Technische Universität Berlin

Master thesis

Design, construction and testing of an 3-axis joint system for a facade greenery maintenance and harvest robot

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Master thesis

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The TU Berlin and further international Partners do research about the potentials and the challenges of widely used facade greenery during an EU funded project.

One big challenge is the time demanding and costly maintenance of the greenery. The Chair Machinery System Design evaluates the capabilities, limits and potential concepts for automated maintenance and cultivation.

The objective of this thesis is to test a joint system from the manufacturer IGUS for the use in a façade greenery maintenance and harvest robot. After analysing the general requirement, a selection of suitable joints has to be made. Then a motor mount has to be build. The main task is the extensive testing of the system against the requirements under field condition.

The following steps need to be accomplished:

- Analysing the requirements for the joint system
- Selecting the best combination of joint for the described problem
- Designing and construction of an motor mount for the joint system
- Extensive testing of the assembly against the requirements
- Conclusion and outlook

The results of the thesis have to be presented at the Chair Machinery System Design and emitted as a printed copy as well as a PDF file. The thesis is available to everyone in the audit

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procedures. The printed copy of the thesis will become property of the Chair Machinery System Design.

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Berlin, the 05/12/2019

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1 Introduction

This master thesis is involved in the project green vertical 2.0, that consists in the transformation of urban areas to more sustainable, efficient and consistent spaces with the extensive use of vertical greening, it has a great potential to cool buildings, to recycle and upcycle wastes, rainwater and grey water, to produce food or bio-energy and to generate green spaces nearly everywhere in cities almost independent of available horizontal space.

On behalf of the Sustainable Urbanization Global Initiative (SUGI), the Chair Machinery System Design at the Technical University of Berlin is involved in this project. To reduce the maintenance costs, a machine system is being developed that automates the care of the green verticals in the walls of the buildings [Neh19].

Figure 1.1. Vertical Green 2.0 [Neh19].

The target of this master thesis, that is involved in the project Green Vertical 2.0, is the developing, construction and testing of a 3 degrees of rotation system, which will have a cutting tool at the top of it. This system will be assembled in the robot that will take care automatically of the harvest and maintenance of the vertical greens. The aim of the work is to build a machine system, that moves with three degrees of freedom allowing the cutting tool of the maintenance robot to be moved precisely to the positions that it is required for making the appropriate maintenance of the vertical greens.

For accomplishing this targets a combination of joints are going to be selected from the manufacturer IGUS that will provide the system the three degrees of freedom required. In a next step the motors and the power system will be chosen for getting the required torque and speed in each joint of the system.

Once all the elements of the system are selected and bought, then different designs with the placement of all the element will be discussed and the most suitable of them chosen. For closing the project, the system will be tested against the requirement list.

2 General requirements analysis

In this chapter a discussion about the requirements of the system is going to be done, in addition a brief research about how the state of the art for similar machine systems with similar requirements is going to be carried out.

2.1 Requirements of the system

For starting the development of the 3 degrees of rotation system an analysis of the general requirements of the system that has to be build will be done and in the following chapters, a specific solution for each of the joint and the motor system will be developed, that can fulfill these general requirements. These requirements have been selected with the supervision and help of Sebastian Schröder and from the previous bachelor thesis done by Björn Lechler [Lec18]. The requirements list can be seen in the table 2.1.

Date	F/W	Requirement	Source
25/04/2019	W	The joint system should have enough space for putting the connection cables through the pipe of the system	Javier Mellado
25/04/2019	 W F	Deflection of the last pipe with a 10 N force 2 mm 5 mm	Sebastian Schröder
20.6.2019	 W F	Deflection of a single axis under a load of 3Nm 2 deg 5 deg	Sebastian Schröder
20.6.2019	 F	Maximum distance from tool turning point to robot base 500 mm	Sebastian Schröder
9/05/2019	F	All axis of rotation must merge in one point	Sebastian Schröder
25/04/2019	 F	**2 Cinematic** The system must have 3 degrees of freedom	Javier Mellado
9/05/2019	 W	Minimum acceleration 1 revolution/s^2	Sebastian Schröder
9/05/2019	 F W	Minimum rotation speed 0.2 revolutions/s 2 revolutions/s	Sebastian Schröder
9/05/2019	 F F W F	Maximum torque for each axis 1º axis 12 Nm 2º axis 10 Nm 3º axis 10 Nm 5 Nm	Sebastian Schröder
9/05/2019	 W F W F	Minimum degree of rotation of each axis 1º axis 200º 120º 2º axis 200º 100º 3º axis	Sebastian Schröder

	W F	400º 190º	
25/04/2019	F	**3 Material** Material should be stress resistance and low weight	Javier Mellado
25/04/2019	W F	**4 Mechanics** Maximum weight of the hole system 3 Kg 6 Kg	Sebastian Schröder
25/04/2019	F	Durability 60 turns/h 300 h/Year 5 Years	Björn Lechler
25/04/2019	W	**5 Others** Easy mounting process	Javier Mellado
9/05/2019	F	Joints must be from IGUS	Sebastian Schröder
25/04/2019	F	Joints and motors must be waterproof and isolated from dust and rests of plants	Javier Mellado
9/05/2019	W F	Maximum price 1000€ + taxes 2000€ + taxes	Sebastian Schröder
15/05/2019	F	The system should have a feedback of the position of the angles of each joint	Javier Mellado
15/05/2019	W	Asymmetric movement angle of some of the joints	Sebastian Schröder
20/6/2019	W	Use Stepper Motors	Sebastian Schröder

Table 2.1. Requirements list of the system.

In the table 2.1 it is said who is the source of the requirement, the date when each of the requirement had been incorporated and if is a fix (F) or a wish (W) requirement, the fixed requirements are the ones that the system must have.

One of the important parts of the requirements of the system that has to be designed is the ones that refer to the deflection of the arms under different forces, this part is particularly important because a higher deflection of the arm or of each of the joint will decrease the precision of the positioning of the cutting tool, which would affect to the efficiency of the process of maintenance of the facade. These points are also related to the maximum distance between the turning point of the cutting tool and the robot base because a higher distance will increase the torque in the joints and the coupling between the machine system, that is going to be developed, and the robot base leading to more stress in the materials.

Some of the points are requirements due to operational issues such as the merging of the rotation angle and the asymmetric movement of the joints because this allows the system to have more mobility and gives the possibility to cut the plants from behind or in more ways than with symmetric rotation angles. Also, for getting more movement possibilities the system should have 3 degrees of freedom for achieving every different position with the cutting tool, also each joint should have enough degrees of rotation to reach every position.

It is also important to know exactly how many degrees have moved the joints, this can be done by getting a feedback of the rotation angles in each joint by having an encoder in the motor or in directly in the gears. The use of stepper motors is more recommend because it allows a better positioning and more precisely movement of the motor.

About the weight of the system is important to say that it must be as low as possible to reduce the power consumed by the robot, as well as the stress in the portal that will carry the robot. It is important to remark that the weight in the pipe should be as low as possible to reduce the bending moment in the robot base and increase the precision of the position system thus decreasing the deflection of the cutting tool.

The following image is a METUS-rhomb analysis of the requirements of the system. The main function that is to move the cutting tool from the robot base, from that function it gets some specific functions like moving with a certain torque and speed or being a waterproof mechanism. These specific functions of the mechanism are solved with different components and then each one of them are integrated in groups that form the machine system which is the target of this thesis.

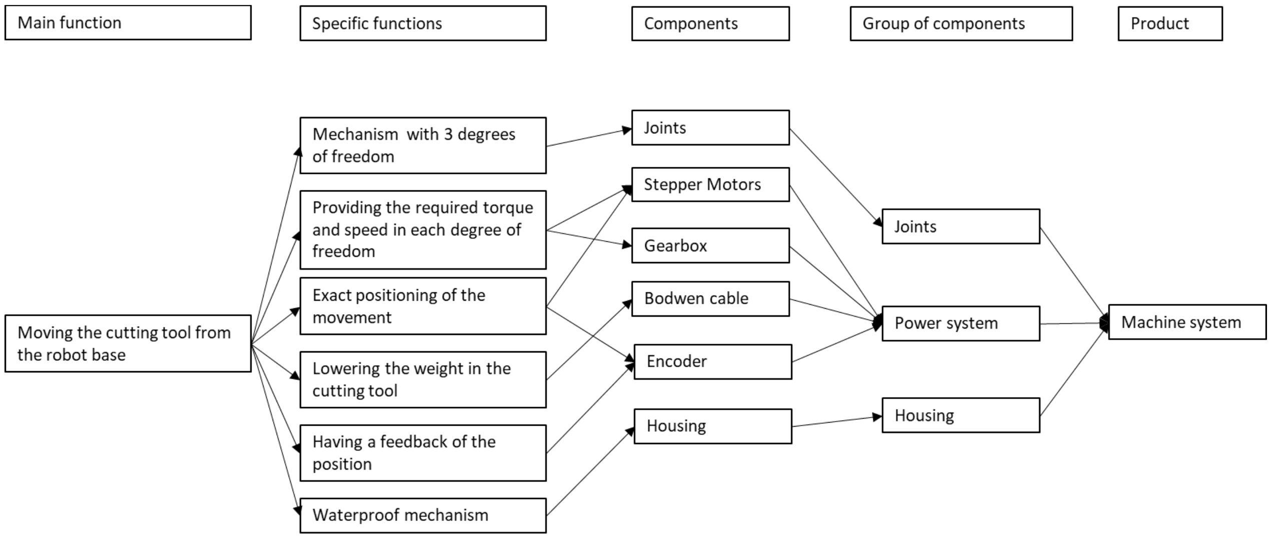

Figure 2.1. METUS-rhomb analysis.

2.2 State of the art

In this chapter a brief introduction about how the state of the art in robotics is. Most of the mechanisms that are used for moving robotic arms uses systems with cable-driven joints, this type of joints allows different kinds of moves using a cable with traction forces called bowden cables. In a bowden cable transmission, a cable is guided inside a flexible sheath. For remote actuation of a robotic joint, force is delivered to the remote joint by mechanical displacement between the cable and the outer sheath and can be actuated in both directions by respective rotation of the motor. To implement a remote-actuated rotary joint, a pull-pull configuration as illustrated in figure 2.2. [Let07]

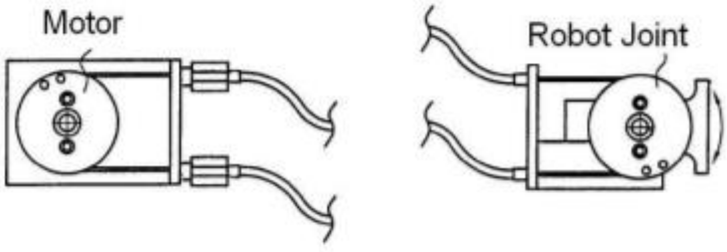

Figure 2.2 Principle of Bowden cable actuator. [Let07]

The main advantage for robotics, is that by using cables for transmitting the power from the motor to the joint the weight of the motor, which usually is the heaviest part, can be displaced to the base of the robot instead of the moving part, this would cause bigger reaction forces in the arm and bigger motors would be required for moving the same mechanism, as the one using bowden cables for moving.

The main disadvantage for this type of cables is that loss of tension in the cables due to the friction and twisting between each other, especially in applications with many degrees of freedom, that would require a difficult design for leading the cables from the motor to the joint.

3 Selection of the joints of the mechanism

In this chapter it is going to be explained how the joint system has been selected according to the general requirements of the last chapter. The first options to develop the joint system was using the cable driven joints that are made by IGUS, this option is the most suitable because it allows to displace the weight of the motors and its gearboxes, which is the heaviest part of the mechanical system, to the base of the robot instead of having it in the machine system and this would increase the deflection of the arm, which would lead to a reduction of the precision of the cutting tool, and, also, to higher forces in the whole arm and the first joint of the system, that would increase the required resistance of the arms, as well, the required power to move the arm. With the other joints systems that IGUS offers the motor must be connected just next to the joint. In the figures 3.1 and 3.2 can be seen the difference between the two kinds of joints.

