

École polytechnique de Louvain

Design of a Delta robot for Pedagogical Purpose

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Abstract

The goal of this master thesis is to design of a Delta robot that will be used for pedagogical purpose. The robot will be used during the "Printemps des Sciences" to showcase to a young audience the capabilities of the Delta robots. The robot must be able to perform original and fun tasks by showing all its capabilities.

This draft is the result of the first iteration of this master's thesis subject. The emphasis is placed on precise dimensioning and design of the mechanical parts. The ultimate aim of this iteration is to provide a working basis so that future students working on the robot can implement numerous tasks.

The Delta robot is modelled thoroughly to predict its geometric, kinematic, elastic and dynamic behavior. From these models and performance indices the kinematic parameters of the Delta robot are obtained for the prescribed workspace. A second stage dimensional synthesis, based on elastic deflection and required torques, yields the link dimensions.

The detail design of the whole robot is discussed. The motors has been chosen first. The whole electronic system is then designed around the motor. The mechanical parts are then designed from the dimensioning and validated through FEM simulations.

The assembly and the programming of the robot is presented. The code used an inverse kinematic model to computes the angles of the motor based on the trajectory and motion laws. A circle, a pick and place and a Helix trajectories have been tested. An IMU has been fixed to the end effector to record the acceleration. A 3D printed mouthpiece has been made to draw on a paper the result for the circle and the pick and place. A maximum acceleration and speed of $11,245[g]$ and $5[m/s]$ have been recorded with the helix trajectory. The circle trajectory the problem with the PWM and draw a perfect circle with a radius of $0,145[m]$ and not $0,15[m]$ due to the fact that the angle value have rounded. The pick and place has shown $2[mm]$ of repeatability in the direction of the movement and the $1[mm]$ in the direction perpendicular to the movement.

The thesis successfully presents an educational Delta robot, combining meticulous design, electronic integration, and programming for captivating demonstrations.

Acknowledgement

Ce mémoire n'aurait pas pu être réalisé sans l'aide de personne clé que nous aimerions par la présente page remercier.

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Introduction

Ever since the industrial revolution, mankind has been constantly looking for ways to optimise production. Over the last century, the development of robots for industrial use has exploded. They have been the main driving force behind the development of the industrial sector and many engineers have taken an interest in them. Robotics engineers set out to find and optimise different kinematic structures in order to find the robot that would revolutionise industry. Clavel was one of them when, in 1985, he developed the Delta robot at EPFL. This robot was one of the first to use the advantages of a parallel kinematic structure. In fact, thanks to its multiple kinematic chains, the Delta robot can achieve high levels of acceleration while remaining extremely precise. Since its creation, both in industry and academia, the Delta robot has never ceased to attract interest.

The Delta robot is characterised by its 3 kinematic chains linking the end effector to the base has been studied from every angle. The kinematic beauty behind the delta robot relies on the fact that from 3 actuator joints in rotation, the end-effector has 3 degrees of freedom in translation in X-Y-Z. This is due to the parallelogram linking the distal arms and the connecting link to the end-effector, which blocks all rotation of the end-effector. Many people have been inspired by these features to create their own version of the Delta robot. Nowadays, we can find linearly actuated delta robots, with 4 arms to add a degree of freedom in rotation etc...

The delta robot has been a subject of research at many universities, and many have developed their own. Now it's UCLouvain's turn to get its own Delta robot. This robot has been designed for educational purposes and to demonstrate the possibilities offered by robotics and parallel structures to a young audience. In fact, it has been commissioned to carry out demonstrations during the Printemps des Sciences organized annually by Sciences.be throughout the Fédération Wallonie-Bruxelles. The robot's qualities are to be demonstrated in a playful and original way.

This master's thesis is the result of the first iteration of the Delta robot developed at the EPL. The aim is to provide a solid base on which future theses can be built

to implement numerous tasks in the future. We made a detailed study of all the robot's kinematic chains and dimensioned carefully. The design has been thought out to ensure that future work can be carried out in a simple and efficient way.

In the course of this thesis, we will first give a history of the Delta robot. Next, the specifications will be presented as well as the reference trajectories that were used to design the Delta Robot.

After that, the kinematics of the Delta robot will be discussed through its inverse and direct kinematics, as well as its velocity kinematics. In the same chapter, an elastic model is implemented with the matrix structural analysis method to study elastic deflection. Followed by a multi-body dynamic model for force and torque computation. An elastic dynamic model is also presented.

Based on velocity kinematics, the singularities of the Delta robot are discussed. Then, several performance indices are shown and used to synthesise the kinematic parameters of the Delta robot.

Following this first stage design, the dimensions of the links are computed in a second stage design. The elastic and dynamic model are used to limit the elastic deflection of the robot and its actuator torques.

The detail design will then be carried out, and the choice of motors and electronics will be presented. The design of the mechanical parts will also be presented and validated using finite element simulation. The manufacture of the robot will be dealt with in turn. The robot will be validated with the 3 reference trajectories. We will finish by discussing improvements and future developments.

Chapter 1

State of the art

It has been 38 years since the robot was developed by Clavel as part of his thesis at the Ecole Polytechnique Federal de Lausanne. The development of his robot was part of the wave of interest in parallel robots in the 1980s. However, it should be noted that traces of the study of parallel structures and their kinematics can be found well before that. The Gough-Stewart platform was one of the first parallel structures to be developed and built. This platform demonstrated the usefulness of parallel robots and the qualities inherent in their particular kinematic structure, which inspired many roboticists, including Clavel. The Delta robot quickly attracted the interest of industry and was developed extensively in a wide range of fields, from food to electronics and even medical applications. The interest in this robot was not limited to industry. It has been studied in many universities around the world. Many structures have been built based on the Delta robot.

1.1 Parallel Robots

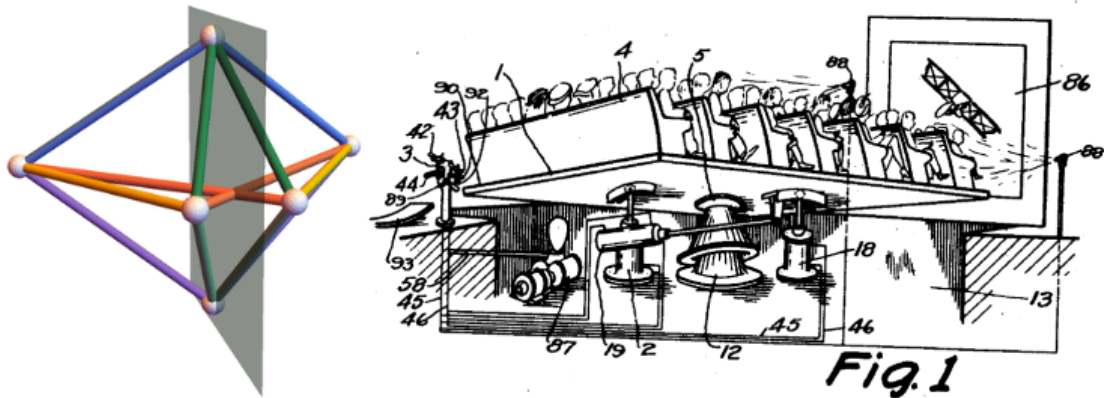
In the industrial robotics field numerous mechanical systems were created. These systems group the robot that allow an end effector piece along a fixed base. The industrial robots can be separated in two categories based on their topology: serial and parallel. Indeed, a robotic system can be categorised through its number of kinematic chains. These are sequences of links and joints that begin at the base and end at the end effector. Serial robots such as the Puma and the Scara robot are composed of only one serial chain. Their workspace, i.e the space in which the robot can operate, depends only on their kinematic chain and more precisely on the types of joints, their range of movement and the lengths of the links connecting them.

