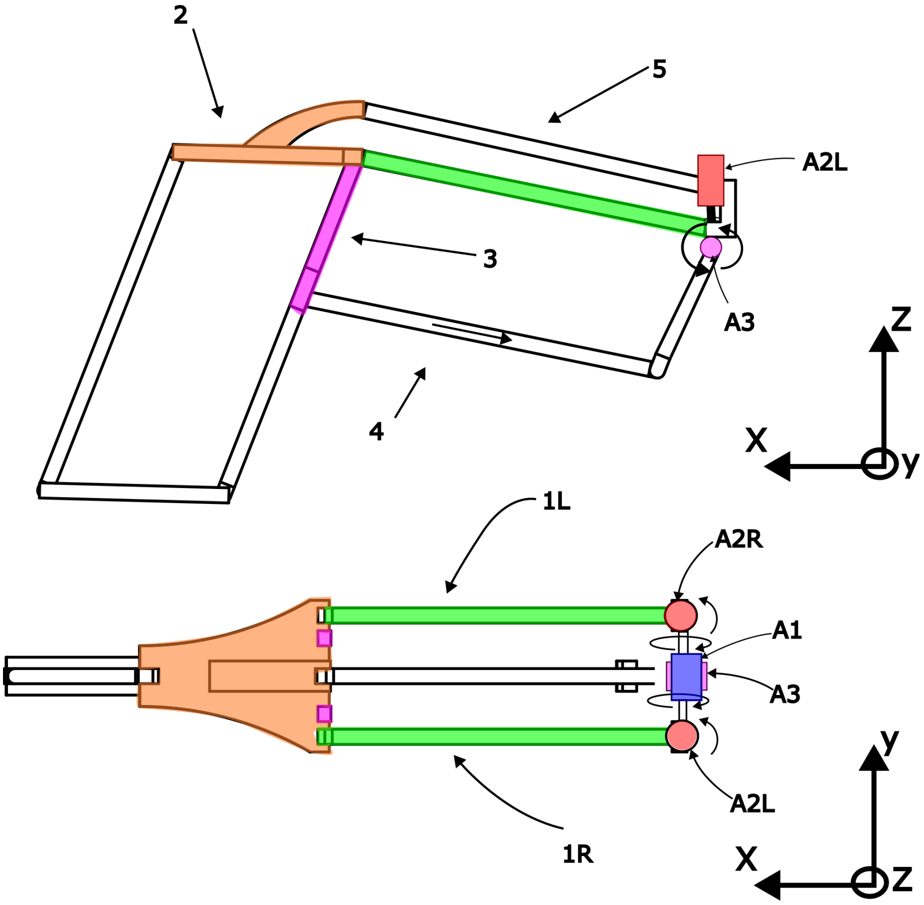


Figure 16: Concept 2

4.3 Evaluation and selection

In concept 1, one rod will take the majority of the load. in contrast, the load is split by two rods in concept 2, thus they can have smaller cross sectional area. in addition, concept 2 will be symmetrical as these two rods are responsible of both rotation around y and z direction. This means that the arm presented in concept 2 will be easier to predict and control the arm.

The elbow joint for concept 1 is much smaller than for the concept 2, this will save in both cost and weight which may help the arm be lighter and faster. Concept 1 will also only have four actuators while concept 2 need five actuators which means concept 1 will be cheaper.

Concept 1 features is better for the task given the robotic arm, than concept 2 features. This leads to the conclusion that concept 1 is the best alternative to move forward with.

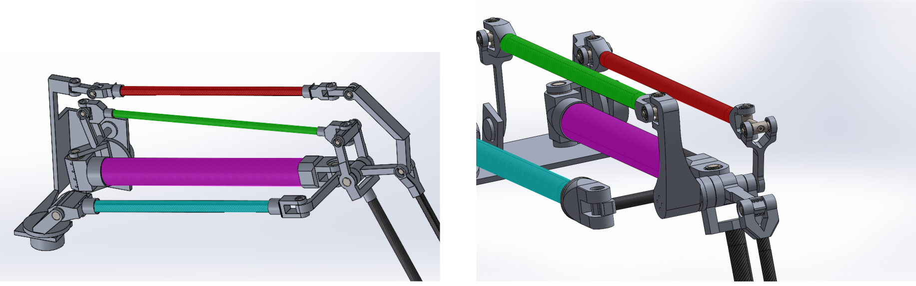
5 Development

Based on the concept selected in the previous chapter (4) a 3D model of the robotic arm was created. This 3D model is used to evaluated the robotic arm and to develop it further. The development of all the different parts will be presented more detail in the following chapters.

5.1 Complete model

The first concept for the model was initially design with the three coloured rods in fig. 17a mounted on top of each other. It was designed this way to have all the rods symmetrical mounted, which would have made the robotic arm easier to control. This since the forces would have been placed in the same plane. What was noticed for this design was a limitation in workspace since the rods would be hindered by other rods to perform its desired motions. It was also hard to design the parts included in the elbow joint in a way that would have been possible to manufacture. After a meeting with Cognibotics and the patent creator it was thought to be better to offset the two rods above (the red and green rod) from the big rod at the bottom (the pink rod). The two rods where moved to each side and the joint was redesigned to be able to house the new parts that needed to be connected to the elbow joint, fig. 17b. With this new design the inner arm of the robotic could be both lifted higher and lower than before. The parts that is connected to the elbow joint could now also be easier designed in a way that would make manufacturing of the parts easier.

The green rod was moved to an offset between the pink rod and the turquoise rod and the red rod was moved to outside the pink rod. Since the green rod was thought to have more load it was believed that it would make the robotic arm more accurate to have this rod "inside" the parallelogram for the inner arm. It was believed this way since it otherwise would give high forces acting on the outside of the robotic arm. Because of this new location of the green rod the actuator for this rod also need to be moved. The optimum location for this actuator would be if it operated around the same axis as the actuator connected to the pink rod. The space between the pink and the turquoise rod is extremely limited, but to achieve the placement of the green rod an angel drive can be used to connect the green rod to its actuator.

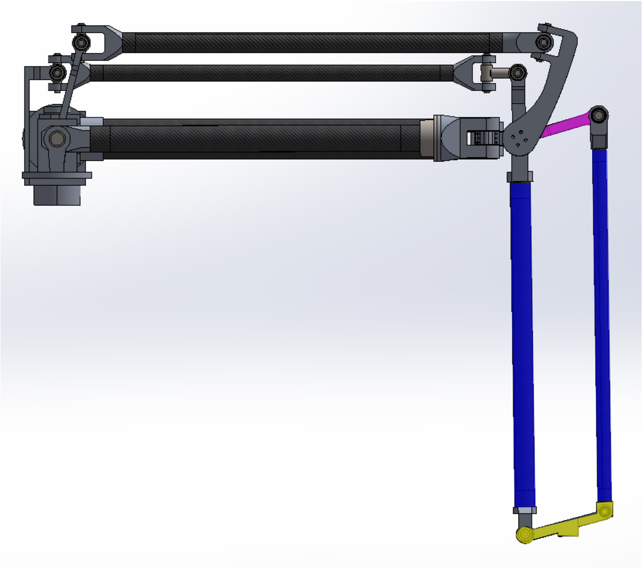


(a) First iteration of the green, red and pink rod

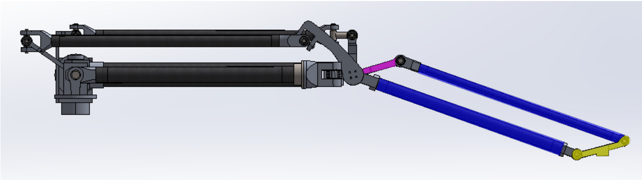
(b) Second iteration of the green, red and pink rod

Figure 17: Redesign of the inner arm

The parallelogram for the outer arm is slightly tilted as can be seen in fig. 18a. The arm is developed this way for the ability to extend the outer arm further out, without the parallelogram collapsing. The parallelogram was tilted by 15 degrees which gives the result seen in fig. 18. In fig. 18b the arm is extended by 70 degrees (β in fig. 23 and the parallelogram have not collapsed. For the optimum degree of tilt, tests need to be conducted to see which position is the most common with load. These test do however not fit within the time frame for this thesis. The tilting angle may also be different depending on how the robot is mounted relative to load and unload area. Since the optimum tilting angle may be different for how the robotic arm is mounted it may be a good idea to have different tilting options. To change the tilting angle only the pink and yellow parts, marked in fig. 18 need to be replaced.



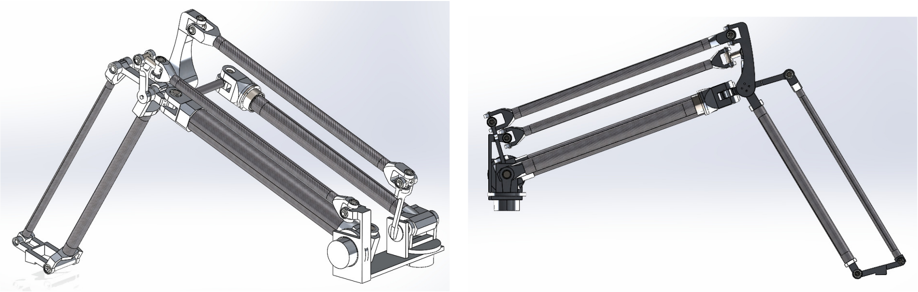
(a) The outer arm straight down



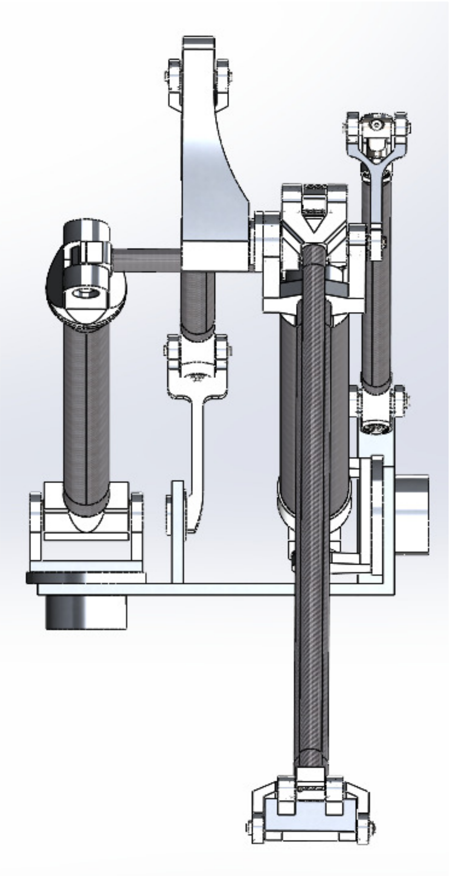
(b) The outer arm extended

Figure 18: The outer arm

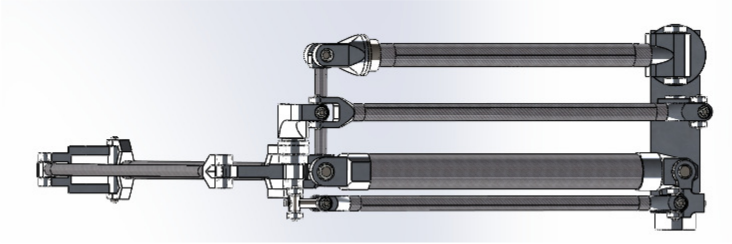
The final model can be viewed from different perspectives in fig. 19.