Figure 3.1. System cable driven joints. [Igu19]

Figure 3.2. Joint system with the motor closed to the joint. [Igu19]

3.1 Different combination of cable driven joints

The first combinations of joints that are going to be developed are:

- The ones that the rotation axis merges in one point.
- The ones that the system has 3 degrees of freedom.

After seeing which combinations of joints are available that fulfilled this condition the ones that don't accomplish the two requirements that were said before will be erased and a utility analysis will be done to select the best combination for the requirements of the joint system.

3.1.1 RL-90-BL-1 +RL-50-TL2

This combination uses the models of cable driven joints RL-90-BL-1 which has two different degrees of freedom (rotation and inclination) and must be always the first joint of the system and RL-50-TL2 which can rotate. The different characteristic of this combination can be seen in the annex 1, as well as the sketch of the system.

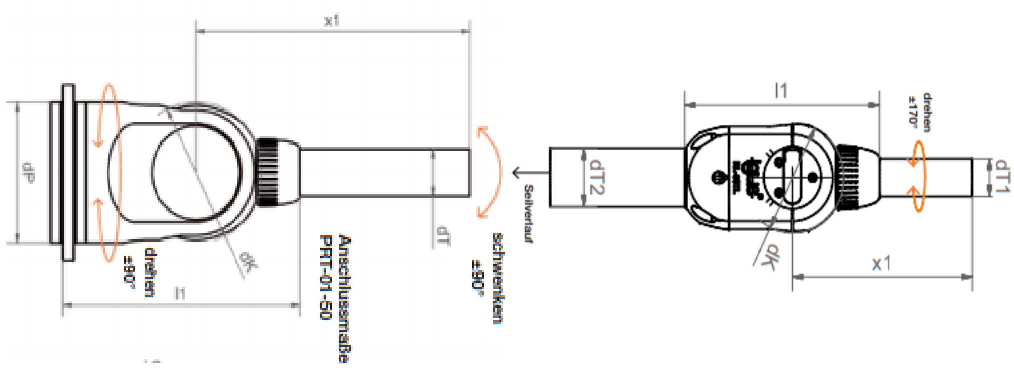

Figure 3.3. Combination RL-90-BL-1 +RL-50-TL2. [Igu19]

This combination could not be used because the torque of the first one is 10 Nm when the minimum required is 12, so this one can't fulfill the requirements that were said in the last chapter.

3.1.2 RL-50-TL1+RL-50-002

This combination is made by the IGUS' joints RL-50-TL1 and RL-50-002, as before the characteristics can be seen in the annex and the figure 3.3 illustrates each joint.

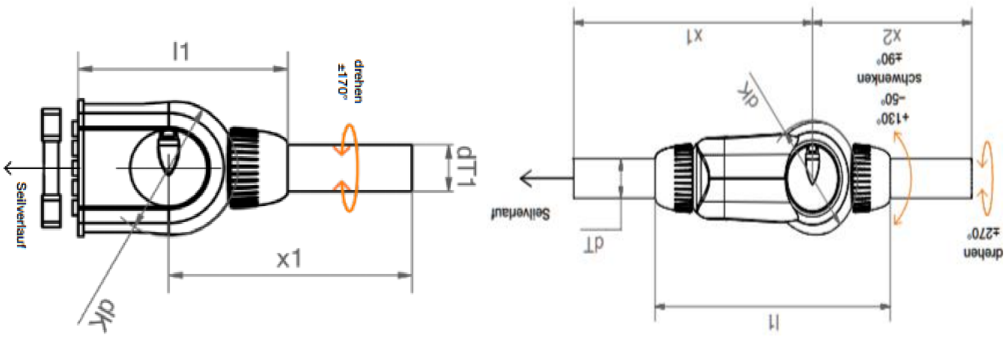

Figure 3.4. Combination RL-50-TL1+RL-50-002. [Igu19]

This combination is better than the last one because it can turn more and, also, the second one has an asymmetric rotation that would allow more different movements for the tool of the robot. However, it doesn't fit the required torque in the first joint as in the last combination.

3.1.3 Conclusions

As no one of the different possible combinations fits the requirements of the system is it necessary to move to a different solution. The main problem of the system designed is in the first joint, because the cable driven joints made by IGUS can't reach the level of torque, so the solution will be to include a worm gear joint from IGUS for the first place with one degree of freedom and then a cable driven joint with two degrees of freedom, with this configuration the requirement of the three degrees of freedom is accomplished. This solution is also suitable because as the first joint is in the base of the robot there is no need of using a cable-driven joint for that one because the motor is already in the base.

3.2 Final joint system

As said in the last sections the final design of the joint system will be a single degree of freedom joint and after a cable driven joint. For the second joint there will be used the RL-50-002 because it has an asymmetric movement and this, because of operational reasons, would allow a better for the movement of the cutting tool of the robot. As there is only one suitable option for the cable driven joints made by IGUS there won't be done any utility analysis to choose it.

For the first joint of the system, after checking the different options of the range of worm gears, which can be seen in the annex 1, is the RL-D-30-101-30-01000. This joint was chosen instead of the smallest version because, even if the RL-D-20 can stand the torque required by the joints, there is not much difference in weight and price but the torque that can reach this one is higher, so it has been selected for having a greater safety margin for a part of the mechanism that is critical. There is no need of further comparison over the different worm gear due the rest of the joints offered by IGUS are heavier and more expensive than the ones in the range of RL-D-30.

The main problem with this setting of joints is that the worm gear joints made by IGUS need to have the motor directly coupled to the joint and maybe is needed to have it another part of the robot because of space problems. The solution for this problem would be to develop a pulley system, which would allow to move the body of the robot next to the motor of the cable driven joints, but the different designs of the motor mount will be discussed in the following chapters. The final configuration of the joints is the following:

- In the first position a worm gear with one degree of freedom the RL-D-30-101-30-01000.
- In the second position a cable driven joint with two different degrees of freedom the RL-50-002.

The final sketch of the system is the following:

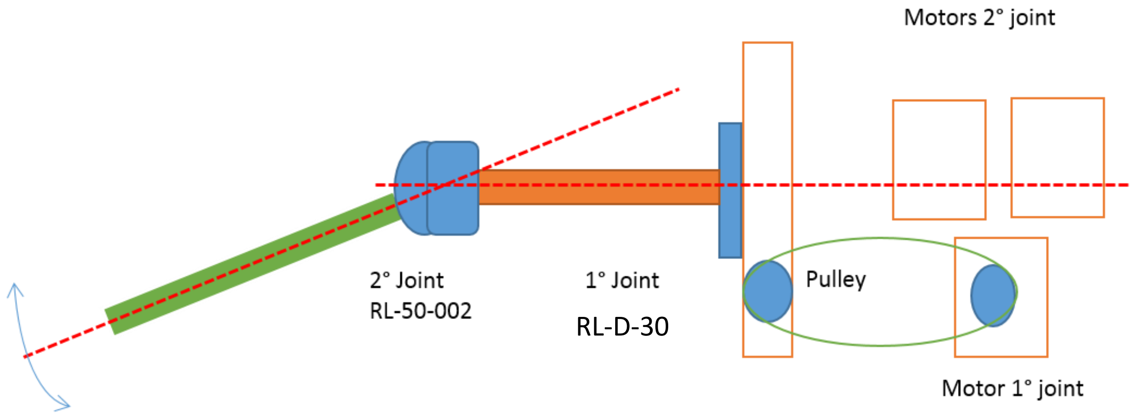

Figure 3.5. Final joint system.

Another issue is the possibility of getting a feedback of the angles, this could be made by putting an encoder either in the motors or in the joints, for the first joint is almost the same because one motor moves one degree of freedom. But for the second one the ideal solution is to place the encoder made by IGUS directly in the joint because it would get the feedback of two degrees of freedom with only one encoder and will allow the possibility of getting a more precise feedback than placing the encoders in the motors.

4 Motor selection

During this chapter there is going to be a discussion about the requirements of the motors and the selection process of the most suitable one along with the reduction system that allows to reach the require torque in each joint.

4.1 Description of the specific requirements attached to the motors part.

The machine system should be moved from the base of the robot in order to decrease the weight in the top of the arm. For accomplishing this the system should use the cable driven joints described in the last chapter.

The main problem with this kind of structure is to get a system that will provide enough tension to the cables and, also, to not get any interference between the cables in motion and the other components. To solve this problem different configurations of the motors mount will be discussed in this chapter to get the best solution possible for the problem described.

Also is it necessary to control precisely the position of each axis, to accomplish this the ideal solution is to use stepper motors instead of normal DC motors, which has a better positioning and control system than other kind of the DC motors.

Achieving the required power in each joint (torque and speed) is also one of the main requirements of the motor part, this will be fulfilled by using a motor with enough torque and if it has not enough torque a reduction system will be used, in case this reduction system is necessary the precision of the rotation movement of each joint shouldn't be compromised or at least minimized.

The specific requirements of the motor system can be seen in the table below:

Requirement list of the motor system			
Date	F/W	Requirement	Source
24/06/2019	F	Connection in parallel	Sebastian Schröder
24/06/2019	F	Maximum current that could be provided to the motors 10A	Sebastian Schröder
24/06/2019	F	Maximum voltage that could be provided to the motors 36V	Sebastian Schröder
24/06/2019	W	The precision of the reduction system should be as high as possible	Sebastian Schröder
24/06/2019	F	Minimum resolution of the step motors 1.8º/step	Sebastian Schröder
27/06/2019	W	The twisting of the bowden cables of the cable driven joint should be reduce	Javier Mellado
27/06/2019	W	The weight of the motors and reduction system should be as low as possible	Javier Mellado
27/06/2019	F	Motors and reduction system must have a protection equal to IP65	Javier Mellado
9/05/2019	 F W	Minimum rotation speed in the joints 0.5 revolutions/s 2 revolutions/s	Sebastian Schröder
9/05/2019		Maximum output torque in each axis that must be provided 1º axis	Sebastian Schröder

	F F F	12 Nm 2º axis 10 Nm 3º axis 5 Nm	
03/07/2019	F	The diameter of the shafts of motors of the cable driven joint must be 12 mm	Javier Mellado

Table 4.1. Specific requirements of the motor system.

The most important requirements for the power train system is about how to place the motors in the robot base for not twisting the cables of the cable driven system, for accomplishing this target the best solution would be to rotate the motors of the second joint along with the first gear. The designing process of the motor position would be discussed in the chapter below.

Also is important to remark that the system should have a level of protection equal to IP65. To make this possible there are two options available, the first one would be to buy motors with this level of protection, but this would increase the budget of the project above the maximum budget. The other option is to design a housing that can provide this level of protection to the motors and the reduction system.

It has to be noticed that the pulley for moving the cable driven joints from IGUS has a diameter of 12 mm, so the shaft of the reduction system of the motors from the second and third axis of rotation must have also this dimension to fit into the pulley without including a diameter adaptor in the shafts.

4.2 Selection of motors and reduction system

For reaching the requirements for the power train system that were said in the last chapter, a set of stepper motors with gearboxes, when is it necessary, will be chosen. The motors and gearboxes are going to be selected from the catalog of Nanotec [Nan19].

In the case of the stepper motors there are two kinds that could reach the requirements of the system, the NEMA 23 and the NEMA 24, the other categories of motors are heavier or has a torque lower than 1 Nm, so the gearboxes should have a reduction rate of more than 10, which would decrease the speed of the motors to a really low level.