A robot is considered parallel when it has two or more serial chain. The workspace of these robot are given by the intersection of the workspace of each individual

chain [1]. In robotics, such structures were introduced to improve the accuracy and the speed of the robot. The parallel structure provides the possibility to use very lightweight part as the load will be distributed on the different kinematic chains. The use of multiple serial chains offers a much higher stiffness and the deformation due to passive compliance (i.e the deformation in the link and the backlash in the actuator due to the external forces) can be counterbalanced by the motors[2].

1.1.1 First trace of parallel structures

Interestingly, has pointed out by Merlet in [2], the problem of parallel geometry has been mentioned theoretically since 1645 by Christofer Wren. In 1813, Cauchy studied the convex polyhedron and develop the Cauchy's rigidity theorem stating that it is impossible to have deformable convex polyhedron[3]. Bricard studied then the deformability of concave octahedron (Fig.1.1a) [4]. He proved that there are polyhedrons whose shape changes without changing the lengths of its sides or the shape of its faces. Those were the first steps into the study of parallel structures.



(a) Bricard octahedron[5]

(b) Oxymoron[6]

Figure 1.1: The Bricard octahedron can be found in (a). Bricard show through this structure that concave polyhedron can be deformable. This mathematical paper has been one of the first trace of the study the parallel structure. The oxymoron is illustrated in the figure (b). The goal of this parallel structure designed by Gwinnet is to make the whole movie theater moving. Unfortunately, this was to ahead of its time and was never build.

The first evidence of the application of such parallel mechanisms dates back to 1931 when Gwinnet has designed the Oxymoron [6]. The Oxymoron (Fig.1.1b) is

a platform that tilts an entire movie theater depending on the movie to increase immersion. This parallel structure has never been built due to the complexity of setting it up at the time. The first parallel robot ever built and used in industry was a spray painting machine(Fig.1.2) designed by Pollard[7].

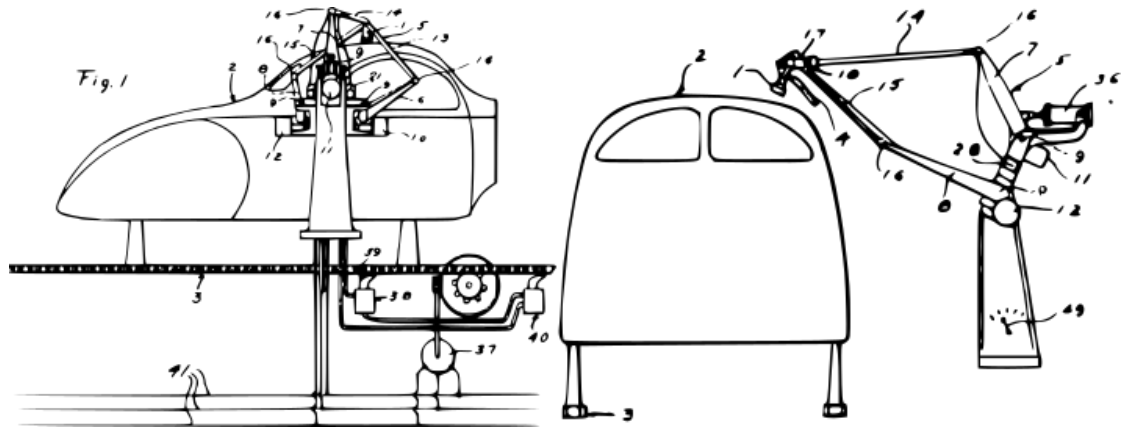
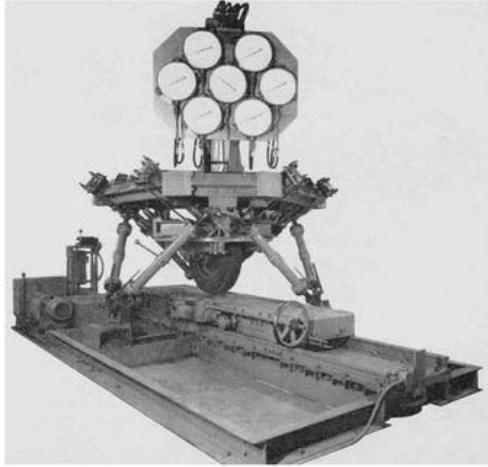


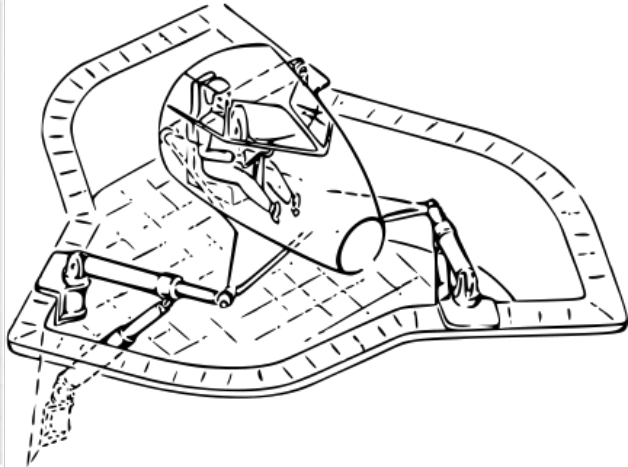
Figure 1.2: This car painting machine has been designed by Pollard. This is the first application of a parallel structure in the industry[7].

1.1.2 Gough-Stewart platform

Although the creation of the oxymoron and that of the spray painting machine date back to before the Second World War, the paternity of parallel robots is often attributed to the Gough-Stewart platform. The kinematic structure has been initially thought by Gough in 1947 **rajouter la référence GOUGH**(Fig.1.3a). The goal of the structure was to test tire wear and tear. In 1966, Stewart rediscovered the mechanism to make a flight simulator[8] (Fig.1.3b). The 6 DOFs of the robot has been made possible by the three legs making the junction between the ground and the platform. Indeed, they are all linked to the platform via spherical joints and fixed to the ground through two universal joints. The legs are composed of two hydraulic pistons: one connected to the ground and the platform and the other connected to the ground and the end of the cylinder of the first piston.



(a) Gough platform[9]



(b) Stewart platform[8]

Figure 1.3: The Gough Stewart platform is a 6 DOF parallel structure initially thought by Gough for a tire testing machine (a). Stewart rediscovered this kinematic structure for a flight simulator (b).

Since the realisation of the platform by Stewart, there were no major advances in parallel robot research until the 1980s. Indeed, the interest in the use of the closed loop kinematic chains has been relaunched by by Hunt and Fichter. The first carried out research into the structural kinematics of in-parallel-actuated robot-arms [10]. In this study, Hunt used the screw theory, i.e. mathematical framework describing the motion of a rigid body both in translation and rotation along the same line to find a systemic approach to design parallel robot arms. His goal was to rekindle the interest of roboticists in the development of parallel structures such as the Stewart platform. Fichter studied deeply the implementation of the generalized Stewart platform as a robot manipulator [11].

The 1980s were undoubtedly the decade of the explosion in the study of parallel robots. In fact, it was during this decade that the development of this type of structures inspired many roboticists, such as Clavel and his Delta robot.

1.2 Delta Robot

The Delta robot was initially thought by Clavel in 1985 at the EPFL and the thesis he conducted on the research and development of the Delta robot has been published in 1991 [12]. The creation of the robot begins with the observation that there were no industrial robots capable of palletising light parts at high speeds at

that time. Indeed, the initial goal of the Delta robot was to handle pralines and place them in trays. Actually, in his thesis Clavel also introduced the possible use of the delta robot in other sectors such as assembly of electronic components, setting up assortments of biscuits, or jars of watercolour paint and even the composition of pharmaceutical cures etc...

The Delta robot designed by Clavel is composed of three kinematic chains linking the end effector to the base (Fig.1.4). The kinematic chains are composed of a proximal arm and a four-bar parallelogram. The latter is composed of two connecting links and two distal arms. The role of the parallelogram is to block all possible rotations of the end-effector and therefore, whatever the input of the motors, the movements of the end effector are purely translational. Therefore, the end effector has 3 DOF in translation due to the rotations of the three motor.