(a) The complete model (b) Side view



(c) Front view



(d) View from above

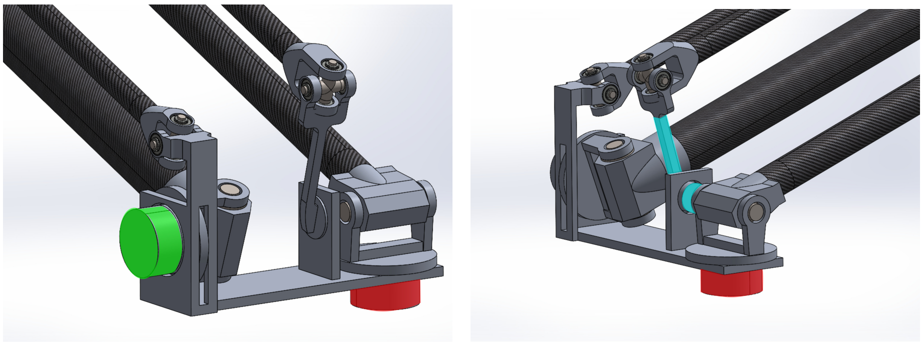
Figure 19: The complete model from different perspectives

5.2 Base

Even if this thesis will not investigate the electric motors and gearboxes, their location on the base is still important to evaluate since they are important for the functions of the robotic arm.

The base need to have space to mount three of the four electric motors and gearboxes. The motors used for lifting the arm (represented in green in fig. 20) and the motor for swinging the arm sideways (represented in red in fig. 20) need to be placed in a way that the axes they rotate around intersect with each other. It is crucial that these two axis intersect to withhold the parallelogram of the rod they are connected to.

It is preferable that the third motor also is placed along the same axis as the green motor. This will decrease the needed torque from the motor. This motor can be placed offset from this axis but that would result in an increase of the needed size of motor. It may be hard to mount this motor straight on the turquoise lever, this since the space is very limited. An angle drive may be a better way to connect the motor to this part.



(a) Base seen from the left

(b) Base seen from the right

Figure 20: The base seen from behind

5.3 Carbon rods

To accomplish the objective to load a roll container, the rods need to have the correct lengths. The shape of the working area will change depending on the length ratio for the arms, this can be seen in fig. 21. To decide the specific length of the inner and outer arm this ratio first need to be selected.

When the length of the arms have been established, the rods can be dimensioned. The rods need to be big enough to keep the displacement low but at the same time not be unnecessary heavy. It is mainly four factors which needs to be established.

- The thickness

- The cross sectional size of the rods
- The cross sectional geometry
- The length of the rods (Since the rods length are not equal to the arms length, this due to the fact that the joints have some part of the arm length).

5.3.1 Lengths of the two arms

To establish the needed length of the arms, the arm ratio needs to be established first. In fig. 21 it can be seen how the working area is changing dependant on the arm ratio. When the arm ration is increasing the length and the height of the working area is increasing. A first conclusion from this could then be that a bigger arm ration should make a bigger working area. But since the shape of the working area is changing this also need to be accounted for. For higher arm rations the shape of the working area is more narrow, which suggest that a too big arm ratio do not have a good shape of the working area. When the arm ration is around 1 it can be seen that the shape is starting to be narrow. This suggest that the arm ratio should be around 1. When looking at other similar robots, it was seen that their arm ratios was around 1,2. Because of this the arm ratio was selected to be in the middle of these two values, which is 1,1.

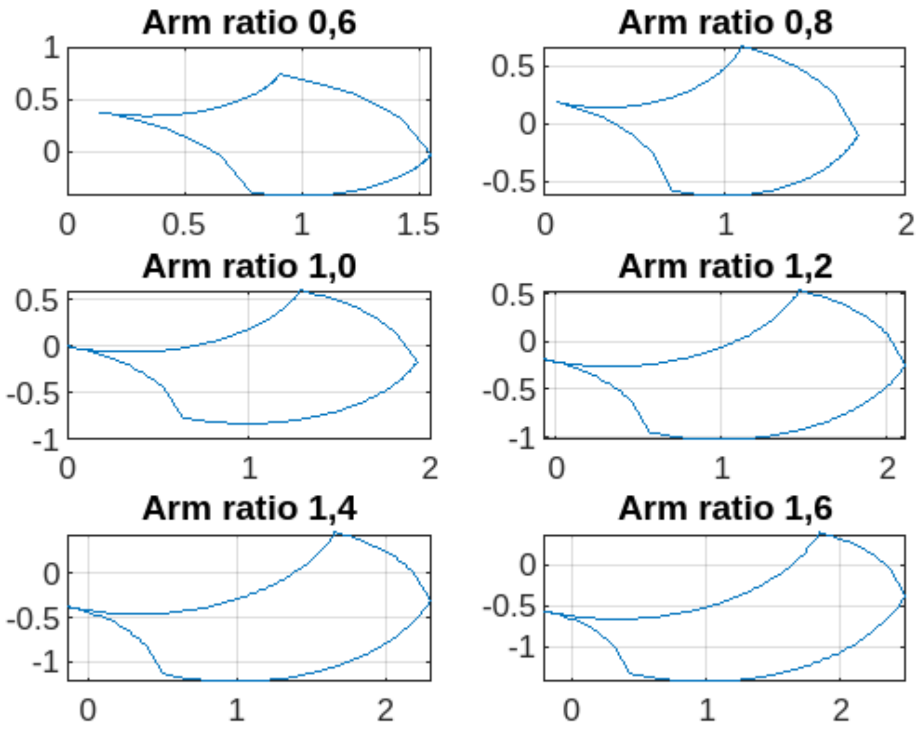


Figure 21: Arm ratios

The next step is to investigate how long the arms should be. Different arm lengths with the ration 1,1 between them was plotted and a container was simulated in them. This show when the arms was long enough to get a working area where it could load a roll container, as can be seen in fig. 22. When the inner arm is 1,3 meter or longer the robotic arm can load the container. In the figure the container move slightly under the working area, this is since the wheels on the container is also counted for in the figure. The robotic arm can also have different tools which can help it reach even further down. The package do also have some heigh meaning the arm do not need to be able to reach completely all the way down. A arm ratio of 1,1 and a inner arm length of 1,3 m can be considered to be enough for the ability to fill a roll container. The length of the outer arm is set to be 1,2 m, based on the selected arm ratio and length of the inner arm.

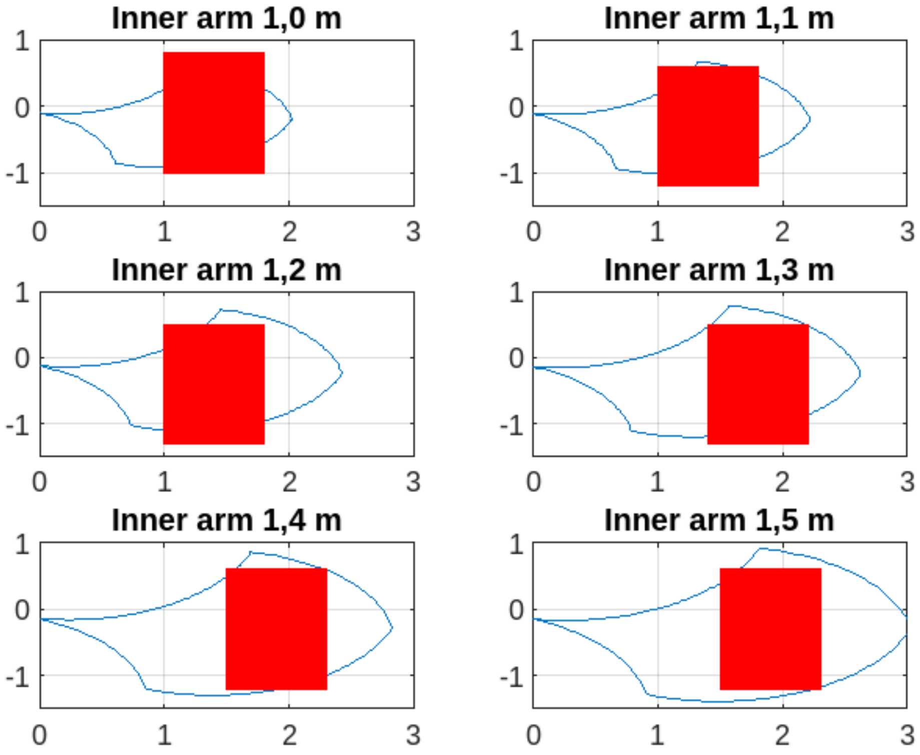


Figure 22: Working area depending with the length of the arms, arm ratio 1,1. The red box represent the roll container

The plots made in fig. 21 and fig. 22 is simplified working areas. It is assumed that β in fig. 23 can be remain at its maximum angle when α is changed from its maximum to its minimum.

Since the cross-section of the working volume is 2 dimensional, two values are needed to calculate the working area, the height y and the length x.

$$x = A\cos(\alpha) + B\sin(\beta) \tag{4}$$

$$y = A\sin(\alpha) - B\cos(\beta) \tag{5}$$

These two values was calculated for each position of the robotic arm when it completed a lap of its maximum and minimum angle for α and β. α is expected to have a range from 60° to $-30°$, while β is expected to have a range from 70° to $-30°$.