From this two ranges of motors we are going to select the NEMA 24 ones because it has a more stable speed-torque curve than the NEMA 23 range, so for reaching the required torque after the gearboxes the speed would be extremely low. The difference of the two different kinds of motors can be seen in the figures 4.1 and 4.2

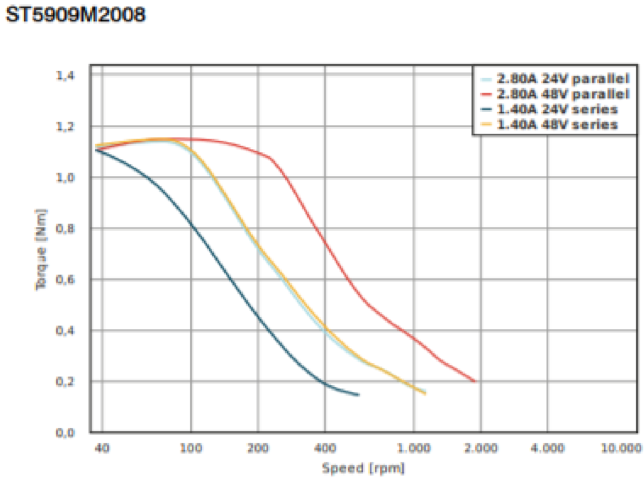

Figure 4.1. Curve torque-speed NEMA 23. [Nan19]

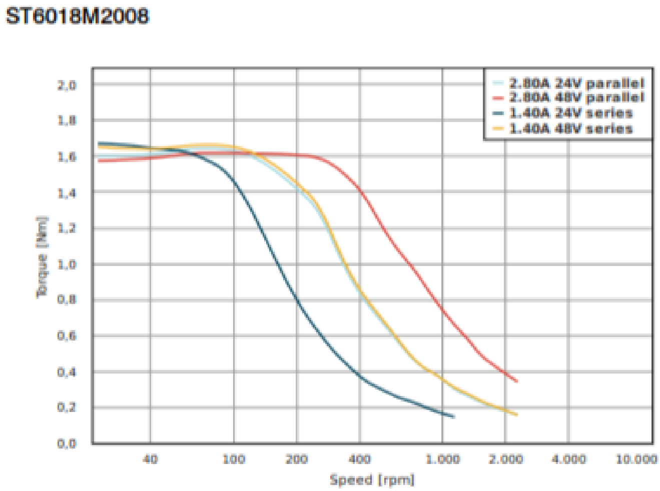

Figure 4.2. Curve torque-speed NEMA 24. [Nan19]

4.2.1 Selection of the power system for the first axis.

This first axis is the one who is working with a worm gear (RL-D-30), in this case is not need a gearbox because the worm gear has a reduction ration of 50. the mechanical requirements of this axis of rotation are:

- Torque of 12 Nm.
- Speed between 12.5 and 120 rpm.

For this joint the motor selected is NEMA 24-ST6018M3008-A from the catalog from Nanotec [Nan19]. The different characteristics of the motor, as well as the curve speed-torque for a parallel connection are in the annex 2. The main characteristics can be seen in the table 4.2.

Name	Length (mm)	Weight (Kg)	Price (€)	Speed at the required torque (rpm)
1º Axis NEMA 24-ST6018M3008-A	60	0.77	55	30

Table 4.2. Main characteristics of the power system for the first axis.

4.2.2 Selection of the power system for the second axis.

This second axis is the one who is working with a cable driven joint (RL-50-002), this joint has two degrees of freedom, in this paragraph the power system that is going to be chosen is only for the inclination movement of the joint. The mechanical requirements of this axis of rotation are:

- Torque of 10 Nm.
- Speed between 12.5 and 120 rpm.

The differences between the set of motor and reduction system of this axis and the one that is going to be used in the first axis is that in this case a smaller motor is more appropriate, because the requirements in this axis are not that high as in the last one, also it is necessary to use a gearbox for fitting the torque. The motor that has been selected is the NEMA 24 ST6018X2008-A, this one has a lower weight and also a lower torque than the NEMA 24-ST6018M3008-A [Nan19]. The characteristics, dimensions and curve speed-torque can be seen in the annex 2.

In the case of the gearbox the requirements that must fit is:

- The diameter of the shaft of the gearbox must be the same as the inner diameter of the pulley (12 mm).
- The output rate torque must be higher than the maximum torque of the axis (10 Nm).
- It can stand the radial load in the shaft, which is obtained dividing the higher torque that is going to be under work conditions by the radius of the pulley of the cable driven joint (25 mm):

$$F = \frac{T}{r} = \frac{10\ \text{Nm}}{0.025\ \text{m}} = 400\text{N}$$

Equation 4.1. Maximum radial load in the shaft of the gearbox of the second axis.

After consideration these requirements the gearbox that can fulfil it with the lower weight and price is the GP56-S2-11-SR [Nan19]. The characteristics and the dimmensions can be seen in the annex said before. The next table shows a brief summary of the combination of motor an gearbox:

Name	**Length (mm)**	**Weight (Kg)**	**Price (€)**	**Speed at the required torque (rpm)**	**Backslash of the gearbox (arc minutes)**	**Admissible radial load (N)**
2º Axis NEMA 24-ST6018X2008-A + GP56-S2-11-SR	114.8	1.4	161	70	31	516

Table 4.3. Main characteristics of the power system of the second axis.

4.2.3 Selection of the power system for the third axis.

The third axis is the one who is working with the rotation of the cable driven joint (RL-50-002). The mechanical requirements of this axis of rotation are:

- Torque of 5 Nm.
- Speed between 12.5 and 120 rpm.

The motor that is going to be selected is the same one as in the second axis of rotation because, even if the requirements are lower, it is the smallest one of the categories of the NEMA 24 motors, so a smaller gearbox will be selected to reach the requirements.

The requirements of the gearbox are the same that the ones of the second axis except for:

- The output rate torque is 5 Nm.
- The radial load is:

$$F = \frac{T}{r} = \frac{5\text{ Nm}}{0.025\text{ m}} = 200N$$

Equation 4.2. Maximum radial load in the shaft of the gearbox of the third axis.

With these requirements the one that fits is the GP56-S1-5-SR, but there is no more in stock, so the gearbox the selected gearbox is GP56-S1-7-SR [Nan19]. The main characteristics of this combination of motor and gearbox are the following:

Name	**Length (mm)**	**Weight (Kg)**	**Price (€)**	**Speed at the required torque (rpm)**	**Backslash of the gearbox (arc minutes)**	**Admissible radial load (N)**
3º Axis NEMA 24-ST6018X2008-A + GP56-S1-7-SR	97.6	1.18	139	120	34	516

Table 4.4. Main characteristics of the power system of the third axis.

5 Design

During this chapter the process of designing the correct position for the motors and the rest of the components that are fixed to the robot base is going to be described, first with the different preliminary designs, where the better position for the motors is going to be chosen and, then, once the placement of the motors is fixed the different components that are needed for building the 3 degrees of rotation system are going to be described.

5.1 Preliminary designs

In this chapter two different designs for the motor are going to be discussed, one with the motors twisting at the back of the arm and another one with the motors fixed to the same plate as the worm gear. The main advantage of the design with the motors turning is that the bowden cables of the cable-driven joints are not twisted, so the is no loss of tension due to the friction. However, the design is more complex and, maybe, problematic to build.

5.1.1 Motors rotating with the first axis

In order to try to reduce the interference between the cables of the pulley the first design of the placement of the motors will consist in making a rotatory platform for both two motors of the cable driven joint, this idea was suggested by IGUS for minimizing the friction between the bowden cables. The preliminary design can be seen in the sketches below:

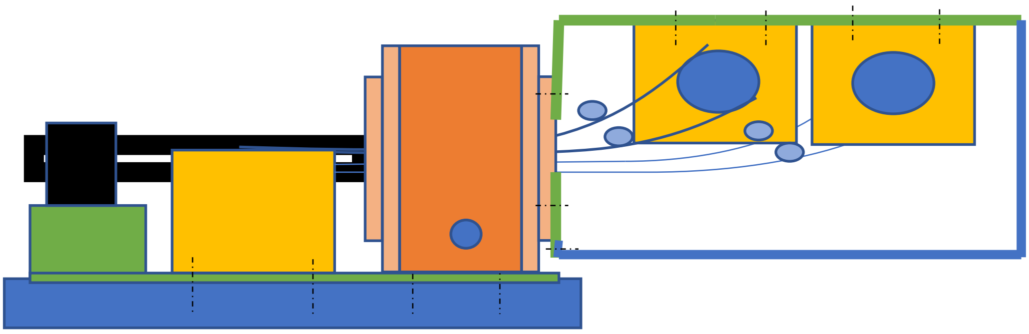

Figure 5.1. Lateral view of the preliminary design.

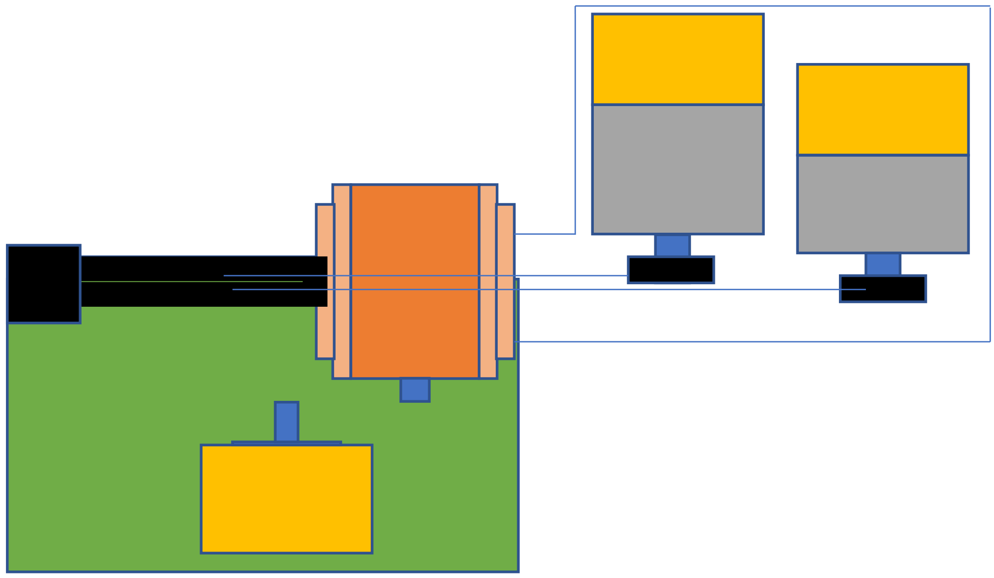

Figure 5.2. Top view of the preliminary design.

As can be seen in the figures 5.1 and 5.2, in this design the motor of the first axis is placed in a support plate in which the first joint is also fixed. The black square that is fixed to the arm is the bearing that is going to be placed in the pipe for increasing its rigidity and decrease the deflection of the arm due to the weight of the cutting tool.

In the case of the motors of the second and third axis are placed behind the gear to decrease the weight in the pipe and fixed to the rotatory part of the gear, so they can freely turn with it making the bowden cables not twisting.

The main problem with this configuration is that the motor's size is too big, more than the worm gear of the first axis, so it would be difficult to make a support for the arm because it would need lot of space behind. Considered this the final design will be with the motors fixed, as is more inconvenient for the system to have the motors turning around in the back of the system than the possible twisting in the cables that could be reduced with a correct disposition of them through the pipe. This also simplifies the problem of designing the motor cover and the placement of the drivers of the motors and allows to place everything easily in the same motor cover.

5.1.2 Static motors

As said in the last paragraph, the new design would be done fixing the motors of the cable driven joints in the back of the 3 degrees of rotation system to the same plate as the motor in the first axis. This configuration would also allow to place the motor driver also in the motor cover. Two different sketches of the placement of the different parts of the 3 degrees of rotation system can be seen in the figures 5.3 and 5.4.