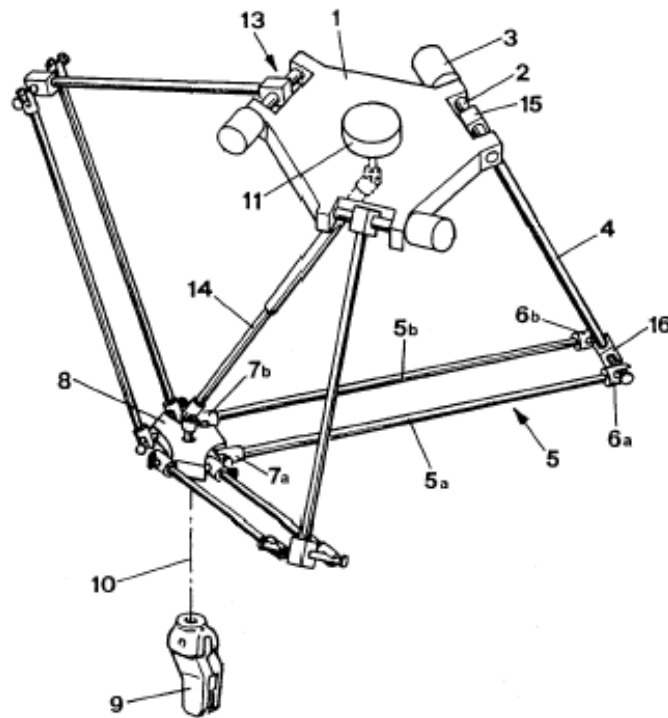


Figure 1.4: The Delta robot as initially thought by Clavel. [12]

1.2.1 Industrial use of the Delta robot

The development of the delta robot in the industry is covered in the paper redacted by Bonev [13]. The delta robot has been used first in the industry by the company Demarex in 1987 with their purchase of the licence of the Delta robot. They

developed the robot for its use in the packaging industry (Fig.1.5a). However, the license was only covering the Delta Robot of small dimensions. This covers all robots with a kinematic chains up to 800mm long. The license for the Delta robot of larger dimension was sold to ABB Flexible Automation. In 1999, the IRB 340 FlexPicker is released (Fig.1.5b). It is equipped with a vacuum pump and can perform pick and place with weights up to 1kg. The industry's aims with this robot were the pharmaceutical, the food and the electronics. The Elekta company has developed the use of the Delta robot in the field of surgery through the SurgiScope (Fig.1.5c).

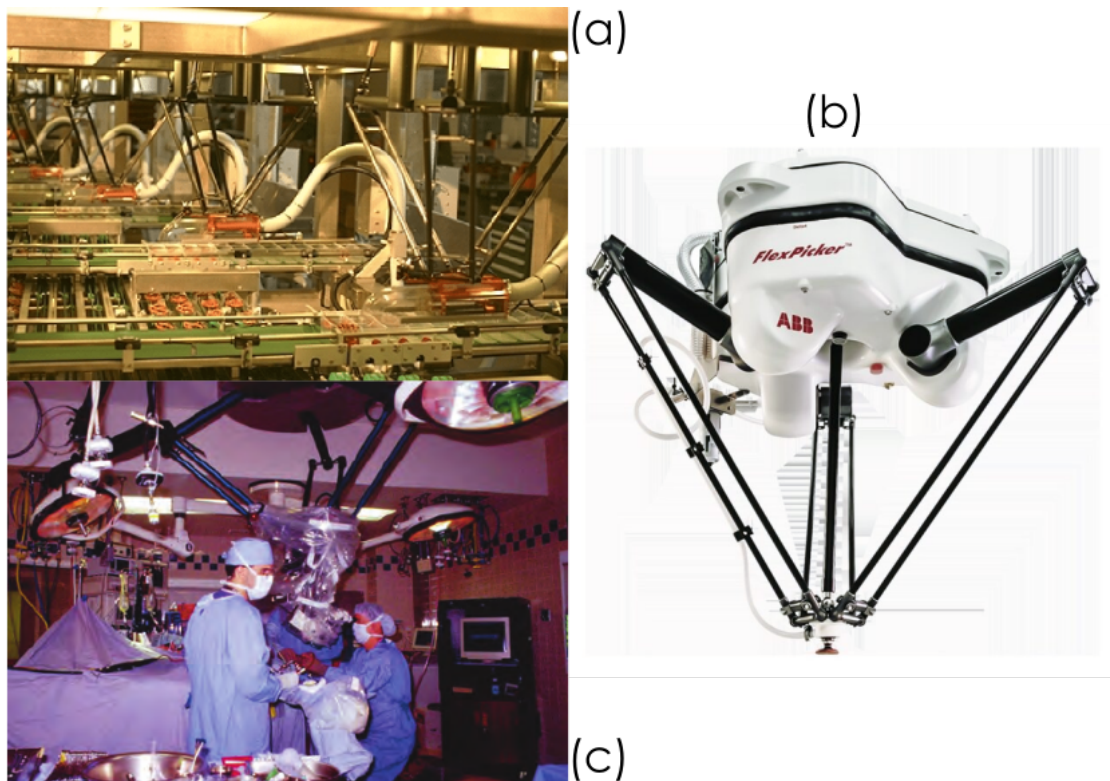


Figure 1.5: The first application of the delta robot in the industry: Demarex delta robot(a)[13], IRB 340 FlexPicker(b)[13], SurgiScope(c)[14].

Nowadays, the Delta Robot is not used a lot in the industry due to its workspace to installation size ratio. The market share of the Delta was only 1 percent in 2012 has shown in the graph 1.6. The industry is still inundated with industrial robots with a series kinematic structure.[15]

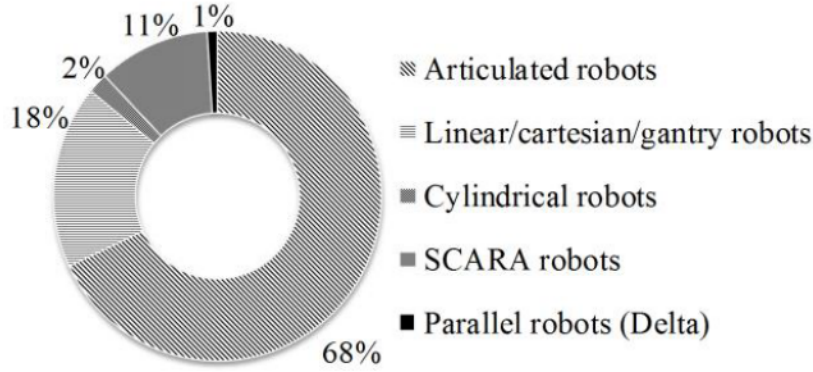


Figure 1.6: Market share of the industrial robots in function of their kinematic structure. [15]

1.2.2 Delta-like Architecture

The Delta robot developed in the universities and in the industry have generally the same form with variants in the types of joints used. However, it is possible to highlight several Delta/Delta-like Robots with interesting designs. The survey conducted by Brinker and Corves cover in more details the different types of Delta-like [15].

1.2.3 Variation of the kinematic chain

The Use of other joint in the kinematic chain of the delta robot has been characterize in [16] by their mobility criterion. The mobility criterion of these kinematic chains is given by the following equation :

$$M = 6(n - g - 1) + \sum_{q=1}^g f_q + \eta + \kappa$$

In which the M is the mobility criterion, n is the number of bodies, g is the number of kinematic chains, f_q the dof of the q th joint, η the number of overconstraints and κ the internal mobilities or idle dof.

In the Fig.1.7 all the possible joints connection of the delta robot kinematic chain are represented. The 3-RUU is the only kinematic chain in which the parallelogram is not present. Thus the stiffness of this configuration is worse than the other one. The main differences in the different kinematic chain is due to the parallelogram structure: 2-SS, 2-US, or 2-UU. The 3-R(2-SS) require that a bar and spring link the two distal arm to maintain the contact. This can lead to parasitic motion. The

3-R(2-UU) in comparison, increase the stiffness. The 3-R(RPaR) is cinematically similar to the 3-R(2-UU), the universal joint is replace by a planar joint that en with a revolute joint.