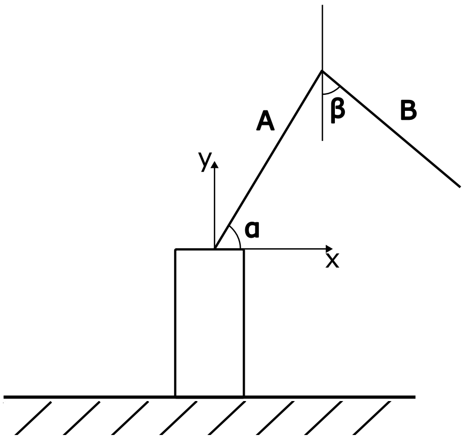


Figure 23: Schematic robot used for calculating the principal working area.

5.3.2 Profile and sizes of the rods

The three green rods in fig. 24 are only loaded axially by their joint constrain, which means that the profile for these rods is not that important, but the cross-sectional area is important. Since circular carbon tubes are more common and cheaper, these are the best choice for these rods. Of the green rods the rod marked with 1, is the on that takes the highest load and because of this this rod need to be bigger than the other green rods. This rod has the dimension D60Xd54 mm. The green rod nr. 4 has the dimensions D40Xd36 mm and the last green rod marked nr. 2 has the dimension D50Xd46 mm.

The two purple rods take up both bending moment and rotational moment. Since the ratio between the rotational and bending moment is unknown, circular profiles is used since they can handle rotational moment better than rectangular. The purple rod nr. 3 need to be bigger than the rest since it is carrying the whole weight of the robotic arm and payload. The this rod have the dimensions D120Xd110 mm and the purple rod nr. 6 have the dimensions D60Xd56 mm.

The turquoise rod nr. 5 is only subjected to bending moment and because of this it may be better with a rectangular profile or maybe a design with two smaller circular rods forming a triangle. During the development it was discovered that the displacement caused by the turning motion was not especially big which means that a circular profile may be enough, especially since a circular carbon rod is cheaper. A circular rod was chosen for this rod, but if it is discovered during future testing that the side displacements is to big, a rectangular profile may be a better option and should then replace the circular rod. The size for this rod is D80Xd76 mm.

The rod marked in red nr. 7 is subjected to a bending moment when the robotic arm is turning sideways. it is also subjected to axial forces caused by the payload. Since the load on this rod not is big, circular rod profiles is selected. The size of this rod is D40Xd36 mm.

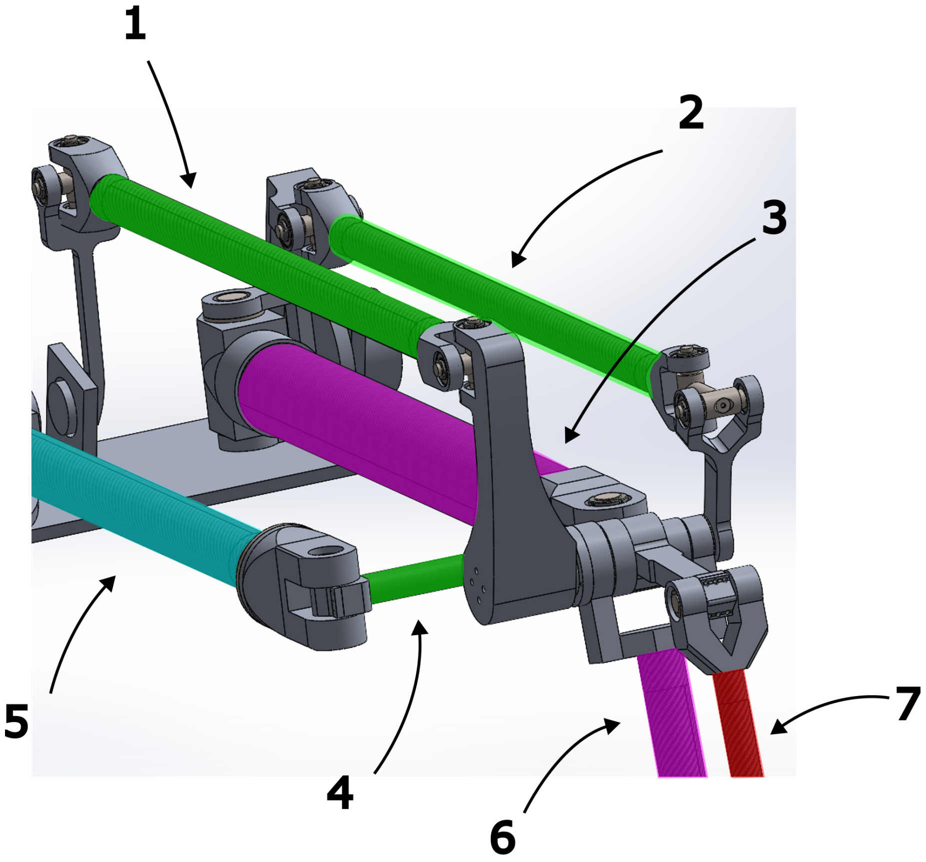
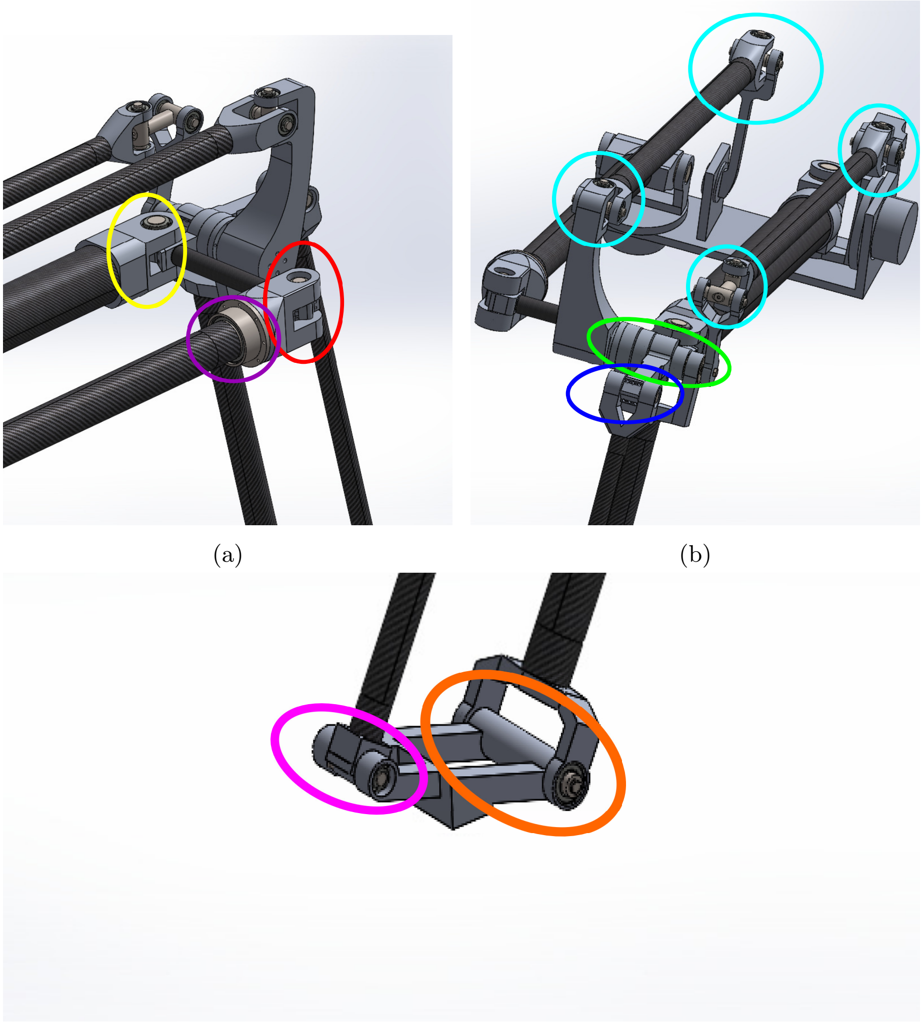


Figure 24: load on the rods

5.4 Joints and bearings

From the complete model eight different joints can be found. The are four universal joints included in the model and one of these are an offset universal joint. These joints are marked with a turquoise ring in fig. 25b. The second joint that can be seen in the complete model is the elbow joint, marked with the green circle in fig. 25b. The main purpose for this joint is to connect the inner arm with the outer arm. Every rod on the model is in some way connected to this joint. Next joints that can be discovered in the model are the joints marked in yellow and red in fig. 25a. These two joints have similar functions. There are one big different between them and that is that the one marked with a yellow ring need to be stronger because it holds the entire weight of the outer arm. The dark blue circle in fig. 25b is connecting one of the carbon rods in the outer arm to the inner arm. This joint will also be similar to the yellow and red joints. When the robotic arm are turning sideways and raise/lowered at the same time a rotational movement occur on one of the rods at the inner arm, one of the because of this needs to be able to rotate freely. To accomplish this the joint marked in dark purple in fig. 25a is needed. The last two joints are located on the tool mounting platform. these two joints are represented with pink and orange in fig. 25c.



(a) (b)

(c)

Figure 25: Location of the joints

5.4.1 Elbow Joint

As described in previous section this joint will connect many different parts. Three of these parts need to move freely from each other. Since this joint connects the inner and outer arm it will be the biggest joint on the robotic arm and therefore the load on this joint will be high. In fig. 27 the three moving parts are represented in green, blue and red. The two red parts are mounted directly to the shaft and thereby are they also directly connected to each other. This is designed this way since the red part to the left is used to position the middle red part horizontally correct. The blue part connecting the joint to the inner arm while the middle red and green parts connecting the outer arm to the joint.

Some of the bearings that could be used for this joint are tapered roller bearings, spherical roller bearings, angular contact ball bearings or needle roller bearings together with needle roller thrust bearings.

To see the implication of bearing selection, a comparison is made in tab. 4. The same inner race diameter of 35 mm is chosen. The bearings in the tab. 4 is data for a single bearing (for the needle bearings the data is for one needle bearing together with one thrust needle bearing).