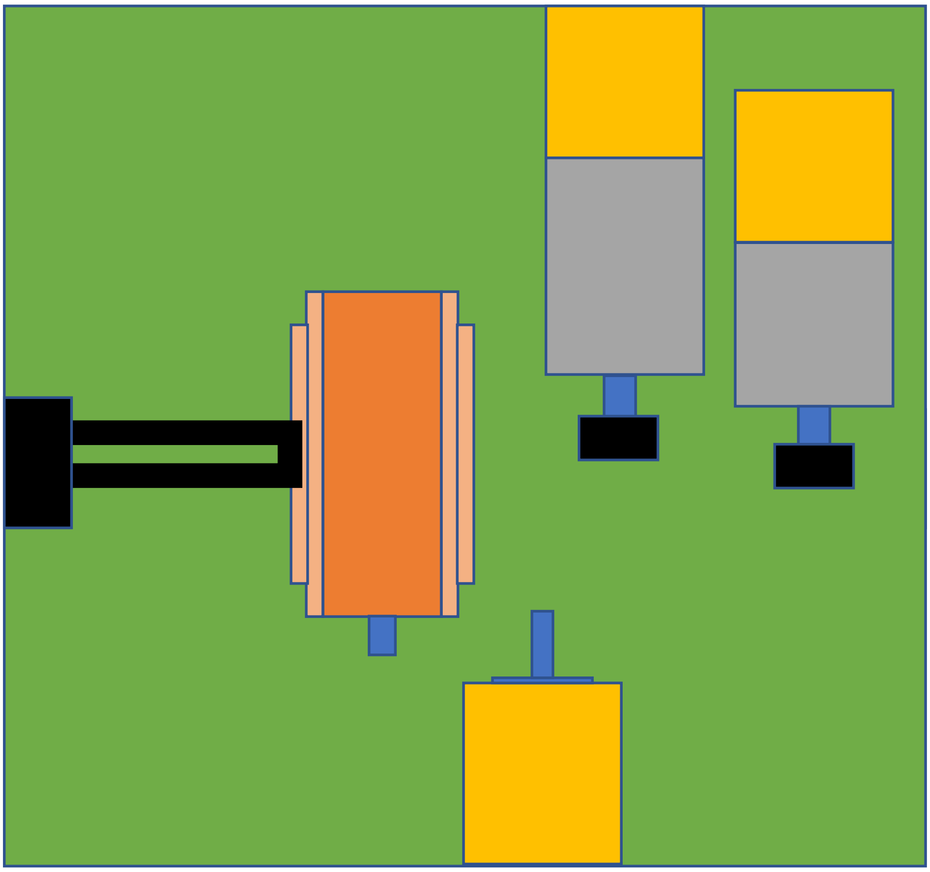

Figure 5.3. Alternative placement of the motors in the back of the worm gear.

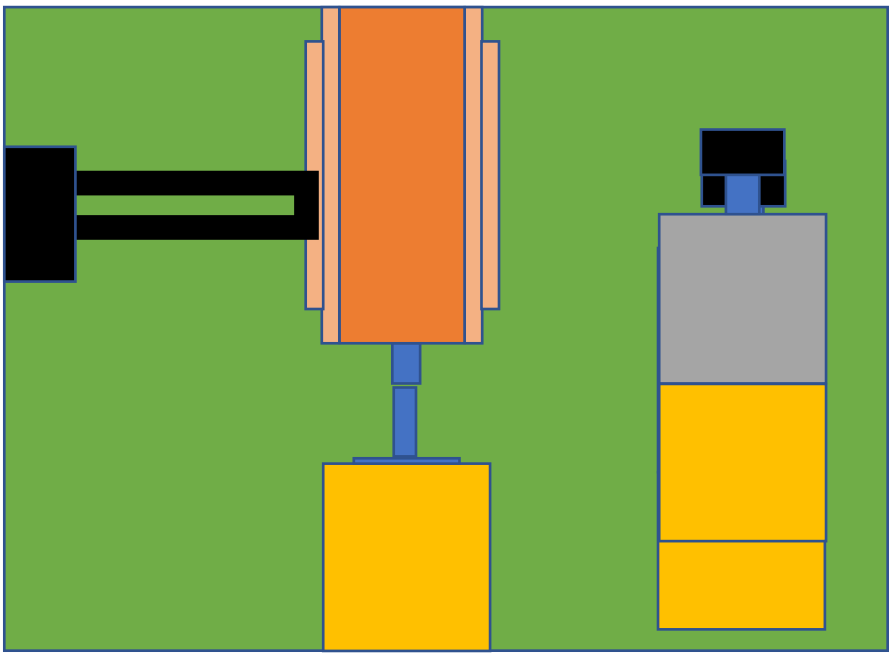

Figure 5.4. Alternative placement of the motors in vertical position.

The main problem is the force transmission in the reaction of the cables driven by the motors. That could cause a problem in the screws that are fixing the worm gear to the plate. The maximum reaction force is equal to 600 N, that is the equivalent of the maximum required torque in the second and third axis (10 Nm and 5 Nm). That's the worst-case scenario, the one in which the maximum torque is required in both axis. The force sketch applied to the worm gear is the following:

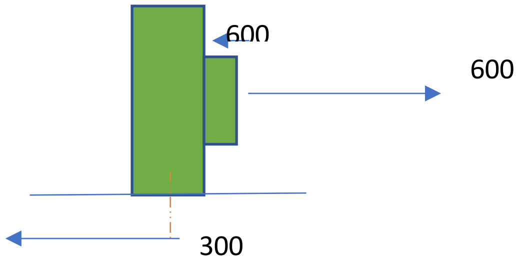

Figure 5.5. Reaction force sketch of the worm gear.

As can be seen the reaction force applied to the cables goes to the fixing plate of the worm gear and after to the gear and goes to the plate through the two screws of the worm gear, these two screws most resist a force of 300 N each. For making sure that the two screws can last the required maximum force an extra support is going to be added to the worm gear, because the two screws are small and maybe couldn't resist the forces.

5.2 Definitive design

In this chapter the definitive design and placement of the different components will be discussed and explained, the main points of this design are:

- Transmission between the first axis and the motor
- Definitive placement of the different components in the back of the worm gear
- Design and production of the parts that need to be built
- Design of the bowden cables from the motors to the cable driven joints through the pipe
- Selection of a box that gives a protection level equal to IP65 and CAD design of the whole rotation system

5.2.1 Transmission for the first axis

The transmission between the first motor and the worm gear is going to be done with a belt system. This system will have a transmission ratio of 0.6 lowering the reduction ratio of the worm gear from 50 to 33, this is needed because with a reduction ratio of 50 the axis would move too slow and that would force the motor to work in the high speed area.

$$i_{\ system} = i_{gear} * i_{pulley} = 50 * \frac{32}{48} = 33{,}33$$

Equation 5.1. Total reduction ratio of the system.

The pulley system described in the last paragraph would be fixed to an aluminum profile to allow to place the motor over the shaft of worm gear, as seen in the figure 5.4, with this placement will be more free space inside the cover, the figure 5.6 shows how is going to be.

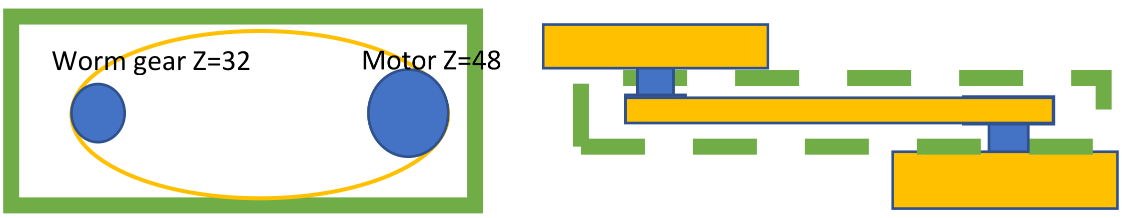

Figure 5.6. Side and top view of the transmission of the first axis.

The definitive pulleys are going to be taken from Mädler, the reduction ratio must be 1,5. The outer diameter of the pulley should be as high as possible for reducing the forces in the belt and the length of the belt should be as low as possible for occupying less space inside the housing. The requirements for the worm gear are:

- Inner diameter: 10 mm
- Outer diameter: less than 40mm
- The selected pulley is the reference 170 232 00

For the motor:

- Inner diameter: 8 mm
- The selected pulley is the reference 170 248 00

Both pulleys correspond with a profile 3M and width of 9mm, because are the smallest belt and then it will occupy less space. The selected pulleys can be seen in the figure 5.7 marked in red.

Profil 3M, Zahnriemenbreite 9 mm

Artikel-Nr. Zahnriemenbreite 9 mm	Zähne-zahl	Aus-führung	Außen-Ø Zahnscheibe mm	Außen-Ø Bordscheibe mm	d mm	ND mm	b mm	L mm	Vorbohrung B mm	Fertigbohrung B max. mm	Gewicht g
170 210 00	10	0F	8,79	13,0	9,55	12,0	10,2	17,5	-	3,5	3,6
170 212 00	12	0F	10,70	15,0	11,46	15,0	10,2	17,5	-	5,0	5,2
170 214 00	14	0F	12,61	16,0	13,37	16,0	10,2	17,5	-	6,0	6,6
170 215 00	15	0F	13,56	18,0	14,32	17,5	10,2	17,5	-	6,0	7,7
170 216 00	16	1F	14,52	18,0	15,28	10,0	12,8	20,6	4	5,5	6,6
170 218 00	18	1F	16,43	19,5	17,19	11,0	12,8	20,6	6	6,5	7,7
170 220 00	20	1F	18,34	23,0	19,10	13,0	12,8	20,6	6	8,0	10,4
170 221 00	21	1F	19,29	25,0	20,05	14,0	12,8	20,6	6	9,0	12,5
170 222 00	22	1F	20,25	25,0	21,01	14,0	12,8	20,6	6	9,0	14
170 224 00	24	1F	22,16	25,0	22,92	14,0	12,8	20,6	6	9,0	15
170 226 00	26	1F	24,07	28,0	24,83	16,0	12,8	20,6	6	10,0	18,6
170 228 00	28	1F	25,98	32,0	26,74	18,0	12,8	20,6	6	11,0	23
170 230 00	30	1F	27,89	32,0	28,65	20,0	12,8	20,6	6	12,5	27
170 232 00	32	1F	29,80	36,0	30,56	22,0	12,8	20,6	6	13,5	32
170 236 00	36	1F	33,62	38,0	34,38	26,0	13,4	22,2	6	15,0	44,2
170 240 00	40	1F	37,44	42,0	38,20	28,0	13,4	22,2	6	16,5	53
170 244 00	44	1F	41,26	48,0	42,02	33,0	13,4	22,2	6	20,0	66
170 248 00	48	2	45,08	-	45,84	33,0	13,4	22,2	8	20,0	72
170 260 00	60	2	56,54	-	57,30	33,0	13,4	22,2	8	20,0	105
170 272 00	72	2	67,99	-	68,75	33,0	13,4	22,2	8	20,0	146

Figure 5.7. Pulley's catalog from Mädler. [Mad19]

The last calculation is about the maximums force that is going to be applied to the belt. This can be done dividing the maximum torque of the motor (1.5Nm) per the radius of the pulley:

$$F = \frac{T}{r} = \frac{1.5}{0.04508/2} = 0.65 \text{ N}$$

Equation 5.2. Equation for calculating the force applied to the belt.

As the force is depreciable, the only requirements for the belt is that it must have a 3M profile, 9 mm width and for calculating the length of the belt the following equation is going to be used, the centers of the pulley will be fixed in 60 mm (C) and the diameters D and d (45.08 and 29.8):

$$L = 2 * C + 1{,}57 * (D + d) + \frac{(D + d)^2}{4 * C} = 238{,}53 \text{ mm}$$

Equation 5.3. Equation for calculating the distance between centers.