Table 1
Mobilities of Delta-like robots depending on the kinematic chain design.

Kin. chain design					
Variant	3- <u>R</u> UU	3- <u>R</u> (2-SS)	3- <u>R</u> (2-US)	3- <u>R</u> (2-UU)	3- <u>R</u> (RPaR)
n	14	11	11	11	17
g	15	15	15	15	21
Σf_q	15	39	33	27	21
ν_C	0	0	0	3	9
ν_{PM}	0	0	0	3	3
κ	0	6	0	0	0
M	3	3	3	3	3

Figure 1.7: Different possible kinematic chains of the delta robot [16]

NUWAR

The University of Western Australia proposed a design, the NUWAR (Fig.1.9), in which the actuator's position and rotation axis are not in the same plane [17]. With this particular disposition developed by Miller, the acceleration and the workspace size were improved.

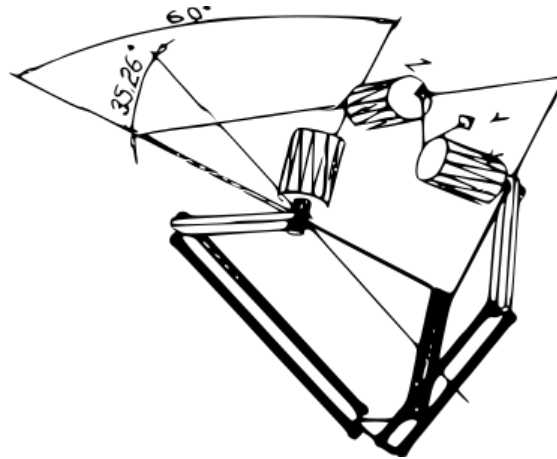


Figure 1.8: NUWAR Delta robot developed by Miller to optimize the classical delta robot workspace. [17]

Linear Delta

Another well know implementation is the linear actuator Delta robot. In the paper [18] Bouri and Clavel have studied the linear actuator and have separated them in families:

1. The orthogonal family: the linear actuator are placed in the X, Y and Z axis. This design has one major flaw: its workspace over structure space ratio.
2. The horizontal family: the parallelograms are directly connected to belts. The movement of the end effector is due to the translational transmission of the parallel belts.
3. The vertical family: Three linear actuators are place at $120[^\circ]$ from each other and are oriented in the z-axis.
4. The Keops linear Delta: Three linear actuator are placed on the edge of a tetrahedron.
5. The Hybrid linear-rotational Delta robot: the robot is an amalgam of two linear actuator and 1 rotational actuator.

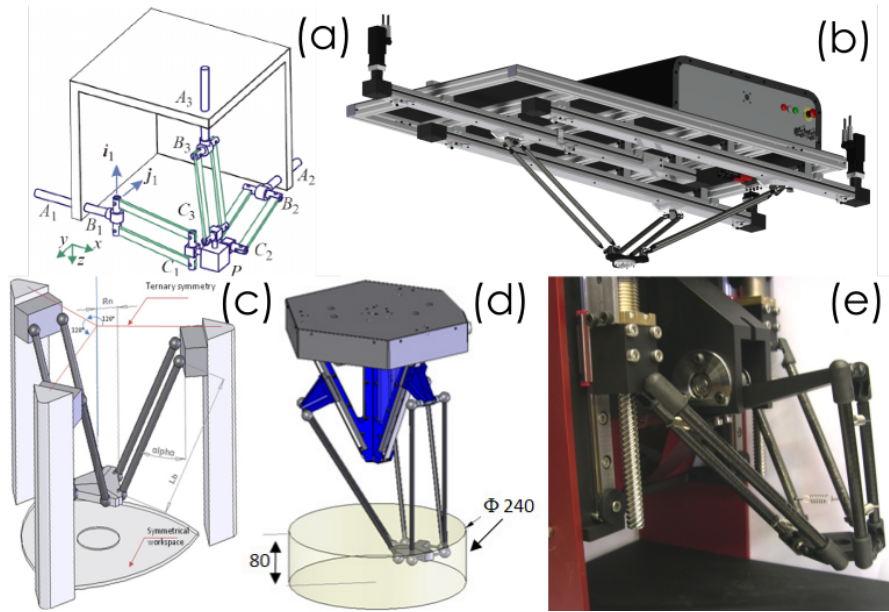


Figure 1.9: In (a) the structure of an orthogonal linear Delta robot is illustrated[18]. The figure (b) shows an application of an horizontal Delta robot produced by the company Mechatronics and Dynamic Devices s.r.l.. The figure (c) illustrate a vertical robot[18]. The Keops Delta robot is shown in (d)[18]. And the Hybrid linear-rotational Delta robot developed at the EPFL can be found in the (e)[18].

Chapter 2

Specifications

To accomplish the pedagogical purpose of 3 d.o.f Delta robot, the main functions and the main constraints must be clearly identified. The advantages of the robot and its parallel structure must be demonstrated through different movements and actions it is capable of performing, while remaining secure as it can be shown to a young audience with the “Printemps des Sciences” event.

2.1 Main Functions

MF1 : Accuracy, Repeatability and Resolution of the robot

The Delta robot thanks to the stiffness of its parallel kinematic chain can exhibit a high precision. For this robot, the required precision has been fixed to $1[mm]$. Repeatability is another important parameter of the robot for the tasks it must accomplish such as pick and place. It has been chosen to be in an interval of $\pm 0,5[mm]$. The resolution of the end-effector has been fixed to $0,6[mm]$.

MF2 : Max payload

The robot should carry at least a $1[kg]$ mass in static and $250[g]$ in dynamic.

MF3 : Speed and Acceleration

The end effector speed must be able to reach $3[m/s]$. The acceleration must be of at least $10[g]$

MF4 : Perform a range of tasks

To fulfil its didactic role, the Delta robot must be able to perform a wide variety of tasks. Some examples are:

- pick and place tasks
- path following tasks
- a race against the user
- draw a figure
- a target reaching task

Of course, these are just a few ideas one can think of, and there are still a number of possibilities that can be imagined.

Some of the trajectories used in this master thesis to validate the design are presented in the section 2.3.

MF5 : Replaceability

The different parts, mechanics and electrical, of the robot must be easily replaceable in case of failure.

2.2 Main Constraints

MC1 : Price of conception

The cost of the robot must not be above 4000€.

MC2 : Workspace dimensions

The robot workspace must contain at least one box of length and width of 300[mm] and height of 150[mm]. The prescribed workspace is a cylinder with a diameter of 500[mm] and a height of 150[mm]. There should be no singularities in the workspace.

MC3 : Power consumption

The maximum power consumption of the robot must be less than 2000[W] to be able to be plugged into a standard socket.

MC4 : Working temperature range

The overall temperature of the robot must be between 0 and 45[°C] to prevent damaging the electrical components.

MC5 : Noise

The noise of the robot must be less than 60[*dB*]. This correspond to the intensity of the sound of a conversation. This choice has been made to make it possible for the user to explain the behaviour of the robot and to discuss with the audience.

MC6 : Safety

The robot should pass the risk analysis of UCLouvain. As mentioned earlier, a young audience can attend demonstrations of the robot. Therefore, the robot must be safe to avoid any possible harm to the participant.

MC7 : Usability

The robot must be usable without risk of overheating, and must not present any terminating mechanical failure for 10 years. It should be easy to use and have clear documentation. The robot must provide an unobstructed view for filming and viewing during the sessions.

MC8 : Transportability

The robot must be able to be transported in a utility vehicle. The robot and its frame must be able to pass through doorways, which are 75[*cm*] wide. This will depend on the size of the box the robot is placed in.

MC9: Future master theses

Allow further work for future master theses by considering the potential upgrades on the robot and have a clear documentation for future work on the robot.