Table 4: Bearing specifications for different bearing options for elbow joint [11]

Bearing type	Angular contact ball bearing 7207 BE-2RZP	Tapered roller bearing 32007	Needle roller bearing NA 4907.2RS And Needle roller Thrust bearing AXK 2542 LS 2542	Spherical roller bearings B22 - 22207 2RS/VT143
m [kg]	0,35	0,23	0,225	0,52
C_0 [kN]	19	54	43 (Radial) 60 (Axial)	85
B [mm]	17	18	29	28
r_{max}/r_{min}	36/17,5	31/17,5	27,5/12,5	36/17,5
Integrated seals	Yes	No	No	Yes

From table. 4 it is clear the angular contact ball bearing has the lowest C_0 value. Roller bearings is also stiffer than ball bearings, which leads to the conclusion that angular contact ball bearings is not the best option for this joint.

There might be misalignment caused by manufacturing tolerances. Spherical roller bearings can handle misalignment best which make it a good candidate. In tab. 4 it can be seen that the spherical roller bearing is also the bearing type which can take the highest static load (highest C_0 value).

The tapered roller bearing is together with the needle bearing option, the lightest option. However the tapered roller bearing takes less space which means that tapered roller bearings also could be a good option for the joint.

The two options left which could work good for this joint is the spherical roller bearings and the tapered roller bearings. The spherical roller bearings have the advantage that it do not need to be pre loaded. The tapered roller bearings need to be pre loaded. Problems can occur when pre loading bearing nr. 1 against bearing nr. 4 and bearing nr. 2 against bearing nr. 3 in fig. 26. The risk when doing so is to change the pre load on the first pair of bearings that is mounted, when mounting the second pair. This problem do not exist with spherical roller bearings since they do not need to be pre loaded. Based on the discussion above the conclusion is made that the spherical roller bearings is the best option for this joint.

The idea for the first iteration of the elbow joint can be seen in fig. 26, here is the spherical roller bearings used and the shaft is one solid piece with a symmetrical shape. The main problem for this iteration is that it can be problem during the assembly of this joint. If bearings nr. 2 and 3 are mounted first it can be hard to get the part marked with C over and on to the shaft. To deal with this problem the shaft was split in two pieces and instead of a symmetrical shape the diameter of the shaft is increasing from the left to the right, as can be seen in fig. 27. For even easier mounting the part in the middle (red part in fig. 27) is split in two pieces (as can be seen in fig. 28) and can thereby be mounted last on to the shaft. The shaft in the middle do also have a rectangular cross sectional area which give the middle part the ability to be fixated to the shaft, which also can be seen in fig. 28. The spherical bearing mounted to the right was designed with a tapered mounting. This was done to be able to get the size down on the spherical bearing to the right. These two bearing could now be the same size, but with different mounting mechanisms.

The final iteration of this joint had four spherical roller bearings with integrated seals. After further analysis of the bearings it showed that there was no need for four spherical roller bearings since the load was smaller than expected. This lead to the solution displayed in fig. 27 with two spherical roller bearings and two needle roller bearings. Since the spherical roller bearing can take axial forces it was enough to only use needle roller bearings to the right. By changing the bearings the joint was lighter and smaller. These needle roller bearings has integrated seals which means no external seals are needed.

For an easier mounting of the needle bearings snap rings is used to hold the bearings in place. Also a distance was designed to keep the correct distance between the two needle bearings. The last part is a distance plate that is mounted outside the bearing to the left. This will hold the outer ring in place. All the parts used for mounting the needle roller bearings is marked with pink in fig. 27.

The bearings used are the following, starting from the left moving to the right;

- Needle roller bearings
  - NA 4906.2RS
  - NA 4907.2RS
- Spherical roller bearings
  - BS2-2208-2RSK/VT143
  - BS2-2208-2RS/VT143

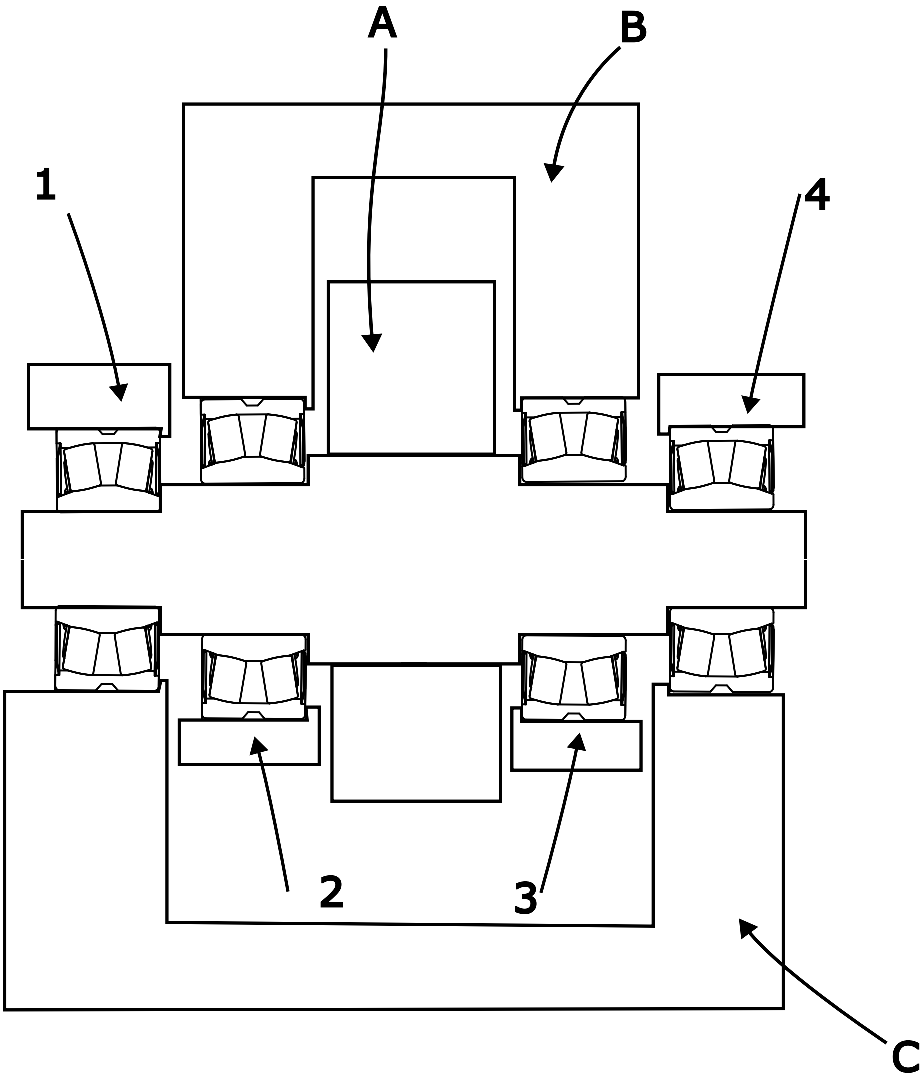


Figure 26: First iteration of the elbow joint

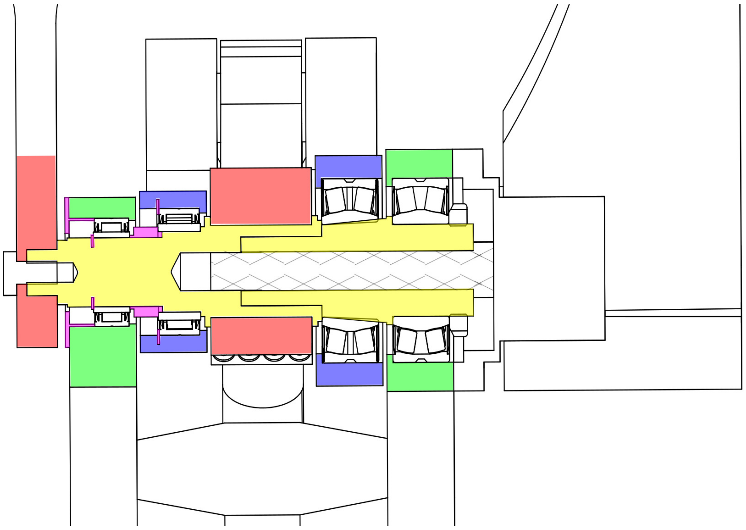


Figure 27: Final iteration for the elbow joint

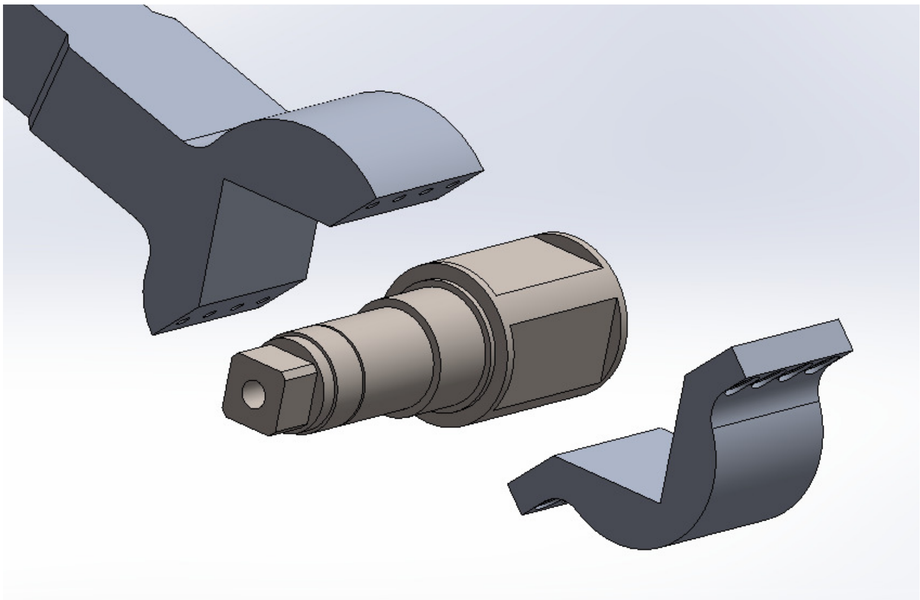


Figure 28: Exploded view of the middle part in the elbow joint

5.4.2 Universal joint

The universal joint is the most common joint on the robotic arm. Since there is a offset between the elbow joint and the joint marked with yellow in fig. 25b, one of the universal joints also need to be offset. The bearings and the mounting of the bearings is still the same for the two different universal joint types. The traditional universal joint can be seen in fig. 29 and the offset joint can be seen in fig. 30.