Profil HTD 3M, Zahnteilung 3 mm

Artikel-Nr. Breite 9 mm	Artikel-Nr. Breite 15 mm	Wirklänge mm	Zähne-zahl
171 105 00	171 305 00	111	37
171 108 00	171 308 00	144	48
171 110 00	171 310 00	150	50
171 112 00	171 312 00	159	53
171 114 00	171 314 00	168	56
171 116 00	171 316 00	177	59
171 118 00	171 318 00	201	67
171 120 00	171 320 00	210	70
171 121 00	171 321 00	213	71
171 122 00	171 322 00	216	72
171 124 00	171 324 00	225	75
171 127 00	171 327 00	252	84
171 128 00	171 328 00	255	85
171 130 00	171 330 00	267	89
171 132 00	171 332 00	285	95
171 133 00	171 333 00	300	100
171 134 00	171 334 00	312	104
171 135 00	171 335 00	318	106
171 137 00	171 337 00	336	112
171 138 00	171 338 00	339	113
171 140 00	171 340 00	363	121
171 142 00	171 342 00	384	128
171 143 00	171 343 00	390	130

Figure 5.8. Belts from Mädler. [Mad19]

The select belt is going to be the 171 124 00, because it is the lower and closest to the number calculated with the last equation, but there is no more on stock so the one selected will be the one smaller than that one, the 171 122 00. Now the corrected distance between the centers of the pulley can be calculated following the next equation, where D and d (45.08 and 29.8) are the diameters and L (216 mm) the length of the belt:

$$C = \frac{L-1,57*(D+d)}{4} + \sqrt{\left(\frac{L-1,57*(D+d)}{4}\right)^2 - \frac{(D-d)^2}{8}} =$$

$$= \frac{216-1,57*(45.08+29.8)}{4} + \sqrt{\left(\frac{216-1,57*(45.08+29.8)}{4}\right)^2 - \frac{(45.08-29.8)^2}{8}} = 50,4 \text{ mm}$$

Equation 5.4. Equation for calculating the distance between centers.

With these parameters the aluminum profile that is going to fasten the motor to the worm gear is going to be designed. The motor is going to be placed in a vertical position over the shaft of the gear, so there is a better use of the available space in the housing.

5.2.2 Transmission of the second and third axis

For developing the transmission for the second axis 2 bearings are needed, one for each cable that doesn’t enter straight to the pipe. The elements are going to be bought in Ingo Quirnbach, and will be the following model:

Benennung	Abmessungen/ Eigenschaften	Zeichnungs-Symbol
Aussendurchmesser Rolle	40 mm	A
Material Rolle	hochleistungs Kunststoff	-
Tragfähigkeit (Hinweis siehe Grafik rechts)	40 daN (~ 40 Kg)	-
Kugellager Ausführung	**rostfrei**	-
Kugellager Bohrung	8 mm	H
Breite der Rolle	13 mm	I
Breite inklusive Distanzscheiben	15 mm	J
Durchmesser der Distanzscheiben	12 mm	K
Seildicke für **Drahtseile** (Bitte bei Bestellung angeben)	2 mm	B
Seildicke für **Faserseile** (Bitte bei Bestellung angeben)	4 mm	B
Produktgewicht	0,03 Kg	-

Figure 5.9. Cable bearings from Ingo Quirnbach. [Ing19]

The bearing selected has the reference number 0104014, with the name 40mm Seilrolle HL Kunststoff mit Kugellager 8mm -rostfrei-. That's the selected one because it is the smallest and lightest for a 2 mm diameter cable.

5.2.3 Different elements that needs to be built

In this chapter the different pieces that were produced are going to be explained. The pieces are:

- Support profile for the motor of the first axis
- Adaptor
- Motor hub
- Bearing supporter
- Support plate
- Cable management system

5.2.3.1 Support profile for the motor of the first axis

As introduced before, the support for the first axis system is going to be made with a rectangular aluminum profile in vertical position and with different holes to fix the gear and the axis together and to give the belt the appropriate tension. The key parameters of the profile are:

- The dimensions of the rectangular aluminum profile are 25x60x95 mm with a thickness of the walls of 2 mm
- In the side of the worm gear four holes are going to be made for screwing it to the gear
- In the side of the motor, it is going to be fixed with slotted holes, because the pulleys and the belt are going to be assembled in the closest position and after the motor will be mounted in its correct position acquiring the required tension in the belt

- In both sides there is a big hole opposite to the shaft for mounting the pulleys into the shafts

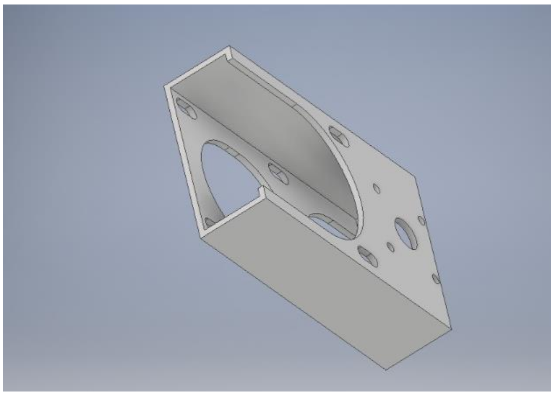

Figure 5.10. Support profile for the first axis.

5.2.3.2 Adaptor between the worm gear and the pipe

As the worm gear screws have a different orientation as the ones in the flange shaft support that fastens the pipe, is necessary to create an adaptor. The different parameters are:

- Four countersink screw to fasten the adaptor to the gear
- Four screws to fix the shaft support to the adaptor
- The inner hole of the adaptor is Ø24, a less than the pipe diameter, so the reaction forces of the second joint goes to the adaptor. This allows a better distribution of the forces in the gear solving the problem of the forces that were mentioned in the last paragraph
- The dimensions are Ø70x6mm

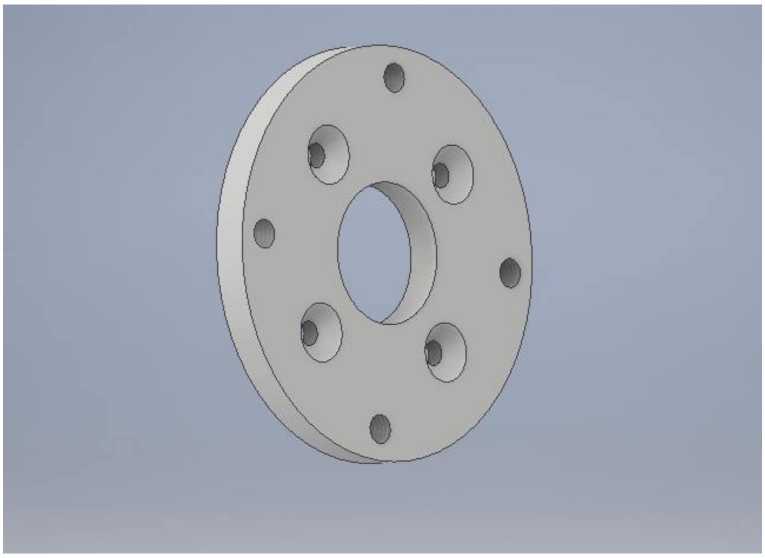

Figure 5.11. Adaptor.

5.2.3.3 Motor hub

For connecting the motors of the cable driven joint to the gear another piece is going to be designed. The parameters of this piece are:

- An L aluminum profile, with the following dimensions: 120x80x3 with a length of 150 mm
- In one of the sides there is going to be 5 different holes for screwing the plate to the gear with a bigger hole for putting the bowden cables through and aligned with the cable bearings and the pulleys
- In the long side there is two holes to fix the cable bearing with an M8 screw and the holes for allocating the motors in the correct position
- An extra metal beam is going to be added to increase the rigidity of the hub, because after building it the hub was bending due to the weight of the motors

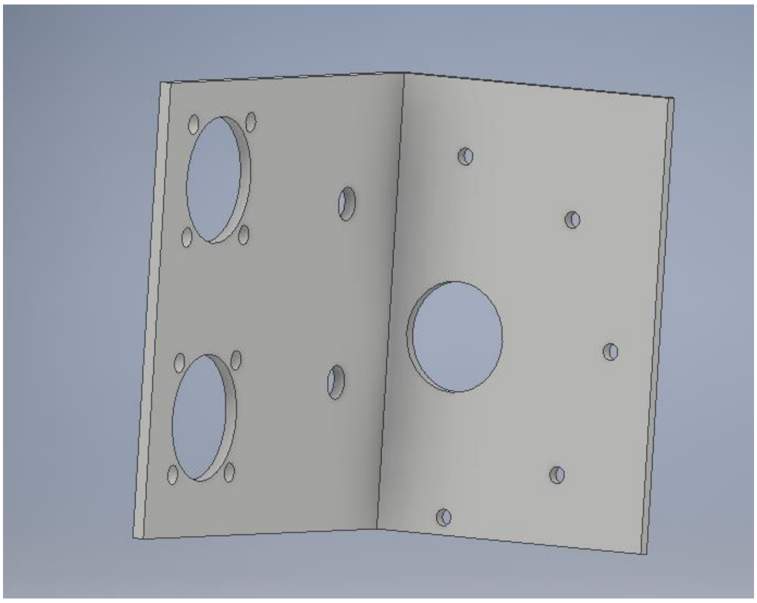

Figure 5.12. Motor hub.

5.2.3.4 Bearing supporter

For placing the bearing in the correct position, a plastic piece is going to be 3D printed. This piece is going to be fixed to the support plate that will be described below and will fasten the bearing in the middle of the pipe.

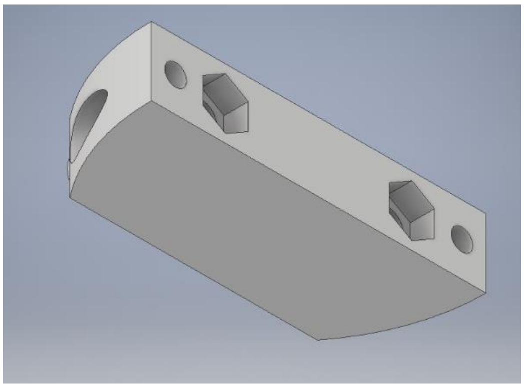

Figure 5.13. Bearing supporter.

5.2.3.5 Support plate

A support plate is going to be made for screwing all the elements to it. The dimensions of the plate are 320x125x4 mm.

The different parts are going to be screwed:

- The worm gear will have countersink screws and is going to be screwed from the bottom of the plate with M3 screws.
- The support piece for the bearing and the cable management system are going to be screwed from the top using screws.

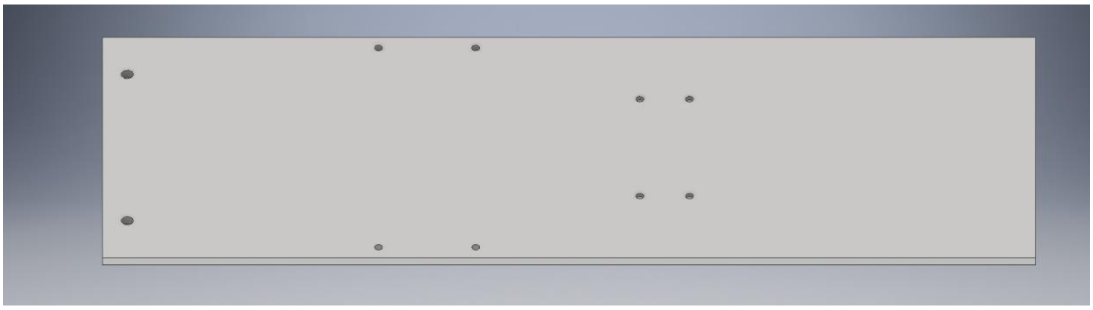

Figure 5.14. Support plate.