2.3 Reference Trajectories

A trajectory can be considered as the combination of a path and a motion law.[19] The path represents a purely geometrical description of the end-effector's motion when specified in the task space. Mathematically, this path can be described as a parametric position curve denoted as $\mathbf{X}(s)$, where s is a scalar path parameter assumed to be 0 at the beginning of the path and 1 at the end. Consequently, as s increases from 0 to 1, the robot follows the prescribed path.

The motion law, represented by a function $s(t)$, complements the path to complete the trajectory. By establishing the relationship between the path parameter s and time t , the motion law guides the robot's movement, influencing the values of position, velocity, acceleration, and jerk along the path.

In summary, a trajectory combines both the geometric information provided by the path and the temporal information provided by the motion law. This combination results in a time-parameterized sequence of states for the robot.

Another type of trajectory planning, frequently employed in industrial settings, involves trajectory planning through the use of via points. This approach offers the advantage of accommodating more intricate trajectories. In this method, the trajectory is defined by specifying particular time, position, velocity, and acceleration, for each via point. Additionally, an interpolation scheme is utilized to connect these via points seamlessly. Various interpolation schemes exist, including polynomial interpolation, B-splines, NURBS, among others. The unique aspect of this approach is that it directly determines the trajectory without the need to predefine a geometrical path or a movement law $s(t)$. This offers flexibility and efficiency in creating complex motion sequences for the manipulator.

The Delta robot is expected to execute three distinctive trajectories (path + motion law), each characterized in the task space. It is assumed that these trajectories lie within the robot's effective workspace, thereby alleviating concerns related to physical bounds and singularities. However, the actuators performances on velocity and torque need to be taken into account. Each trajectory will feature a different motion law.

2.3.1 Pick And Place trajectory

The pick and place trajectory is the standard trajectory carried out by a delta robot. The delta robot was originally conceptualized to pick and place pralines boxes in a swiss factory. This trajectory will be used as the main trajectory for the design of the Delta robot.

There are different paths possible for the pick and place trajectory. A traditional path is the rectangular path (fig2.1a) and is composed of straight lines and circular segments in the corner. The transition between a straight line and a circular segment gives a discontinuous acceleration [20]. To avoid that discontinuous acceleration a clothoid can be used [21].

Another possibility is the semi-elliptical path (fig2.1b). The disadvantage of the semi elliptical path is that it does not allow the pick and place of objects located at different heights. [21] Nonetheless, the semi elliptical path will be the path used in this thesis.

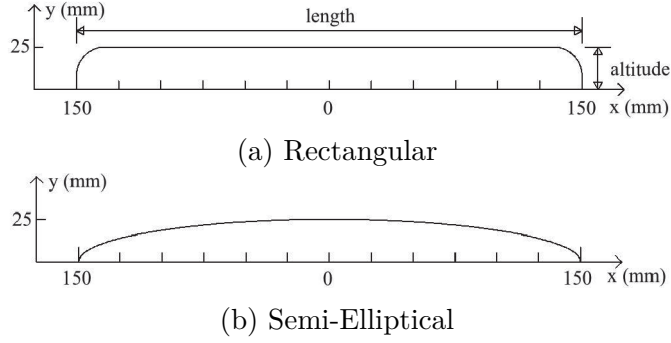


Figure 2.1: Pick and place trajectories from [20]

The pick and place trajectory equation of the semi ellipse is the following:

$$\mathbf{X}(t) = \mathbf{C} + A \cdot \mathbf{a} \cdot \cos\left(\frac{\pi \cdot s(t)}{x_f}\right) + B \cdot \mathbf{b} \cdot \sin\left(\frac{\pi \cdot s(t)}{x_f}\right) \quad (2.1)$$

Where $\mathbf{C} = \frac{1}{2}(\mathbf{X}_s + \mathbf{X}_e)$ with $\mathbf{X}_s$ and $\mathbf{X}_e$ the starting position vector and the end position vector respectively. A, B are equal to half of the lengths of the big and small axis respectively, and $\mathbf{a}, \mathbf{b}$ are their unitary vectors. More detail on the trajectory can be found in [21].

The motion law that is going to be used for the pick and place trajectory is the modified sinusoidal law or mod-sin (figure 2.2). It consists of three sinusoidal functions. In the following, x_f stands for the path lenght and T stands for the trajectory time.

1. Sinusoidal function with positive jerk for $t \in [0; \frac{T}{8}]$.

$$s(t) = \frac{\pi}{\pi + 4} x_f \left[\frac{t}{T} - \frac{1}{4\pi} \sin\left(4\pi \frac{t}{T}\right) \right]$$

2. Sinusoidal function with negative jerk for $t \in [\frac{T}{8}; \frac{7T}{8}]$.

$$s(t) = \frac{\pi}{\pi + 4} x_f \left[\frac{t}{T} - \frac{9}{4\pi} \cos\left(\frac{4\pi}{3} \left(\frac{t}{T} - \frac{1}{8}\right)\right) + \frac{2}{\pi} \right]$$

3. Sinusoidal function with positive jerk for $t \in [\frac{7T}{8}; T]$.

$$s(t) = \frac{\pi}{\pi + 4} x_f \left[\frac{t}{T} - \frac{1}{4\pi} \sin\left(4\pi \frac{t}{T}\right) + \frac{4}{\pi} \right]$$

This motion law presents a two-part starting phase: a rapid start ($0-T/8$) followed by a "soft" acceleration phase ($T/8-T/2$). Subsequently, it transitions to a "soft" deceleration phase ($T/2-7T/8$) and concludes with a quick braking phase ($7T/8-T$). This behavior can be seen on figure 2.2. This motion law is used because it yields the lowest required torques with acceptable finite jerk values.

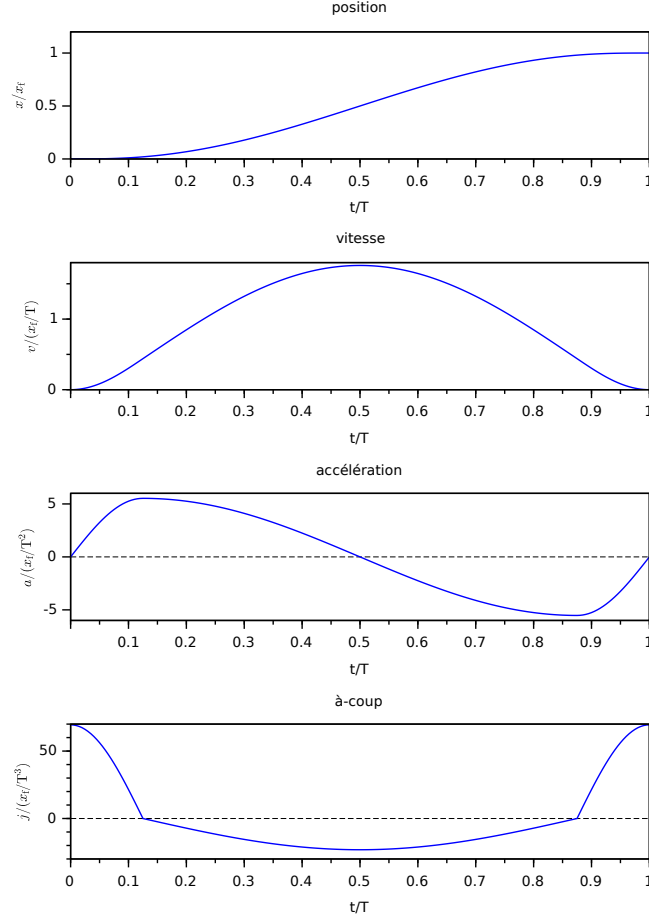


Figure 2.2: Behavior in position, velocity, acceleration and jerk of the modified sinusoidal movement law (image by Cdang¹)

The reference pick and place trajectory has a frequency of 2 pick and place cycles per second for a point-to-point distance of $0.3[m]$.