Since the universal joint will not handle any of the weight of the robotic arm, the loads on them will most likely be small. Because of this it is preferable to try to keep the size down on these joints to save space and weight. To save space it will also be preferable with bearings that have internal seals, but not necessary.

Bearings that could be a good option for this joint is angular contact ball bearings, tapered roller bearings and needle roller bearings with needle roller thrust bearings. In tab. 5 data for the different bearings is given.

Table 5: Bearing specifications for different bearing options for universal joint [11]

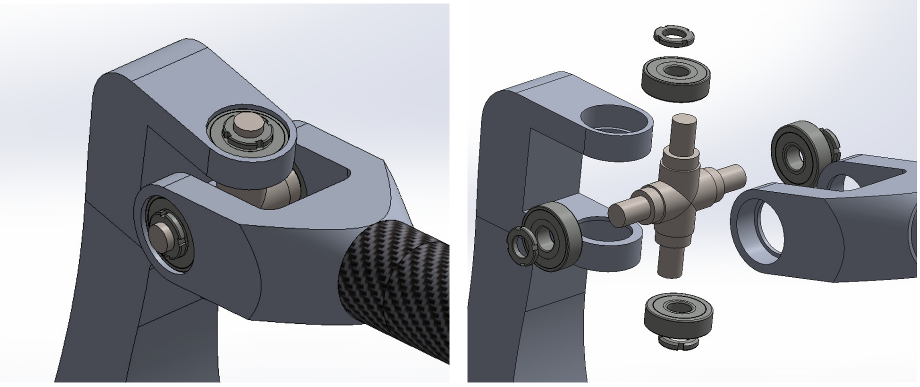
Bearing type	Angular contact ball bearing 7203 BE-2RZP	Tapered roller bearing 30203	Needle roller bearing NA 4903.2RS And Needle roller Thrust bearing AXK 0619 LS 0619
m [kg]	0,063	0,079	0,053
C_0 [kN]	5,5	18,6	12,9 (Radial) 16 (Axial)
B [mm]	12	13,25	21,5
r_{max}/r_{min}	20/8,5	20/8,5	15/3
Integrated seals	Yes	No	No

The combination with needle roller bearing and needle roller thrust bearing are the lightest solution. This solution are on the other hand the biggest in both radial size and axial size. The tapered roller bearing and the angular contact ball bearing are roughly the same size. For the tapered roller bearing and the needle bearing the seals needs to be mounted externally between the housing and shaft, while the angular contact bearing has integrated seals. Because of the size of the needle bearings it is better to use angular bearings or tapered roller bearings.

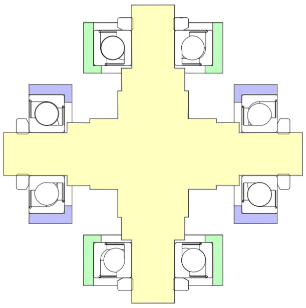
The tapered roller bearing do have higher C_0 value but are also heavier. To design this joints as light and small as possible it is better to use the angular contact ball bearings. This since space can be saved since there is no need for external seals. This lead to the conclusion that the angular contact ball bearings is the best option for this joint. The specific bearing used for this joint is 7303 BE-2RZP.

Since the angular contact ball bearings have integrated seals it is only needed to design the shaft and housing in a way where the bearings could be tightened against each other. This was done by simply using lock nuts on the shaft. This way the bearings could be tightened in an easy way. The mounting technique is the same for both the traditional universal joint and the offset one.

The challenging part with the offset joint was to design it in a way where it could be manufactured. To accomplish this the joint was designed to be in three parts, hold together with a screw in each end as can be seen in fig. 30b.

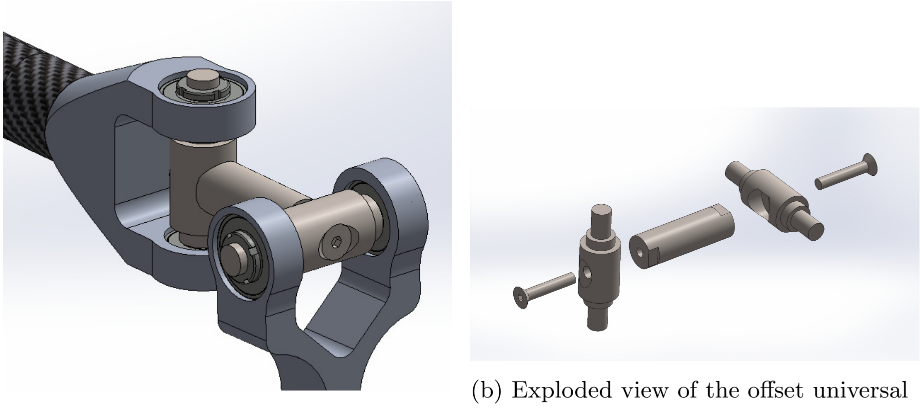


(a) Universal joint (b) Exploded view of the universal joint



(c) Drawing of the universal joint

Figure 29: Universal joint



(a) Offset universal

(b) Exploded view of the offset universal joint

Figure 30: Offset universal joint

5.4.3 Single motion joint

These three joints is marked with a yellow and a red circle in fig. 25a and with a dark blue circle in fig. 25b. These joints need to handle big radial loads and some axial loads. The two joints marked in fig. 25a is placed vertical which will lead to higher axial forces.

The forces on these joints will probably be smaller than for the elbow joint since there is lesser parts which will put load on the joint. But since some of this type of joint will handle much of the weights of the robotic arm, the load will probably also be bigger than for the universal joint. These joints will be bigger than the universal joints and because of this it will probably be easier to mount external seals, which opens up more for bearings without internal seals.

Bearings that could be an option for this joint is Angular contact ball bearings, tapered roller bearings, spherical roller bearings and needle roller bearings with needle roller thrust bearings.

Table 6: Bearing specifications for different bearing options for single motion joints [11]

Bearing type	Angular contact ball bearing 7207 BE-2RZP	Tapered roller bearing 32007	Needle roller bearing NA 4907.2RS And Needle roller Thrust bearing AXK 2542 LS 2542	Spherical roller bearings B22 - 22207 2RS/VT143
m [kg]	0,35	0,23	0,225	0,52
C_0 [kN]	19	54	43 (Radial) 60 (Axial)	85
B [mm]	17	18	29	28
r_{max}/r_{min}	36/17,5	31/17,5	27,5/12,5	36/17,5
Integrated seals	Yes	No	No	Yes

From table 6 it is clear the spherical roller bearings have the highest C_0 value. The tapered roller bearing and needle bearings do also have high C_0 values which also make them a good option. The angular contact bearing have the lowest C_0 value and is because of this not the best option since the load may be high. Roller bearings do also have a general higher stiffness which is also preferable in this case. [11]

Weight is another factor that needs to be considered. The two lightest bearing solution is with tapered roller bearing or needle bearings and they weight around the same. The heaviest bearing is the spherical roller bearing and since the tapered roller bearing or the solution with the needle roller bearing both have high C_0 values they are a better choice.

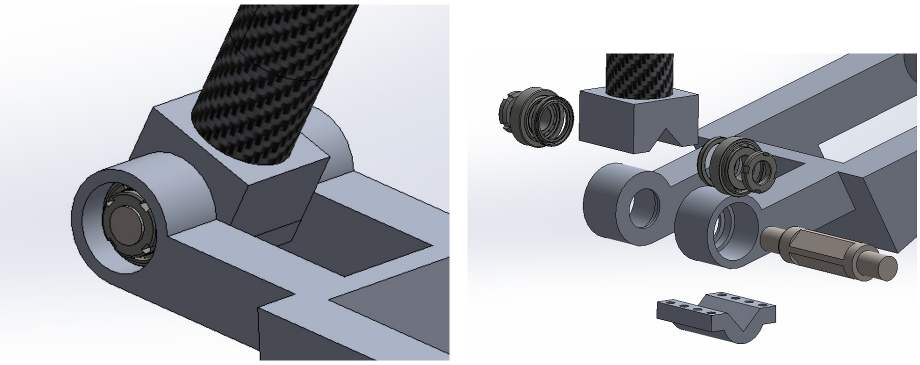
Neither tapered roller bearing or needle roller bearings have integrated seals (needle roller bearings do have integrated seals but needle roller thrust bearings do not). Since the difference between them is not that significant the tapered roller bearings is selected since they is smaller than the needle roller bearings.

The specific bearings and external seals used for these three joints is the following;

- Tapered roller bearings for the joint marked with yellow in*25a*

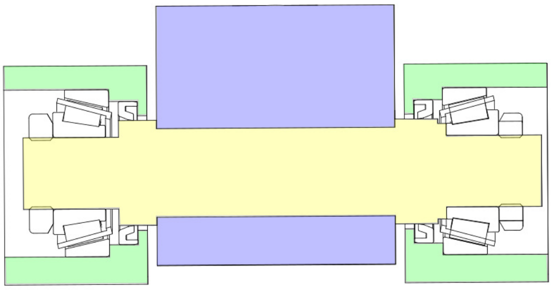
  - 32007 X
  - seal 40x47x4 HM4 R
- Tapered roller bearing for the joint marked with red in *fig. 25a* and dark blue in *fig. 25b*
  - 32005 X
  - Seal 30x40x4 HM4 R

To fixate the part in the middle to the shaft, the shaft is rectangular in the middle ans so is also the part connecting to the carbon rod, see fig. 31b. One of the joints connecting the tool mounting platform will also be using this type of joint.



(a) Single motion joint located at the tool mounting platform

(b) Single motion joint located at the tool mounting platform, exploded view



(c) Single motion joint located at the tool mounting platform, drawing

Figure 31: Single motion joint located at the tool mounting platform

5.4.4 Tool mounting platform joints

There are two different joints used to connect the tool mounting platform to the outer arm. The first joint displayed in fig. 31 and the second joint is displayed in fig. 32. The load on these joints is the smallest on the robotic arm since the load on them is only from the payload. The forces acting on the bearings is mostly radial forces due to the payloads weight, but some axial forces will also appear during the robotic arms acceleration or deceleration when turning. Since these joints are located at the end of the robotic arm, it is preferable to keep the weight down.