5.2.3.6 Cable management system

The cable management system has been developed by Sebastian Schröder and it has the following characteristics:

- It consists in two different pieces that allows the turning of the connection cables of the cutting tool through a flexible pipe
- The total dimensions are: 120x125x125mm

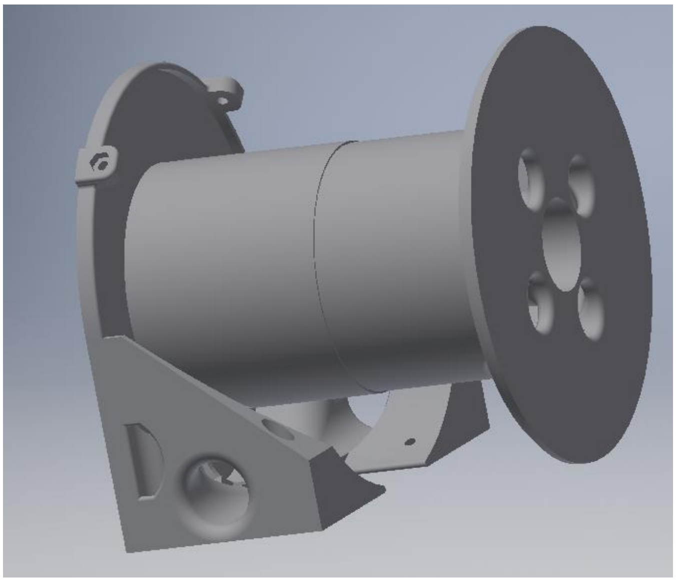

Figure 5.15. Cable management system.

5.2.4 Design of the pipe and the disposition of the bowden cables

The main issue in the designing of the pipe is to have enough space in the middle of the pipe for getting all the connection cables through it. Also, the separation of the bowden cables must be enough for reducing the friction between them. The design can be seen in the figure 5.16.

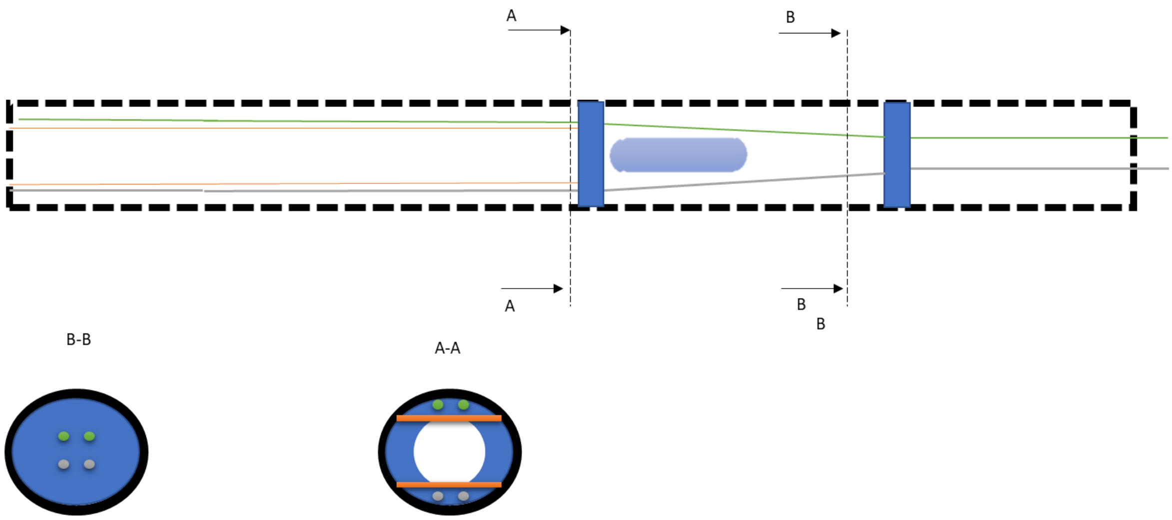

Figure 5.16. Disposition of the motion cables through the pipe.

For making the connection wires do not interfere with the bowden cables a plastic separator has been added, is the orange part that can be seen in the figure 5.16. The bowden cables enter the pipe divide by axis, the ones that goes for the second axis goes up (green in the figure) and the ones of the third axis goes down (gray in the figure). There is two different separators in the pipe the A-A and the B-B, the figure 5.17 shows the separators IGUS and how are they positioned in the pipe. The separator A-A is placed just after the hole for putting the connection wires through, so there is no interference between them.

Figure 5.17. IGUS separator and placement in the pipe. [Igu19]

5.2.5 Motor cover and CAD assembly

The main functions of the motor cover are to support all the elements and give a level of protection equal to IP65. For that reason, an electrical box is going to be bought with that level of protection and the components will be placed there. A simple sketch of the final disposition for all the different components can be seen below:

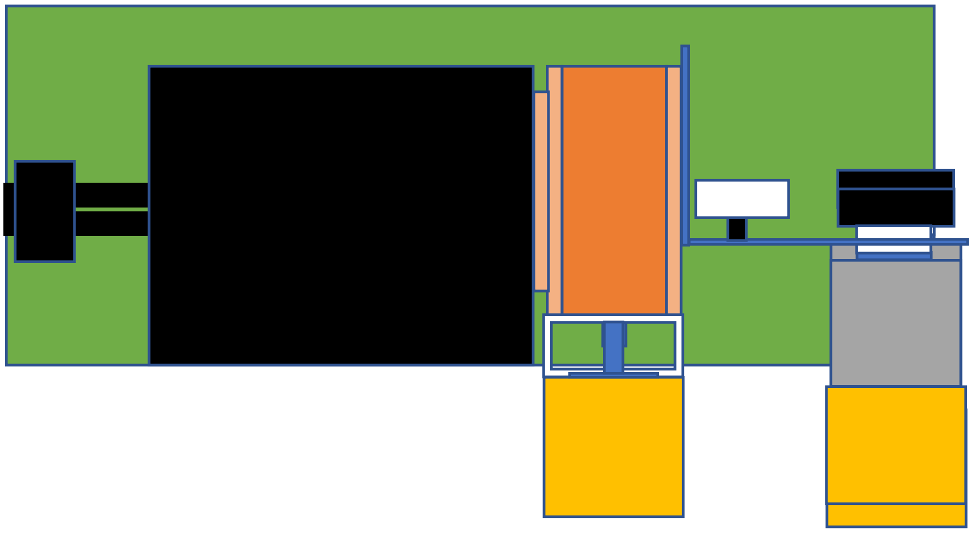

Figure 5.18. Final placement of the components in the box.

The components are:

- Yellow and grey are the motors and gearboxes
- The black box in the front of the gear is the cable management mechanism
- The other components are the pipe, the support plate and the cable bearings

The box is going to be selected from the ones that Conrad Electronic SE has available in the catalog. The minimum dimensions of the box for fitting all the components without the motor drivers inside, are:

- Height: 140 mm
- Length: 365 mm
- Wide: 215 mm

The selected box is Bopla EUROMAS T 260 Universal enclosure 400 x 360 x 150 [Con19], with the following characteristics:

Material	Acrylonitrile butadiene styrene
IP rating	IP66
Colour	Light grey
Length	400 mm
Width	360 mm
Height	150 mm
Content	1 pc(s)
RoHS-compliant	Yes
Type	EUROMAS T 260
Material (details)	ABS

Figure 5.19. Characteristics of the box. [Con19]

This box is bigger than the minimum required for placing correctly the motor drivers and for having enough space for assembling it easier. For keeping the level of protection equal to IP65, once the hole for the pipe has been done a seal ring is going to be added. The figure 5.20 shows the hole system assembled in the box with all the components except the motor drivers to prove that it fits in the selected box:

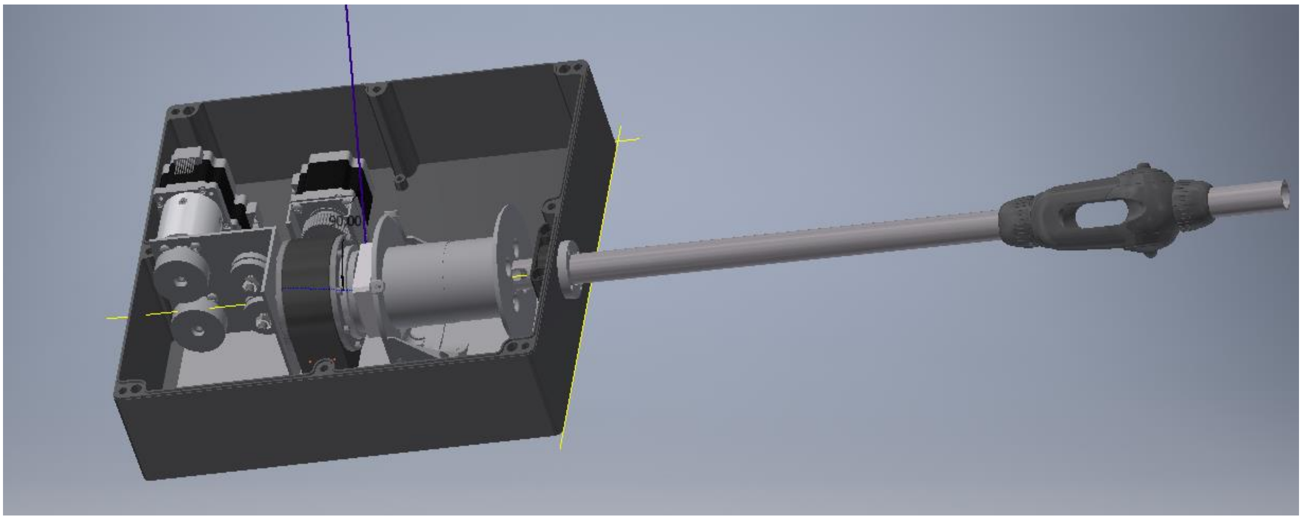

Figure 5.20. Parts assembled in the box.

5.3 Final assembly

Once all the parts have been produced the 3 degrees of rotation system has been assembled all together as it has been described during the last chapters. The only difference from the CAD assembly of the figure 5.20 is that an extra beam has been added to the motor hub of the motors of the cable-driven joints, because it was bending due to its own high weight. The final assembly can be seen in the figures 5.21.

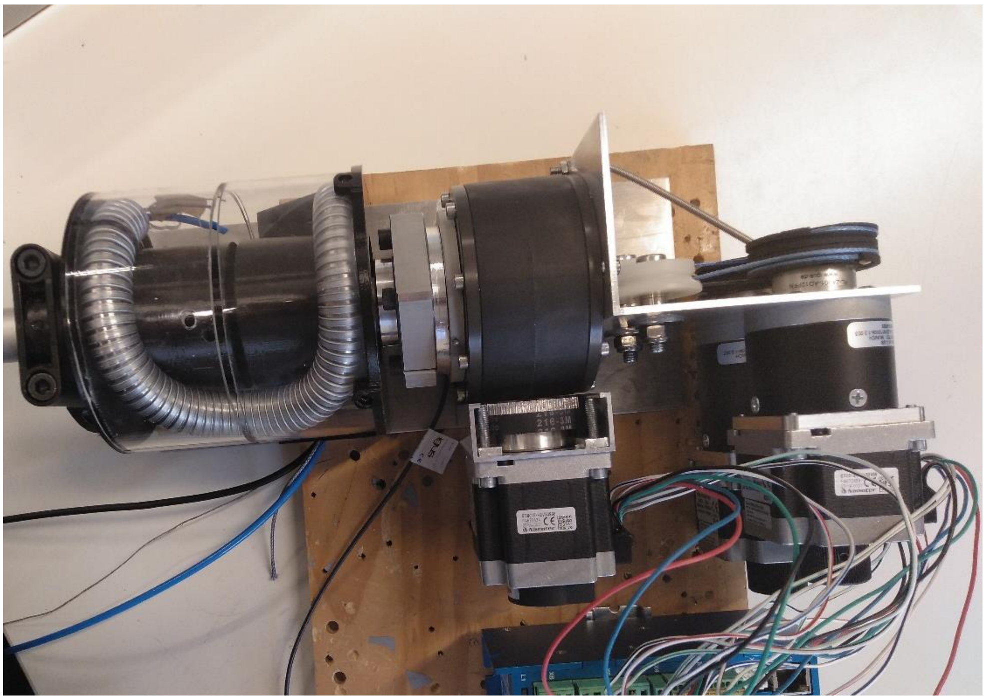

Figure 5.21. Machine system assembled, upper view.