¹Cdang— Travail personnel, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=72180329>

2.3.2 Circle trajectory

A circle is a subset of an ellipse, where the big and small axis length are the same and equal to the diameter of the circle. The same semi ellipse trajectory described by equation 2.1 can thus be used and changed slightly to obtain the trajectory of a circle.

$$\mathbf{X}(t) = \mathbf{C} + R \left[\mathbf{a} \cdot \cos \left(\frac{\phi \cdot s(t)}{x_f} \right) + \mathbf{b} \cdot \sin \left(\frac{\phi \cdot s(t)}{x_f} \right) \right] \quad (2.2)$$

Where $\mathbf{C}$ becomes the position vector of the circle center, R is the radius of the circle, $\mathbf{a}$ and $\mathbf{b}$ are unit vectors perpendicular to the rotation axis of the circle, such that they form an orthonormal basis. $\phi = 2\pi fT$ where f is the number of revolutions per seconds and T stands for the total time of the trajectory.

The motion law used for the circle trajectory is the famous 5th degree polynomial:

$$s(t) = x_f \frac{t^3}{T^3} \left(10 - 15 \frac{t}{T} + 6 \frac{t^2}{T^2} \right) \quad (2.3)$$

The reference circle trajectory has a frequency of 3 circles per second with a radius of 0.15[m].

2.3.3 Helix trajectory

A helix is the combination of a circular trajectory and a linear trajectory. The trajectory equation of circle can thus be used and combined with the equation of a line.

$$\mathbf{X}(t) = \mathbf{C} + \mathbf{D} \cdot \frac{s(t)}{x_f} + R \left[\mathbf{a} \cdot \cos \left(\frac{\phi \cdot s(t)}{x_f} \right) + \mathbf{b} \cdot \sin \left(\frac{\phi \cdot s(t)}{x_f} \right) \right] \quad (2.4)$$

Where $\mathbf{C}$ is the starting position of the displacement and $\mathbf{D}$ is the displacement vector. The other parameters do not change from the circle trajectory.

The motion law used for the Helix trajectory is the 7th degree polynomial for a very smooth trajectory:

$$s(t) = x_f \frac{t^4}{T^4} \left(35 - 84 \frac{t}{T} + 70 \frac{t^2}{T^2} - 20 \frac{t^3}{T^3} \right) \quad (2.5)$$

The reference helix trajectory has a frequency of 2 circles per second with a radius of 0.25[m], which is on the boundary of the prescribed workspace. The linear distance is equivalent to the height of the prescribed workspace, and equal to 0.15[m]

Chapter 3

Modelling the Delta Robot

3.1 Nominal Kinematic model

In 1987 the first nominal kinematic model of the delta robot was proposed by Sternheim [22]. In 1991 the father of the delta robot Reymond Clavel, proposed a model using geometric analysis based on the intersection of a sphere and 3 circles [12], which had the advantage to be computed faster than the previous model. In the same year, Codourey highlights and fixes the mathematical singularities (of type $\frac{0}{0}$) in the inverse kinematic algorithm. Guglielmetti [23] further optimizes the algorithm in his thesis. Zsombor-Murray (2004) [24] proposes his own take on the model by using a different the reference frame for efficient computation.

The nominal kinematic model, comprising six geometric parameters, operates under the assumption of a flawless delta robot. This model envisions the three kinematic chains to be precisely rotated by 120° relative to one another. It further supposes perfection in both geometry and orientation of the parallelograms in relation to the structure's base frame. Consequently, the platform's orientation, upheld by these parallelograms, remains fixed. According to these assumptions, each parallelogram can be simplified by substituting it with a straightforward distal link joined via a universal joint. These joints connect the proximal link and the platform. The model's parameters encompass the three motor angles $q_{i=1,2,3}$, a singular proximal link length l_a , a singular distal link length l_b , and the difference $r = r_a - r_b$. Notably, the nominal model replaces the linearly dependent r_a and r_b with the single parameter r (Fig.3.1), as noted in [25].

3.1.1 Notations and conventions

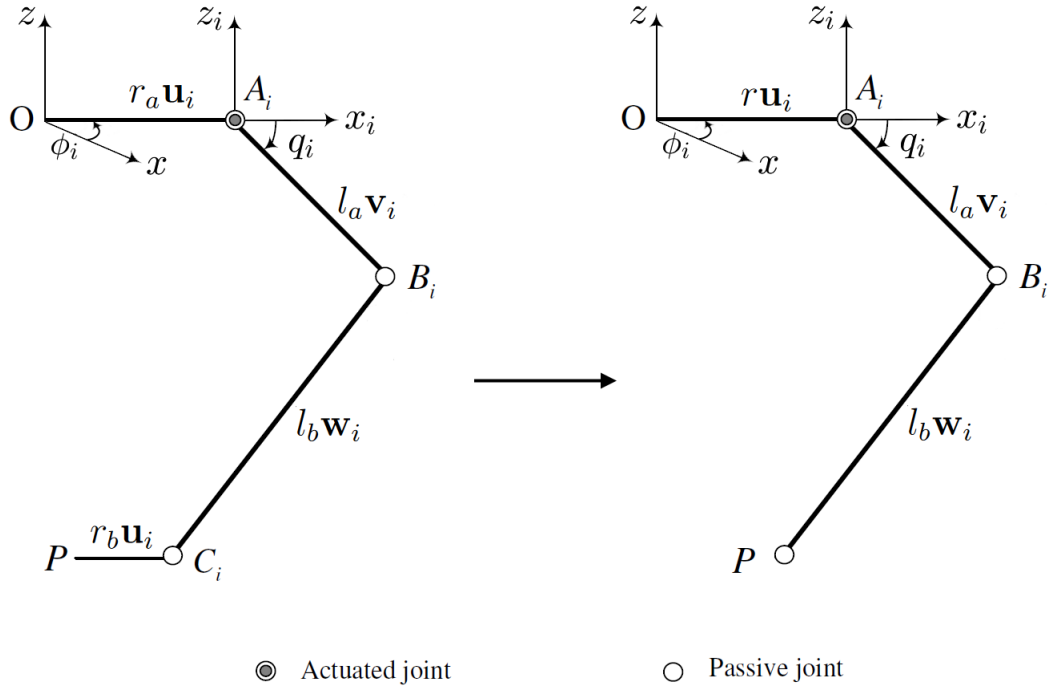


Figure 3.1: Schematic of a kinematic chain of the Delta robot.

Fig.3.1 shows a schematic of a kinematic chain of the Delta robot. Three of these kinematic chains are arranged 120° symmetrically from each-other:

$$\begin{cases} \phi_1 = 0 & (3.1a) \end{cases}$$

$$\begin{cases} \phi_2 = \frac{2\pi}{3} & (3.1b) \end{cases}$$

$$\begin{cases} \phi_3 = \frac{4\pi}{3} & (3.1c) \end{cases}$$

We define the following rotation matrices:

$${}^i\mathbf{R} = \mathbf{R}_z(\phi_i) = \begin{bmatrix} \cos \phi_i & -\sin \phi_i & 0 \\ \sin \phi_i & \cos \phi_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.2)$$

That transform between the reference frame and the i th kinematic chain frame (also called auxiliary frame [23]). We have thus the following identities:

$$\mathbf{p} = {}^i\mathbf{R} \cdot {}^i\mathbf{p} \iff {}^i\mathbf{p} = {}^i\mathbf{R}^T \cdot \mathbf{p} \quad (3.3)$$

$$\mathbf{u}_i = {}^i\mathbf{R} \cdot {}^i\mathbf{u} \iff {}^i\mathbf{u} = {}^i\mathbf{R}^T \cdot \mathbf{u}_i \quad (3.4)$$

$$\mathbf{v}_i = {}^i\mathbf{R} \cdot {}^i\mathbf{v} \iff {}^i\mathbf{v} = {}^i\mathbf{R}^T \cdot \mathbf{v}_i \quad (3.5)$$

$$\mathbf{w}_i = {}^i\mathbf{R} \cdot {}^i\mathbf{w} \iff {}^i\mathbf{w} = {}^i\mathbf{R}^T \cdot \mathbf{w}_i \quad (3.6)$$

Where $\mathbf{u}_i$, $\mathbf{v}_i$, $\mathbf{w}_i$ are unit vectors defined in the reference frame, and ${}^i\mathbf{u}$, ${}^i\mathbf{v}$, ${}^i\mathbf{u}$ are defined in the kinematic chain frame.