The bearing that can be used for these two joints are angular contact ball bearings, tapered roller bearing or needle roller bearings in combination with needle roller thrust bearing.

Table 7: Bearing specifications for different bearing options for end effector joints [11]

Bearing type	Angular contact ball bearing 7202 BE-2RZP	Tapered roller bearing 30202	Needle roller bearing NA 4902.2RS And Needle roller Thrust bearing AXK 0619 LS 0619
m [kg]	0,045	0,055	0,048
C_0 [kN]	4,4	14,6	12 (Radial) 16 (Axial)
B [mm]	11	11,75	21,5
r_{max}/r_{min}	17,5/7,5	17,5/7,5	14/3
Integrated seals	Yes	No	No

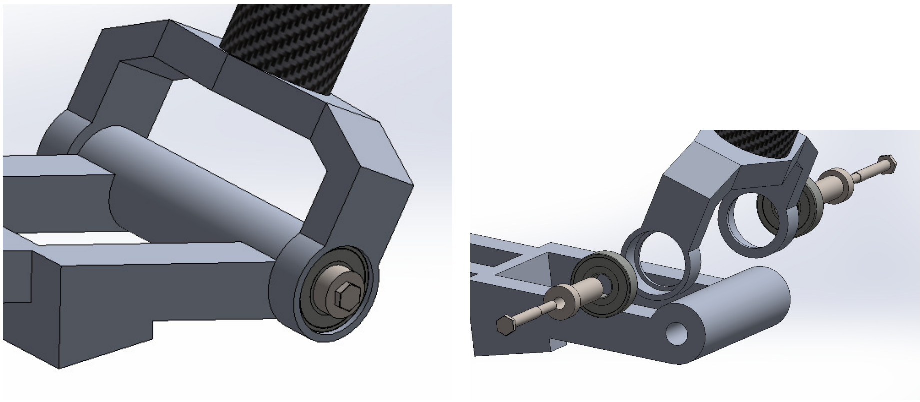
The axial forces at the end effector are considered to be low and because of this the bearing combination with needle bearing and needle thrust bearing would be to use larger bearings than needed. They are the widest option and would maybe make the joint bigger than needed.

The angular contact ball bearing and tapered roller bearing are both very good options for these two joints. The angular bearing do have integrated seals, while the tapered roller bearings do not. Since it is unknown how the tool will be mounted to the tool mounting platform, multiple joint options could open up for more development options when developing the tool mounting platform. Because of this, both solutions (one with tapered roller bearings and one with angular contact bearings) will be used. One of the joint will be the ”single motion joint” described in chapter 5.4.3. Since this joint have been presented earlier it will not be described here.

The second joint at the tool mounting platform is connected on the outside of the tool mounting platform. This solution will provide some space for the eventual electric motor to move freely when the outer arm is moved in or out. This joint will use the angular contact ball bearings since they have integrated seals and therefore no external seals is needed. To provide a higher stiffness the tool mounting platform will be closed between the two connection points for this joint. As can bee seen in fig. 32c the shaft is mounted directly on to the tool mounting platform by a screw.

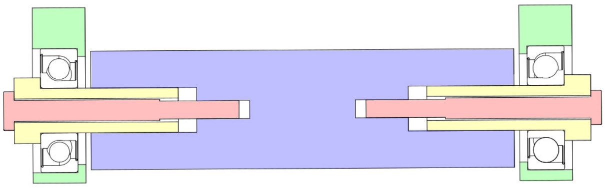
The specific bearings used for the joints connecting the tool mounting platform is the following;

- Tapered roller bearing
  - 30202
- Angular contact ball bearing
  - 7303 BE-2RZP



(a) End effector joint with angular contact ball bearings

(b) End effector joint with angular contact ball bearings, exploded view



(c) End effector joint with angular contact ball bearings, drawing

Figure 32: End effector joint with angular contact ball bearings

5.4.5 Carbon rod rotation joint

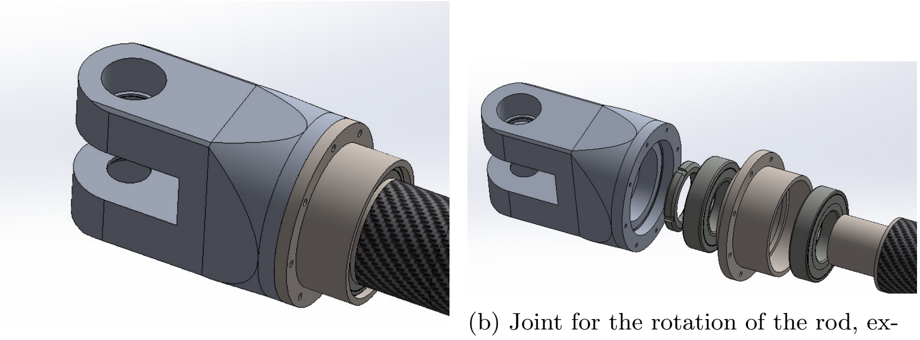
As can be seen in fig. 25a, this joint is located at the end of the carbon rod to the right (it is marked with a purple circle). This joint is needed since the carbon rod will rotate when the robotic arm is raised/lowered at the same time it is turning sideways. The joint will mostly need to handle radial forces but some axial forces will occur as well.

To make this joint without any play, two bearings will be mounted against each other. The joint will also be designed in a way where the joint can be assemble before it is mounted on the robotic arm. Since the bearings will be mounted against each other tapered roller bearings and angular contact ball bearings is the two options considered for this joint. They will also be mounted in a back to back configuration since this is stiffer. The joint can be seen in fig. 33.

Table 8: Bearing specifications for different bearing options for link joint [11]

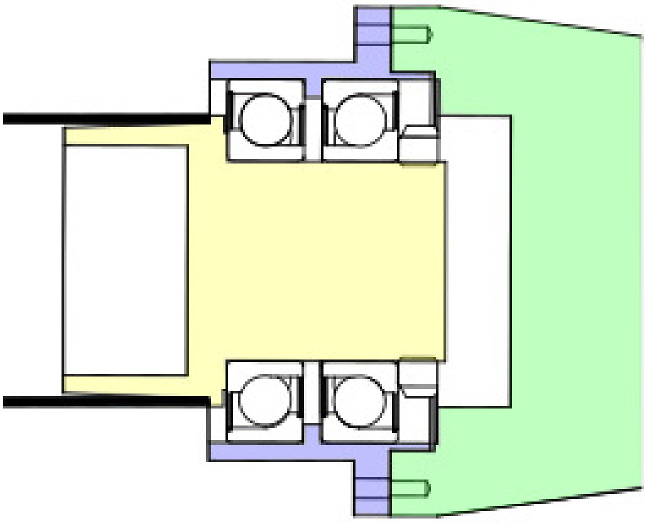
Bearing type	Angular contact ball bearing 7211 BE-2RZP	Tapered roller bearing 30202
m [kg]	0,62	0,28
C_0 [kN]	36	69,5
B [mm]	21	17
r_{max}/r_{min}	50/27,5	40/27,5
Integrated seals	Yes	No

From table 8 it is seen that the tapered roller bearing have a higher C_0 value than the angular bearing. But it will be hard to design this joint with an external sealing. This leads to the angular contact bearing which have an integrated sealing which will make designing of the joint easier. Because of this the angular contact ball bearings are more suitable for this joint. The specific bearing selected for this joint is 7211 BE-2RZP.



(a) Joint for the rotation of the rod

(b) Joint for the rotation of the rod, exploded view



(c) Joint for the rotation of the rod, drawing

Figure 33: Joint for the rotation of the rod

5.5 End effector

The tool mounting platform is located at the end of the outer arm. The tool mounting platform must be large enough to accommodate the tool, which consist of a motor, potentially gearbox, suction cup or gripper. At this stage it is unknown what needs to be accommodated and the size needed, but two versions of joints are developed and presented in chapter 5.4.4.

5.6 Verification

To verify that the dimensions selected of the rods and the selected bearings size are big enough, a FEM study was performed on the model. The study will provide information of the displacements and stress levels on the model. The study will also provide the axial and radial forces subjected to the bearings.

Based on the result from the study, the dimensions of the rods and bearings can be evaluated. The displacement and stress levels from the result will be used to evaluate the rods and aluminium parts. The axial and radial forces from the study will be used to select and evaluate the sizes of the bearings

5.6.1 FEM study

The first step in setting up the FEM test is to calculate the forces applied to it. A worst case scenario is assumed when the end effector is at its maximum horizontal distance from the base. This is done since it is at this position the robotic arm will be exposed to the highest stress levels.

Since the payload is known to be 25 kg the vertical force applied at the end effector can be estimated to 250 N. To calculate the horizontal force applied to the robotic arm, eq. 6 is used.

$$\overline{M} = \frac{dI}{dt}\overline{\omega} + I\frac{d\overline{\omega}}{dt} \tag{6}$$

The worst case would be if the robot swings at high speed when fully extended, and stops abruptly. During this event the inertia is assumed constant, which leads to eq. 7.

$$\overline{M} = I\frac{d\overline{\omega}}{dt} = I\ddot{\theta} \tag{7}$$

The total inertia consist of two parts, the robot and the payload. The moment of inertia for the robotic arm is provided from Solidworks, the moment of inertia for the robotic arm around the Zw-axle (fig. 34 is $88,5[kg \cdot m^2]$. The payload can be assumed to be in a spherical shape with a diameter of $20[cm]$. Eq. 8 is the equation for the moment of inertia of a sphere.

$$I_{sphere} = \frac{2}{5}mr_{sp}^2 \tag{8}$$

The payload is situated at the end effector of the robotic arm. The payload inertia must be adjusted using Steiner's theorem to account for its effect to the total inertia at the robot base.