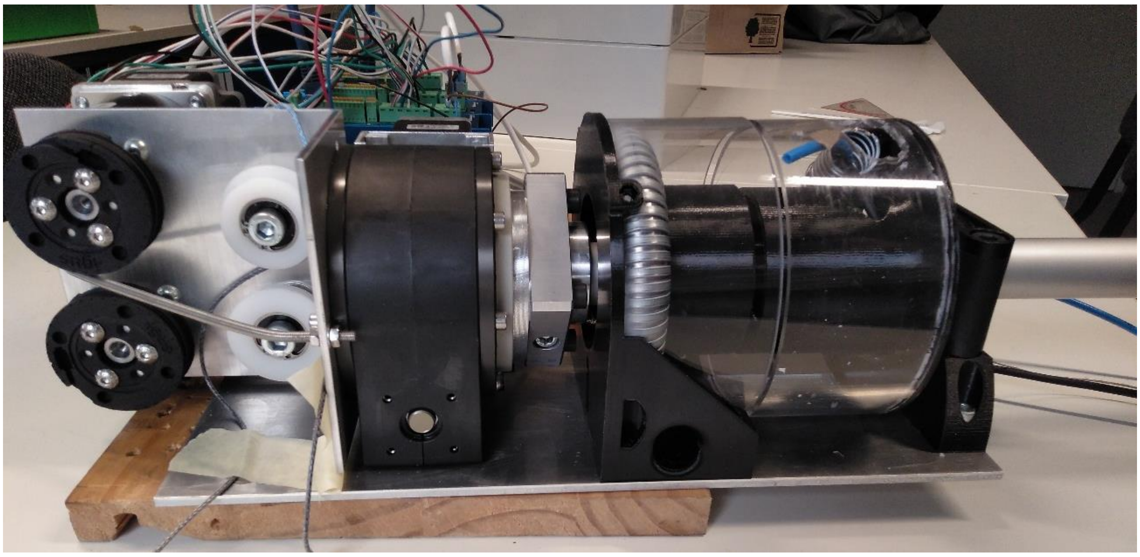

Figure 5.22. Machine system assembled, side view.

In the requirement list it was said that the assembly of all the components should be easy, but in the reality, it was quite hard to fit all the component inside the machine system, due to the reduced space of itself. Also, for assembly the system in the housing the pipe and the bowden cables has to be removed and added again once the motors and the other parts are placed.

6 Testing against the requirement list

In these chapter there is going to be a testing against the requirement list. The explanation of each test is going to be explained in each chapter. For making the testing easier the arm has not been put in the box.

6.1 Final degrees of rotation of each joint

This data is going to be taken from the data sheet of each joint. The 1º axis is limited to 360º, but it could turn more. In the table 6.1 the values for each axis can be seen, all of them fulfilled the degrees of rotation requirement.

Axis	Degrees(º)
1º	360º (±180º)
2º	180º (+130º/-50º)
3º	340º(±170º)

Table 6.1. Degrees of rotation of each axis.

6.2 Final weight of the system

The weight of the system has been measured in a normal weight scale giving a value of 7 Kg, this doesn't fulfill the weight requirement, which was 6 Kg maximum.

6.3 Distance from the robot base to the turning point of the tool

This distance is the distance from the end of the housing until the turning point of the second axis. The final distance is 350 mm, which fulfill the requirement.

6.4 Deflection of the pipe

For checking the deflection of the pipe first the distance between the second joint and the ground is going to be measured, after a load of 10 N is going to be fixed and then the distance measured again. The deflection is the difference between the two values.

The table with the values can be seen below:

Distance without load (mm)	Distance with load (mm)	Deflection (mm)
95	91	4

Table 6.2. Values of the deflection of the pipe.

The maximum deflection is 5 mm, so it fulfill the minimum requirement.

6.5 Waterproofness of the box

The housing has a level of protection IP66, so it fulfills the requirement of being waterproof.

6.6 Final budget consumed in the project

The final budget that the project has used can be seen in the following table divided in different parts. The final budget is less than 2000 + taxes, so the requirement is fulfilled.

Bills	Price before taxes (€)
IGUS	1085
Nanotec	498
Mädler	34,7
Ingo Quirnbach	56,88
Gemmel Metalle	25

Conrad	137,49
Total	1837

Table 6.3. Simplified budget.

6.7 Traction test to the bowden cables

There was not a requirement for the load that the cables can last but is important to know where the limit is. For that reason, a traction test was carried out to the cables with the end part glued, which should be the weakest part of the mechanism.

First a load of 500 N was applied for one day. Then more load was applied until it broke at 1400 N, more than the maximum traction load that is going to be applied in any of the axis

6.8 Requirements that couldn't be tested

Some of the requirements couldn't be tested for different reasons. In each paragraph it gets explained

6.8.1 Maximum output torque in each joint

This requirement couldn't be tested, because by the time that this thesis is finished the program that controls the movement is not done, so it can't be proved that the motors can reach the level of torque that is required.

6.8.2 Speed of the motors and acceleration

As in the paragraph 6.8.1 for testing the real speed of the motors the program is needed, as it is still undone by the time this thesis is handled this requirement couldn't be tested.

6.8.3 Deflection of each joint under a torque

In this case the deflection couldn't be measured because there was no way to feed the motors so there was no possible to apply a constant load in each axis. Once the program is done and the motors feed it could be tested.

6.8.4 Durability of the mechanism

This requirement is not going to be tested because making a life cycle test requires more time than the one available for making this master thesis.

6.9 Summary

6.9.1 Requirements that are fulfilled

The table 6.4 shows the requirements that are fulfilled and its values.

Requirement	Value
The joint system should have enough space for putting the connection cables through the arms of the system	OK
Maximum deflection of the last arm with a 10 N force: 5mm	4 mm
Maximum distance from tool turning point to robot base: 500mm	350 mm
All axis of rotation must merge in one point	OK
The system must have 3 degrees of freedom	OK
Minimum degree of rotation of each axis 1º axis: 120º 2º axis: 100º 3º axis: 190º	 360º 180º 340º
Joints must be from IGUS	OK

Joints and motors must be waterproof and isolated from dust and rests of plants	OK
Maximum price: 2000€+taxes	1850€ + taxes
The system should have a feedback of the position of the angles of each joint	OK
Asymmetric movement angle of some of the joints	OK
Use Stepper Motors	OK

Table 6.4. Fulfilled requirements.

6.9.2 Requirements that are not fulfilled

The table 6.5 shows the requirements that are fulfilled and its values.

Requirement	Value
Maximum weight of the hole system: 6 Kg	7 Kg
Easy mounting process	NO

Table 6.5. Requirements that are not fulfilled.

7 Conclusions and further work

The aim of this work is the development, construction and testing of a 3 axis of rotation system of the robot that takes care of the automatic maintenance of vertical gardens in the walls of the buildings. The concept and development of the robot is not yet complete, but the system, that has been created, is independent of the type of robot that carries it.

For the development of the machine system a requirement list has been created and, in base of it, the machine system has been developed. To fit with the requirement of having 3 axis of rotation, several joints from the manufacturer IGUS has been chosen, an important remark is that the joint that is not in the base of the robot is cable-driven joint, which works by the use of bowden cables, the goal of using this kind of transmission is that it allows to decrease the weight in the pipe itself making it easier to be carried and lowering the reaction forces in the pipe.

In order to make each joint move some motors have been bought from Nanotec and for fitting the requirements of speed and torque in each joints a reduction system was made with gearboxes. Once the power system and the joints were selected, different designs have been discussed and, then, the most suitable one selected. For this design some side parts were produced by 3D printing the plastic parts and by CNC the metal ones.

Once all the parts of the prototype have been discussed and the assembly is done, there is the need to test it against the requirement list, For this testing only some general requirements could be tested, as the weight of the system, the final dimensions or the degrees of rotation of each axis. The other requirements couldn't be tested by the time this thesis is handled because the program that controls the movement of each joint is not developed yet, so the operational requirements, such as the final output torque and speed of the motors couldn't be tested.

The further work that this project needs for being complete is the program that controls the movement of each joint and motor needs to be finished and, once this happens, a proper testing against the requirements of the system needs to be done to check that it fulfills the requirements of the system.

In a further view once the robot is complete, the machine system, that has been developed, should be placed in it and an extensive testing under field conditions with the cutting tool should be carried out.

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Annexes

Annex 1. Characteristics different combinations of joints

1 RL-90-BL-1+ RL-50-TL2

RL-90-BL-1	Dimensions (mm)	l1	217
		dK	120
		dT	40
		dP	120
	Rotation angles	1º Axis (rotation)	+/-90º
		2º Axis (inclination)	+/-90º
	Weight (g)		1250
	Maximum torque	1º Axis (rotation)	10
		2º Axis (bending)	20
	Price (€)		998
RL-50-TL2	Dimensions (mm)	l1	125
		dK	76
		dT1	26
	Rotation angle		+/-170º
	Weight (g)		245
	Maximum torque (Nm)	Rotation	5
	Price (€)		350
Total	Dimensions (mm)	longitude (without arms)	342
		maximum dK	120
	Weight (g)		1495
	Price (€)		1348

2 RL-50-TL1+RL-50-002

RL-50-TL1	Dimensions (mm)	l1	125
		dK	76
		dT1	26
	Rotation angle		+/-170º
	Weight (g)		245
	Maximum torque (Nm)		5
	Price (€)		350
RL-50-002	Dimensions (mm)	l1	200
		dK	76
		dT	40
	Rotation angles	1º Axis (inclination)	+130/-50
		1º Axis (rotation)	+/-170º
	Weight (g)		345
	Maximum torque	1º Axis (bending)	12
		2º Axis (rotation)	5
	Price (€)		495
Total	Dimensions (mm)	longitude (without arms)	325
		maximum dK	76
	Weight (g)		590
	Price (€)		845

3 Characteristics worm joints by IGUS

RL-D-20-101-	Gewicht / *Weight* [gr]	Wirkungsgrad / *efficiency *)* η	Bruchmoment/ *breaking torque* **Statisch / *static***	Max. Abtr. Moment/ *Max. output torque* Dynamisch / dynamic at 12 rpm Periodic duty (<30%) **)	permanent duty***)
38-01000 (1:38)	**410**	**0,40**	**30 Nm**	**10 Nm**	**5 Nm**
38-01033 (1:38)	**610**	**0,45**		**10 Nm**	**5 Nm**
70-01000 (1:70)	**410**	**0,30**	**20 Nm**	**5 Nm**	**2,5 Nm** (9 rpm)
70-01033 (1:70)	**610**	**0,35**		**5 Nm**	**2,5 Nm** (9 rpm)

RL-D-30-101-	Gewicht / *Weight* [gr]	Wirkungsgrad / *efficiency *)* η	Bruchmoment/ *breaking torque* **Statisch / *static***	Max. Abtr. Moment/ *Max. output torque* Dynamisch / dynamic at 9 rpm Periodic duty (<30%) **)	permanent duty***)
5-01000 (1:5)	**790**	**0,55**	**40 Nm**	**10 Nm**	**5 Nm**
5-01033 (1:5)	**1.180**	**0,65**		**10 Nm**	**5 Nm**
30-01000 (1:30)	**790**	**0,40**	**80 Nm**	**20 Nm**	**10 Nm**
30-01033 (1:30)	**1.180**	**0,45**		**20 Nm**	**10 Nm**
50-01000 (1:50)	**790**	**0,35**	**60 Nm**	**20 Nm**	**10 Nm**
50-01033 (1:50)	**1.180**	**0,40**		**20 Nm**	**10 Nm**
70-01000 (1:70)	**790**	**0,25**	**30 Nm**	**12 Nm**	**7,5 Nm** (6 rpm)
70-01033 (1:70)	**1.180**	**0,30**		**12 Nm**	**7,5 Nm** (6 rpm)