The closed-loop position equation associated with the i th kinematic chain can be written as

$$r\mathbf{u}_i + l_a\mathbf{v}_i + l_b\mathbf{w}_i = \mathbf{p}, \quad i = 1, 2, 3 \quad (3.7)$$

3.1.2 Inverse kinematics

The inverse kinematics algorithm is the most important algorithm for the delta robot and computes the 3 angles of the actuators $\mathbf{q}$ from the end effector position $\mathbf{p}$. First, a slight variation on the version of Clavel will be presented. Despite the mathematical singularities, this version is frequently used in the modern literature of the delta robot. After highlighting the singularities, the algorithm proposed by Guglielmetti [23] will be presented. Which is the most optimized algorithm free of mathematical singularity found during the writing of this thesis.

A) Clavel's algorithm

As mentioned above, Clavel uses the intersection between a sphere centered on point P (figureX) with radius l_b , and three circles centered on points A_i to get the system of equations. The present algorithm uses the loop closure constraints instead, which states that the connection points of the 3 distal arms must be at a distance l_b from each other:

$$\|\overrightarrow{B_iP}\|^2 = \|l_b\mathbf{w}_i\|^2 = l_b^2 \quad (3.8)$$

Substituting the expression of $l_b\mathbf{w}_i$ from Eq.3.7 in Eq.3.8 gives the system of equations:

$$\Phi_i \cos q_i + \Psi_i \sin q_i - \Omega_i = 0 \quad (3.9)$$

With:

$$\Phi_i = x \cos \phi_i + y \sin \phi_i - r$$

$$\Psi_i = -z$$

$$\Omega_i = \frac{1}{2l_a} \left(x^2 + y^2 + z^2 + l_a^2 + r^2 - l_b^2 - 2r (x \cos \phi_i + y \sin \phi_i) \right)$$

By setting:

$$t_i = \tan \frac{q_i}{2} \quad (3.10)$$

Equation Eq.3.9 is expressed as a function of t_i using trigonometric identities:

$$\cos q_i = \frac{1 - t^2}{1 + t^2} \quad \sin q_i = \frac{2t}{1 + t^2} \quad (3.11)$$

$$(3.12)$$

$$(\Omega_i + \Phi_i) t_i^2 - 2\Psi_i t_i + (\Omega_i - \Phi_i) = 0 \quad (3.13)$$

Which is a simple quadratic function with the following solution:

$$t_{i1,2} = \frac{\Psi_i \pm \sqrt{\Psi_i^2 + \Phi_i^2 - \Omega_i^2}}{\Phi_i + \Omega_i} \quad (3.14)$$

Of these two solutions, only the negative sign is valid for the delta robot (Fig.3.2). These two solution can also be seen as two intersections between the circle of the i th kinematic chain and the sphere (Fig.3.2). The expression of the angle of the i th kinematic chain due to the position of the end effector is thus:

$$q_i = 2 \arctan \frac{\Psi_i - \sqrt{\Psi_i^2 + \Phi_i^2 - \Omega_i^2}}{\Phi_i + \Omega_i} \quad (3.15)$$

As mentioned before, the problem with this algorithm is the mathematical singularities. Plugging the expressions of Φ_i and Ω_i into the condition $\Phi_i + \Omega_i = 0$, gives the following equation:

$$(x - (r - l_a) \cos \phi_i)^2 + (y - (r - l_a) \sin \phi_i)^2 + z^2 = l_b^2 \quad (3.16)$$

Which is the equation of a sphere centered on $[(r - l_a) \cos \phi_i, (r - l_a) \sin \phi_i, 0]$ with radius l_b . As consequence, from each kinematic chain originates a sphere on which the algorithm has to compute $\arctan \frac{0}{0}$ and degenerates. The fact that the singularity is of type $\frac{0}{0}$ can be seen by plugging back $\Phi_i = -\Omega_i$ in equation 3.15.

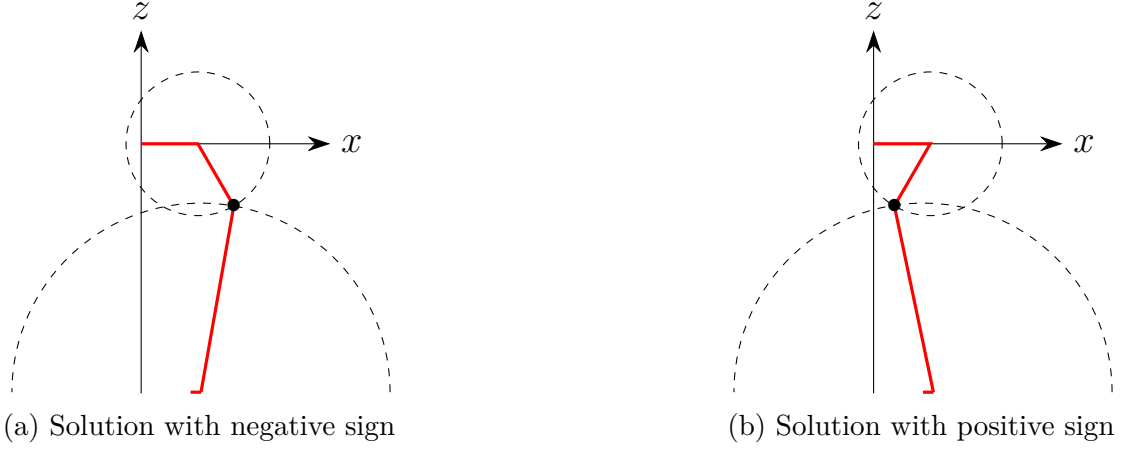


Figure 3.2: Two solutions of the quadratic function of kinematic chain 1, corresponding to the two intersections between the circle centered on A_1 and the sphere centered on $\mathbf{p}$

B) Guglielmetti's algorithm

To avoid mathematical singularities, Guglielmetti works in the frame of the kinematic chains instead of the reference frame. Equation 3.7 becomes:

$$r\hat{\mathbf{e}}_x + l_a {}^i\mathbf{v} + l_b {}^i\mathbf{w} = {}^i\mathbf{p}, \quad i = 1, 2, 3 \quad (3.17)$$

The loop closure equation can be written as:

$$\|l_b {}^i\mathbf{w}\|^2 = \|{}^i\mathbf{p} - r\hat{\mathbf{e}}_x - l_a {}^i\mathbf{v}\|^2 = l_b^2, \quad i = 1, 2, 3 \quad (3.18)$$

Which gives:

$${}^i v_x {}^i\Phi + {}^i v_z {}^i\Psi - {}^i\Omega = 0 \quad (3.19)$$

Where:

$$\begin{aligned} {}^i\Phi &= {}^i p_x - r \\ {}^i\Psi &= {}^i p_z \\ {}^i\Omega &= \frac{1}{2l_a} \left(l_a^2 - l_b^2 + ({}^i p_x - r)^2 + {}^i p_y^2 + {}^i p_z^2 \right) \end{aligned}$$

Knowing that ${}^i\mathbf{v} = [\cos q_i, 0, -\sin q_i]$, We have the exact same system of equations as 3.9 but expressed in the kinematic chain/auxiliary frame.