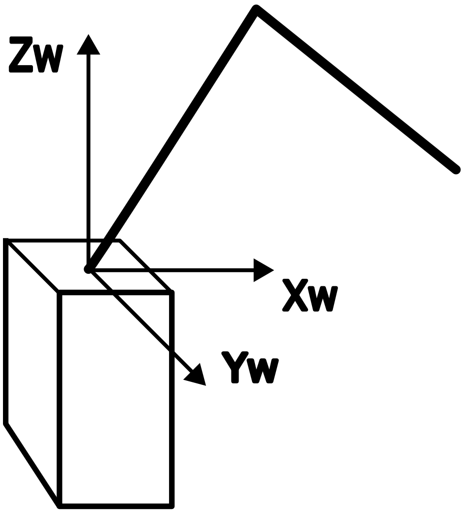


Figure 34: Reference coordinate system

The total moment of inertia is the sum of $I_{sphere,Zw}$ and I_{robot}.

$$I_{tot} = I_{sphere,Zw} + I_{robot} \approx 245[kg \cdot m^2] \tag{9}$$

As the robot arm swings in a circular motion, the tangential speed v is:

$$v = \omega r_r \tag{10}$$

The angular acceleration is given by differentiating both sides with the respect to time.

$$\dot{v} = a = \dot{\omega} r_r = \ddot{\theta} r_r \rightarrow \ddot{\theta} = \frac{a}{r_r} \tag{11}$$

With maximum payload an acceleration of about 1g is assumed for this analysis ($a = 1 \cdot 9,82[m/s^2]$ and $r_r = 2,5[m]$), the angular acceleration ($\ddot{\theta}$) could then be calculate using eq. 11 to $3,9 rad/s^2$.

With both the moment of inertia and the angular acceleration calculated, eq. 7 can be used to calculate the moment applied to the robotic arm, the moment was calculated to $961[Nm]$. To convert the moment to force, eq. 12 is used, which give the total horizontal force to be $F \approx 385[N]$.

$$F = \frac{M}{r_r} \tag{12}$$

When the load is estimated the rest of the boundary conditions for the FEM study need to be established. Examples of where the different boundary conditions can be found, can be seen in fig. 35. For parts which are fixated against each other "component interaction" will be used, nr. 4. "Fixed geometry" will be used to represent the actuators and the connection to the ground, nr. 3. For the connection between the rods and the joints "Rigid connection" will be used, nr. 1. "Bearing connection" will be used to represent the bearings, nr. 2.

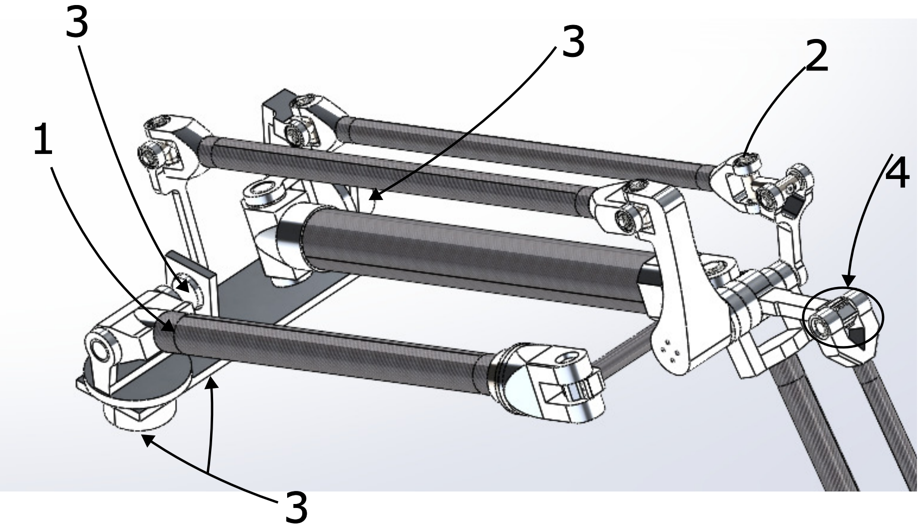


Figure 35: Examples of where the different boundary conditions is used

5.6.2 Bearing size evaluation

Since the forces on the bearings will be given from the FEM study, the bearings will be in first hand dimensioned by their static load capability. If there would be enough time to also do a dynamical study on the bearings, they will be dimensioned according to this as well.

To evaluate the bearings the static safety factor (s_0) will be used. A static safety factor of 2 is selected. This is selected since the forces on the bearings might be higher for some of the joints when the robot is operating at different positions, but the forces will most likely not be twice the size as for the simulated position. If a bearing breaks it will most likely not cause any personal harm and because of this it is not considered necessary for a higher static safety factor. The static safety factor is determined through eq. 13 [11].

$$s_0 = \frac{C_0}{P_0} \tag{13}$$

Every bearing has a specific C_0 value which is specified from the manufacturer. P_0 need to be calculated and it is depending on both data specific for each bearing and on the load applied to the bearing. The equation for the P_0 is slightly different depending on bearing type and if it is paired with an other bearing and how they are paired, but they all is based on eq. 14 [11].

$$P_0 = Y_{0r}F_r + Y_0F_a \tag{14}$$

For the equations above F_r is the radial load and F_a is the axial load and these will be different from bearing to bearing. The Y_{0r} and Y_0 is a value given from the manufacturer and listed in their product catalogues. The Y_{0r}, Y_0 and C_0 values for the bearings used in this model is displayed in tab. 9.

Table 9: Y_{0r}, Y_0 and C_0 values for bearings used in the model [11]

Bearing	Y_{0r}	Y_0	C_0 [kN]	Condition
7303 BE-2RZP	0,5	0,52	8,3	$P_0 < F_r \rightarrow P_0 = F_r$
7211 BE-2RZP	0,5	0,52	36	$P_0 < F_r \rightarrow P_0 = F_r$
32007 X	1	0,7	54	$P_0 < F_r \rightarrow P_0 = F_r$
32005 X	1	0,8	32,5	$P_0 < F_r \rightarrow P_0 = F_r$
30202	1	0,9	14,6	$P_0 < F_r \rightarrow P_0 = F_r$
BS2-2208-2RSK/VT143	1	2,5	90	-
NA 4907.2RS	1	0	43	-
NA 4906.2RS	1	0	32	-

From table 9 and eq. 14 the static safety factor can be calculated for each bearing. In table 10 the maximum load applied to each bearing type will be presented and each of the calculated static safety factors for them.

Table 10: Maximum forces applied to the bearing and their static safety factor [11]

Bearing	F_r [kN]	F_a [kN]	P_0 [kN]	s_0
7303 BE-2RZP	1,13	0,11	0,62 (1,13)	7
7211 BE-2RZP	2,35	0,95	1,67 (2,35)	15
32007 X	1,34	0,13	1,43	37
32005 X	1,04	0,10	1,12	29
30202	0,13	0,02	0,15	97
BS2-2208-2RSK/VT143	10,18	1,19	13,16	6
NA 4907.2RS	8,41	0	8,410	5
NA 4906.2RS	3,90	0	3,9	8

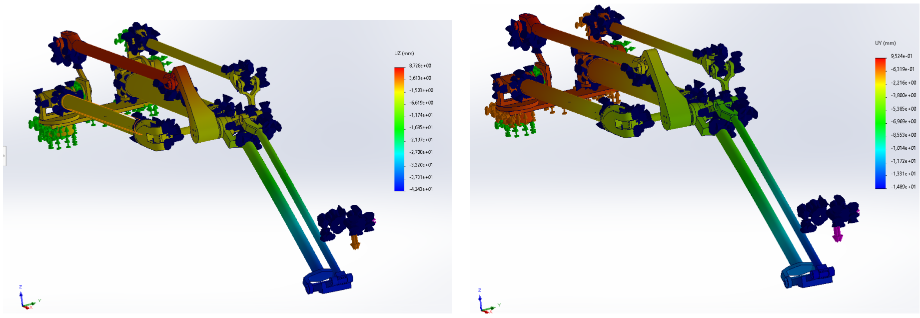
From tab. 10 it can be seen that all bearings have a higher static safety factor than the targeted safety factor, which was 2. Since some bearings do have a static safety factor much higher than 2 they may be a little over sized. But this means that the bearing also can handle bigger loads. It may occur higher loads when the robot perform other movements, but since the static safety factor was this high over the targeted one. The conclusion can be made that they have the capability to handle even these loads.

5.6.3 Model evaluation

From fig. 37 it can be noticed that the highest amount of stress is exerted on the short carbon rod between the two inner arms. From the bar at the right in fig. 37 the stress levels can be read to be around 150 MPa. The carbon rods used have a tensile strength of around 650 MPa [12], which means that the carbon rods can handle the load applied to it.

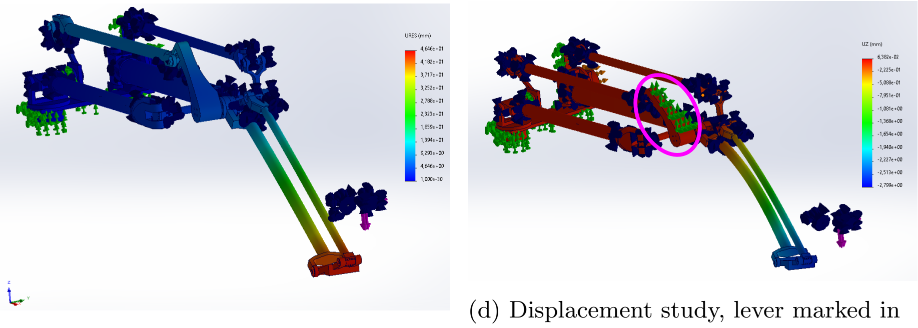
As can be seen in fig. 36a the displacement in the z-direction is around 42 mm. To investigate what causes this displacement, the aluminium lever marked with a pink circle (fig. 36d) is hold fixated and and a new study will be made. Since the new displacement of the end effector is 2,8 mm, which is mush lesser than the previous result (fig. 36a). The conclusion can be drawn that the big displacement in the first study probably is due to small rotations of the lever marked in the pink circle in fig. 36d and the lever marked in green in fig. 37. These small rotations are due to small displacements in the carbon rod and the aluminium lever which is connected to the gearbox. The displacement caused by this can therefore be compensated by the actuator.

In fig. 36b the displacement in the y-direction is around 15 mm. Since this displacement occurs during acceleration and deceleration during side motions the size of this displacement can be considered good enough and they can also be regulated by the actuator.