RL-D-50-101-	Gewicht / *Weight* [gr]	Wirkungsgrad / *efficiency *)* η	Bruchmoment/ *breaking torque* **Statisch / *static***	Max. Abtr. Moment/ *Max. output torque* Dynamisch / dynamic at 6 rpm Periodic duty (<30%) **)	permanent duty***)
48-01000 (1:48)	**2.050**	**0,35**	**180 Nm**	**50 Nm**	**25 Nm**
48-01033 (1:48)	**3.050**	**0,40**		**50 Nm**	**25 Nm**
70-01000 (1:70)	**2.050**	**0,25**	**140 Nm**	**40 Nm**	**20 Nm**
70-01033 (1:70)	**3.050**	**0,30**		**40 Nm**	**20 Nm**

***) mittlerer Wirkungsgrad bei 3Nm Abtriebslast** / *average efficiency measured at output torque 3Nm*

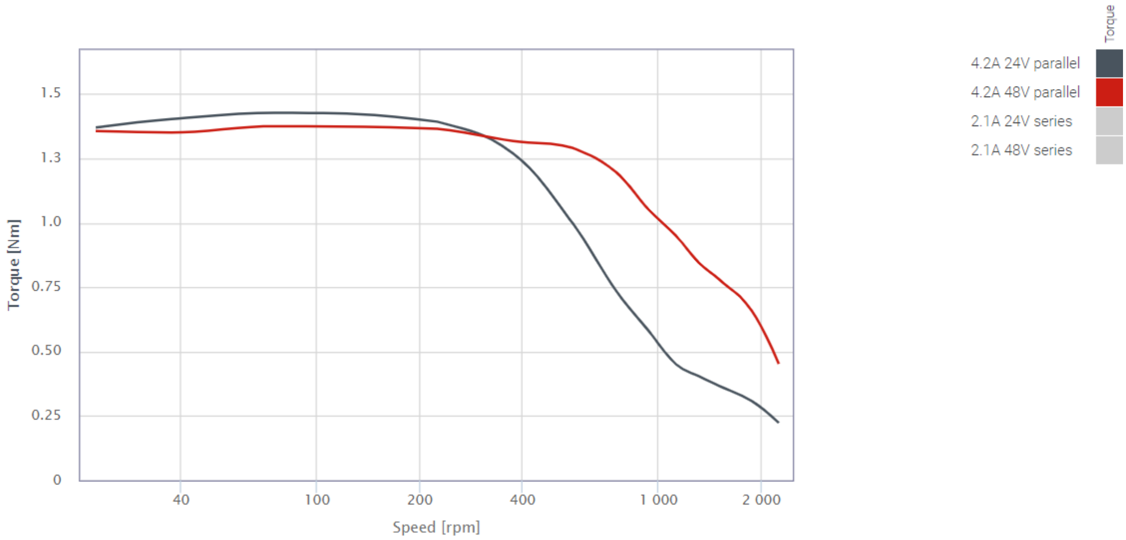
****) max. zulässiges Abtriebsmoment bei Aussetzbetrieb mit ED <30% (Robotik) /** *max. perm. output torque in periodic duty with duty time <30% (i.e. robotic applications)*

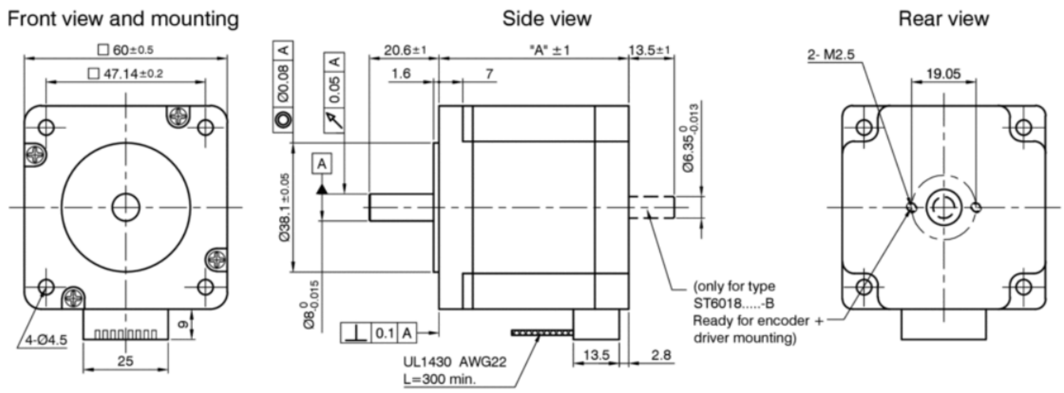
*****) max. zulässiges Abtriebsmoment im Dauerbetrieb /** *max. perm. output torque in permanent duty* (**tested at >1.000.000 cycles**)

Annex 2. Characteristics of the different motors and gearboxes considered

1 Motor NEMA 24-ST6018M3008-A

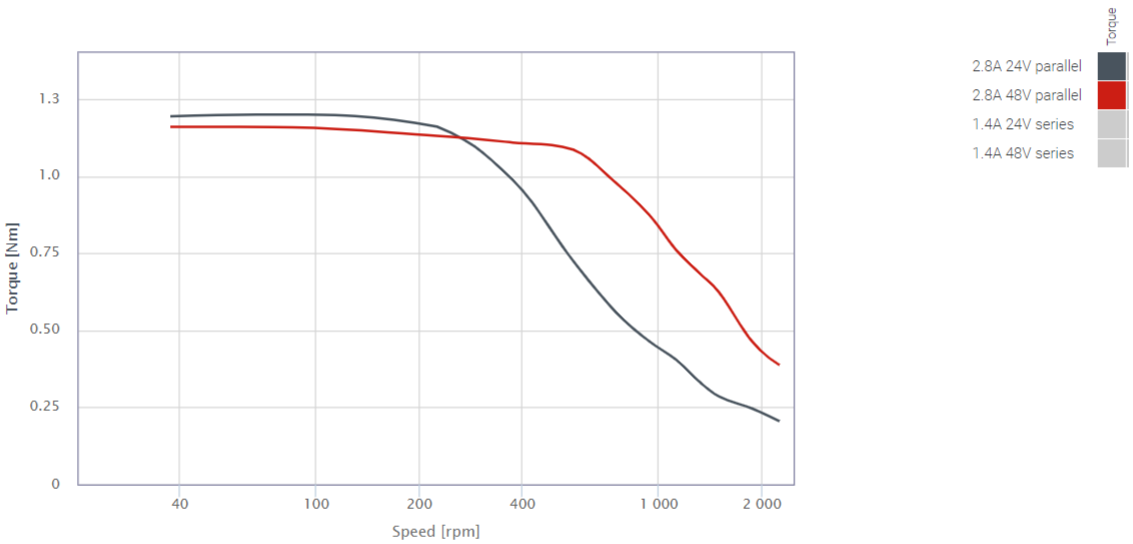
NEMA	24	Size	60 mm
Current per Winding	3 A	Holding Torque Unipolar	117 Ncm
Holding Torque Bipolar	165.46 Ncm	Rotor Inertia	400 gcm²
Resistance per Winding	0.8 Ohm	Inductance per Winding	1.38 mH
Resolution	1.8 °/step	Length "A"	56 mm
Weight	0.77 kg	Shaft Modification	✔

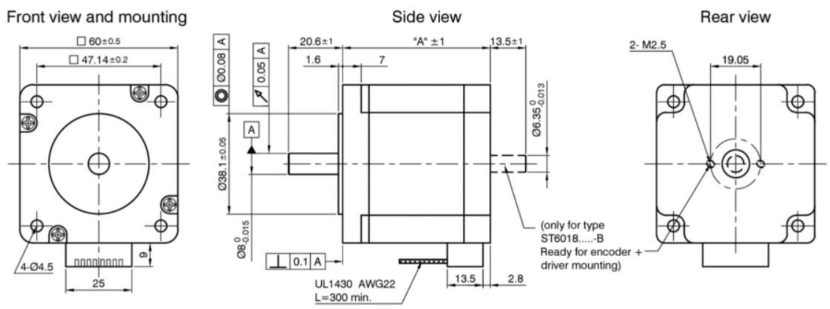




2 Motor NEMA 24- ST6018X2008-A

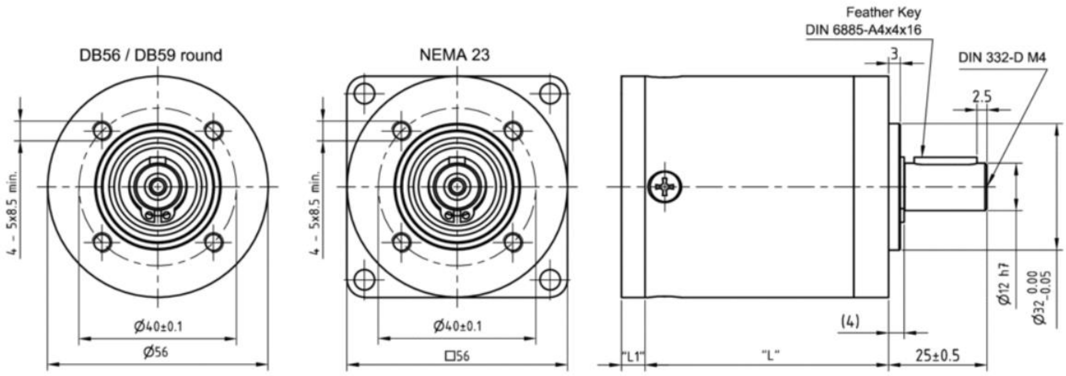
NEMA	24	Size	60 mm
Current per Winding	1.41 A	Holding Torque Unipolar	75 Ncm
Holding Torque Bipolar	106.07 Ncm	Rotor Inertia	275 gcm²
Resistance per Winding	1.7 Ohm	Inductance per Winding	2.2 mH
Resolution	1.8 °/step	Length "A"	47 mm
Weight	0.6 kg	Shaft Modification	✔





3 Gearbox GP56-S2-11-SR

For Motor Size	NEMA 23, NEMA 24	Type	Standard Bearing
Efficiency	89 %	Max. Backlash	31 ´(arc minutes)
Rated Output Torque	19.2 Nm	Max. Output Torque	32.9 Nm
Reduction Ratio	11	Max. Input Speed	4658 rpm
Moment of Inertia	8.4 kg mm²	Service Life	10000
Operating Temperature	-15 °C - 90 °C	Length "L"	61.8 mm
Flange Length L1	6 mm	Weight	0.8 kg
Admissible Axial Shaft Load	1302 N	Admissible Radial Shaft Load	516 N
IP Protection (Except Shaft Output)	IP54		



4 Gearbox GP56-S1-7-SR

For Motor Size	NEMA 23, NEMA 24	**Type**	Standard Bearing
Efficiency	92 %	**Max. Backlash**	34 ´(arc minutes)
Rated Output Torque	12.1 Nm	**Max. Output Torque**	26.1 Nm
Reduction Ratio	7	**Max. Input Speed**	8988 rpm
Moment of Inertia	3.7 kg mm²	**Service Life**	10000
Operating Temperature	-15 °C - 90 °C	**Length "L"**	44.6 mm
Flange Length L1	6 mm	**Weight**	0.58 kg
Admissible Axial Shaft Load	1302 N	**Admissible Radial Shaft Load**	516 N
IP Protection (Except Shaft Output)	IP54