(a) Displacement in z-direction

(b) Displacement in y-direction



(c) Resultant displacement

(d) Displacement study, lever marked in pink is fixed

Figure 36: The models resultant displacement and the displacement in y- and z-direction

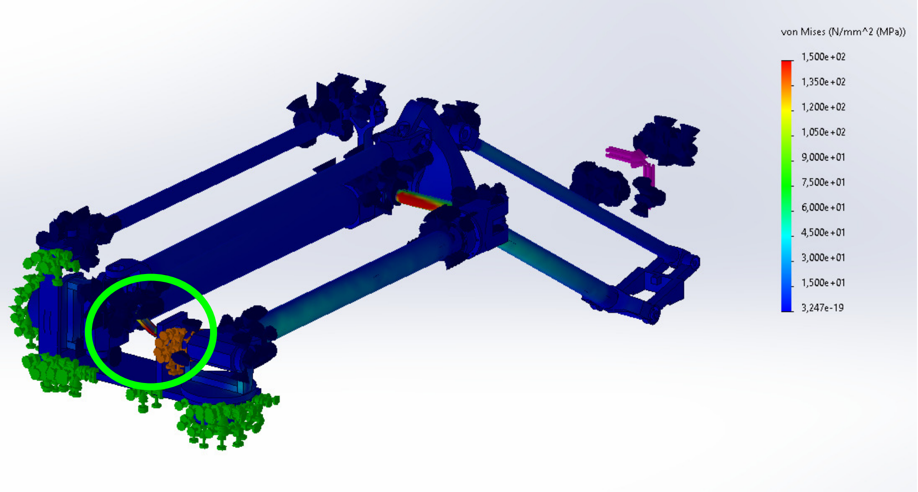


Figure 37: Stress on the model

6 Cost analysis

For a price estimation, the price on the different component will be estimated. The bearings can be divided in two groups, small bearings and large bearings. The small bearings includes the angular contact ball bearings, tapered roller bearings and needle roller bearings. The cost for these bearings can be estimated to around 300 sek/bearing. Tapered roller bearings is slightly more expensive then angular contact bearings and needle bearings. 300 sek/bearing is between the cheaper and the more expensive bearings. In the model there are 30 smaller bearings, which lead to the total cost for the small bearings to be 9 000 sek. The large bearings include the spherical roller bearings. These can be estimated to cost around 800 sek/bearing. There are 2 larger bearings in the model which give a total price on 1 600 sek.

The cost for the carbon rods will be estimated by first calculate the price per volume [sek/dm^3]. A rod with the dimension 60x57x1000 was selected as a reference. This rod would cost around 1050 sek [12]. The volume of the reference carbon rod is calculated to around 0.276 [dm^3], which give a price of around 3 800 [sek/dm^3]. From the total volume presented in table 11 and the cost of the carbon rods per dm^3 the total cost of the carbon rods can be estimated to 15 300 sek.

Table 11: dimension and sizes of the rods in the model

Rod size [mm]	Rod length [mm]	cross-sectional area [dm^2]	Volume [dm^3]
40x36	1368	0,024	0,327
50x46	1100	0,030	0,332
60x54	1150	0,054	0,618
60x56	985	0,036	0,359
80x76	1000	0,049	0,490
120x110	1050	0,181	1,897
Total			4,023

The cost for the metal parts is mostly manufacturing costs. Since the cost for these parts are mostly manufacturing costs, the cost will be estimated based on their estimated manufacturing times. The cost per hour is estimated to be around 600 sek/h. all the small aluminium parts is estimated to take around 4 h which gives a cost of 2400 sek/part. There are 12 aluminium parts which gives a cost of 28 800 sek. The tool mounting platform is estimated to take around 8 h which give a cost of around 4 800 sek. The base is the biggest part and is estimated to take around 10 h, which give a cost of around 6 000 sek. The manufacturing time for the shafts is estimated to around 2 h which give a cost of around 1 200 sek/part. There are 10 shafts which give a cost of 12 000 sek. The total cost from all the metal parts are 51 600 sek.

For the electric motor, gearboxes and control systems for the robot it is harder to estimate since nothing of them have been discussed or developed in this thesis. However, the price can be estimated based on average prices and estimated prices from the company. Two different electric motors can be thought to be mounted on the robot. Three bigger which is located on the base and one smaller located at the end effector. The bigger motor can be estimated to cost around 8 000 sek/motor and the smaller to cost 7 000 sek/motor. For the gearbox three different size can be thought to be mounted. One large gearbox for the motor controlling the up and down motion. The medium gearbox will be used for the motors controlling the side motion and in and out motion of the outer arm. The last small gearbox will be mounted to the motor located at the end effector. The large gearbox cost around 24 000 sek/gearbox, the medium gearbox costs around 17 000 sek/gearbox and the small gearbox costs around 10 000 sek/gearbox. the last part needed for the robot is a control system. This system cost around 210 000 sek/unit.

The time for assembly the robot is estimated to around 40 h. The cost per hour is estimated to around 600 sek/h. This give a total cost of 24 000 sek for the assembly of the robot.

Table 12: Sum of the costs

Item	Price/unit	Units	Total cost
Small bearings	300	30	9 000
Large bearings	800	2	1 600
Carbon rods	3 800	4,023	15 300
Aluminium parts	2 400	12	28 800
Tool mounting platform	4 800	1	4 800
Base	6 000	1	6 000
Steel shaft	1 200	10	12 000
Electric motor	8 000	3	24 000
Small electric motor	7 000	1	7 000
Large gearbox	24 000	1	24 000
Medium gearbox	17 000	2	34 000
Small gearbox	10 000	1	10 000
Control system	210 000	1	210 000
Assembly cost	600	40	24 000
Total cost			410 500

From table 12 the total cost for the robot can be estimated to cost around 410 500 sek.

7 Conclusion

To fill a gap in the market for pick and place robots a robotic arm have been developed according to the patented robotic arm presented in fig. 9. The robotic arm selected is one of the lighter, cheaper and with a good weight distribution.

Different concept was created for the robotic arm. Concept 1 was selected to be used for the rest of the development, since this concept was the lightest and cheapest of the concepts.

To optimize the workspace the length ratio between the inner and and outer arm was set to 1,1 and with a length 1,3 m for the inner arm the outer arm has a length of around 1,2 m, This will provide a workspace which can load a roll container without the need of any other equipment.

The robotic arm need to be stiff and lightweight and the rods therefore needs to be made by carbon fibre. One rod will carry the weight of the arm and the payload, therefore this rod needs to be big. The dimension D120xd110 mm was found to be enough for this rod. Since this rod will take the highest loads. The diameter for the other rods is between 40 mm to 80 mm and have a thickness of around 2 mm. With this dimensions the robotic arm can handle a payload of 25 kg.

Since there is a offset between the y-axis and the z-axis at the elbow joint, there will be small angular differences for the end effector. The elbow joint need to carry high loads, both axial and radial. Spherical roller bearings was used since they are stiff and can take both high radial and axial loads.

The cost for this robot is estimated to around 400 000 sek.

8 Future work

8.1 Left to be developed

Electric motor and gearbox
Since the motor and gearboxes have not been treated during this thesis, they need to be selected. All the parts which are connected directly to the gearbox do also need to be developed further.

Base
Even if the location of the motor and gearboxes have been established throughout this thesis the actual base and how it should be designed have not been established. When developing the base new features can be evaluated like if the whole robot should be able to move in different directions.

Tool mounting platform
The tool mounting platform and the motor on it have not been developed or treated in this thesis. Because of this it will need to be further developed. What tools should be used and if it should be able to switch between different tools. The joints connecting the tool mounting platform do also need to be selected. Two options is presented in the thesis.

8.2 Use as a SCARA robot

By rotating the 90 degree around the x-axis the robotic arm could be used as a SCARA robot. If this is done it would not be necessary with the parallelogram at the outer arm. Since the outer arm could be moving up and down it would not need a ball screw as the existing SCARA robots have. This would allow the robot to get in to small areas.

8.3 Actuate a fifth axis

If the rod that holds the outer arm horizontal (rod nr. 2 in fig. 24) would be actuated, it would give control of the tilt for the tool. Since the tool will tilt a little bit during operations, this problem would be solved if the rod would be actuated.

References

[1] C. Mohan Raj et al. "Material Handling Using Pick and Place Robot". In: *2022 8th International Conference on Smart Structures and Systems (ICSSS)*. 2022, pp. 1–6. DOI: `10.1109/ICSSS54381.2022.9782275`.

[2] Nationalencyclopedin. *Parallellogram*. Swedish. 2023. URL: `https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/parallellogram` (visited on 05/23/2023).

[3] ABB. *product specification IRB 360*. 2023. URL: `https://search.abb.com/library/Download.aspx?DocumentID=3HAC075723-001&LanguageCode=en&DocumentPartId=&Action=Launch` (visited on 03/31/2023).

[4] Daily automation. *Delta robot_Workspace*. 2023. URL: `https://www.dailyautomation.sk/delta-roboty/delta-robot_workspace/` (visited on 05/01/2023).

[5] ABB. *product specification*. 2023. URL: `https://search.abb.com/library/Download.aspx?DocumentID=3HAC075723-001&LanguageCode=en&DocumentPartId=&Action=Launch` (visited on 03/31/2023).

[6] ABB. *product specification*. ABB. 2023. URL: `https://search.abb.com/library/Download.aspx?DocumentID=3HAC075723-001&LanguageCode=en&DocumentPartId=&Action=Launch` (visited on 03/31/2023).

[7] Uniarc. *Cobra 450*. 2016. URL: `vhttp://www.uniarc.co.th/products/omron/scara-robot/cobra450.html` (visited on 05/01/2023).

[8] Cognibotics. *HKM*. 2023. URL: `https://cognibotics.com/hkm/` (visited on 05/04/2023).

[9] ABB. *Productimage*. URL: `https://cdn.productimages.abb.com/9IBA032406_720x540.jpg` (visited on 05/01/2023).

[10] Brogardh T and Nilsson K. "AN AGILE ROBOT ARM FOR POSITIONING A TOOL WITH CONTROLLED ORIENTATION". EP3838499A1. June 23, 2021.

[11] SKF-koncernen. *Rullningslager*. 2019.

[12] Easy composites. *60mm woven finsh carbon fibre tube*. 2023. URL: `https://www.easycomposites.eu/60mm-woven-finish-carbon-fibre-tube` (visited on 05/03/2023).