From Eq.3.19 we have:

$${}^i v_z = \frac{{}^i\Omega - {}^i v_x {}^i\Phi}{{}^i\Psi} \quad (3.20)$$

Since ${}^i\mathbf{v}$ is a unit vector with ${}^iv_y = 0$:

$${}^iv_x^2 + {}^iv_z^2 = 1^2 \quad (3.21)$$

Substituting the expression of iv_z from Eq.3.20 into Eq.3.21 yields a quadratic equation in iv_x with solutions:

$${}^iv_x = \frac{{}^i\Omega^i\Phi \pm {}^i\Psi\sqrt{{}^i\Psi^2 + {}^i\Phi^2 - {}^i\Omega^2}}{{}^i\Psi^2 + {}^i\Phi^2} \quad (3.22)$$

The solution with the plus sign is excluded since it corresponds to a situation where the proximal link is directed towards the inside of the robot (Fig.3.2). Finally we have:

$$q_i = -\text{atan2}({}^iv_z, {}^iv_x) \quad (3.23)$$

Where the use of atan2 is made, which computes an arc-tangent in the four quadrants. Because atan2 measures the counterclockwise angle as positive, a negative sign is added to respect our reference frame convention. Thanks to the use of atan2 and the expression of the denominator of iv_x , there are no mathematical singularities in the algorithm.

In practice however, when using the inverse kinematics on discretized points inside the workspace, there is a very slim chance of encountering a point exactly on one of the three singularity spheres. This is probably why the first algorithm is still very popular to this day.

3.1.3 Forward kinematics

The forward kinematics algorithm computes the end effector position $\mathbf{p}$ from the three actuator angles q_i . Contrary to the inverse kinematics, the use of the forward kinematics is more scarce. It's computation is also more complicated. The following algorithm is taken from Deblaise [26]. It is a slightly different version from Clavel's forward kinematics, and is also slightly faster.

The algorithm starts again with the loop closure equation in the reference frame Eq. 3.8, which gives the following system of equations function of x, y, z :

$$\begin{cases} x^2 + y^2 + z^2 + 2xE_{11} + 2yE_{21} + 2zE_{31} + F_1 = 0 \end{cases} \quad (3.24a)$$

$$\begin{cases} x^2 + y^2 + z^2 + 2xE_{12} + 2yE_{22} + 2zE_{32} + F_2 = 0 \end{cases} \quad (3.24b)$$

$$\begin{cases} x^2 + y^2 + z^2 + 2xE_{13} + 2yE_{23} + 2zE_{33} + F_3 = 0 \end{cases} \quad (3.24c)$$

Where:

$$E_{1i} = -\cos \phi_i (l_a \cos q_i + r)$$

$$E_{2i} = -\sin \phi_i (l_a \cos q_i + r)$$

$$E_{3i} = l_a \sin q_i$$

$$F_i = E_{1i}^2 + E_{2i}^2 + E_{3i}^2 - l_b^2$$

Note that E_{1i} , E_{2i} , E_{3i} are respectively the negative x , y , z coordinates of point B_i . Solving the system of equations can thus be interpreted as finding the intersection points of 3 spheres with center B_i and radius l_b .

Solving the system starts by subtracting Eq.3.24b from Eq.3.24a and then Eq.3.24c from Eq.3.24a we get the following expressions for x and y :

$$x = yG_1 + zG_2 + G_3 \quad (3.25a)$$

$$y = xK_1 + zK_2 + K_3 \quad (3.25b)$$

Where:

$$\begin{aligned} G_1 &= \frac{E_{21} - E_{22}}{E_{12} - E_{11}} & G_2 &= \frac{E_{31} - E_{32}}{E_{12} - E_{11}} & G_3 &= \frac{F_1 - F_2}{2(E_{12} - E_{11})} \\ K_1 &= \frac{E_{11} - E_{13}}{E_{23} - E_{21}} & K_2 &= \frac{E_{31} - E_{33}}{E_{23} - E_{21}} & K_3 &= \frac{F_1 - F_3}{2(E_{23} - E_{21})} \end{aligned}$$

After substituting Eq.3.25a in Eq.3.25b we get an expression for y that is independent of x :

$$y = zM_1 + M_2 \quad (3.26)$$

Where:

$$M_1 = \frac{G_2K_1 + K_2}{1 - G_1K_1} \quad M_2 = \frac{G_3K_1 + K_3}{1 - G_1K_1}$$

By substituting Eq.3.26 in Eq.3.25a we get an expression for x that is independent from y :

$$x = zN_1 + N_2 \quad (3.27)$$

Where:

$$N_1 = G_1M_1 + G_2 \quad N_2 = G_1M_2 + G_3$$

Finally, the substitution of equations 3.26 and 3.27 in equation 3.24a gives the quadratic equation:

$$Q_1z^2 + Q_2z + Q_3 = 0 \quad (3.28)$$

With solutions:

$$Z_1 = \frac{-Q_2 \pm \sqrt{Q_2^2 - 4Q_1Q_3}}{2Q_1} \quad (3.29)$$

Where:

$$\begin{aligned} Q_1 &= N_1^2 + M_1^2 + 1 \\ Q_2 &= 2M_1M_2 + 2N_1N_2 + 2E_{11}N_1 + 2E_{21}M_1 + 2E_{31} \\ Q_3 &= M_2^2 + N_2^2 + 2E_{11}N_2 + 2E_{21}M_2 + F_1 \end{aligned}$$

Only the solution with the minus sign is kept, as the solution with the plus sign leads to impossible configurations (Fig.3.3).

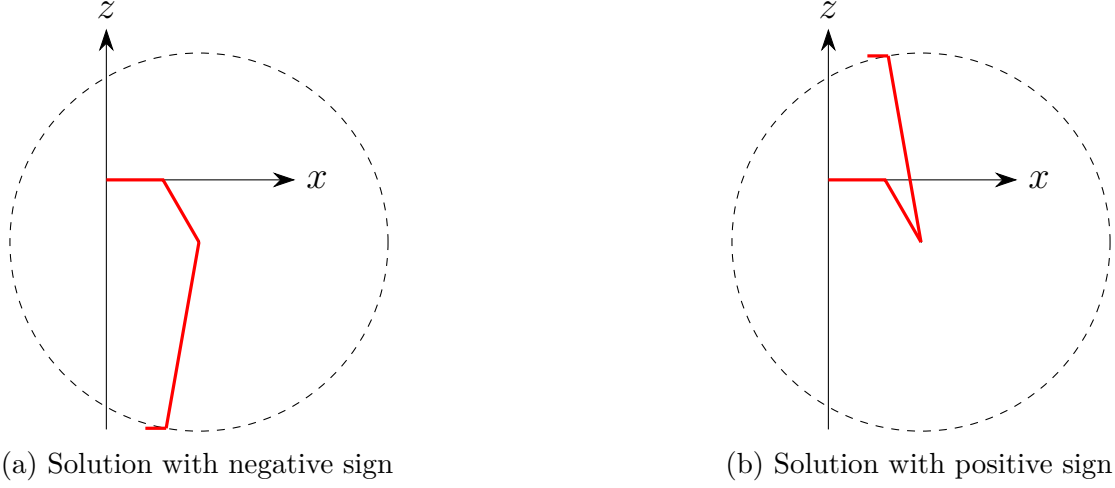


Figure 3.3: Two solutions of the forward kinematics quadratic function of kinematic chain 1, corresponding to the two intersections between the 3 spheres with radius l_b centered on B_i

P Guglielmetti [23] argues that the condition of existence of the closed-form forward kinematics is very delicate, as a single change in one of the robot's parameters is sufficient to destroy it. Instead, an iterative Newton-Raphson algorithm should be used when applied in the control scheme of the Delta robot.

$$\begin{cases} \Delta \mathbf{q} = f^{-1} \left({}^{k-1}\mathbf{p} \right) - \mathbf{q} & (3.30a) \\ {}^k\mathbf{p} = {}^{k-1}\mathbf{p} + {}^{k-1}\mathbf{J} \cdot \Delta \mathbf{q} & (3.30b) \\ {}^k\mathbf{J} = \left[\mathbf{J}^{-1} \left({}^k\mathbf{p} \right) \right]^{-1} & (3.30c) \end{cases}$$

For $k = 1, 2, \dots$ until a desired precision for $\Delta \mathbf{q}$ is reached. Where f^{-1} is the inverse kinematics and $\mathbf{J}$ denotes the Jacobian Matrix. The Jacobian is described in the next section.

3.1.4 Velocity/Differential kinematics

The Jacobian matrix $\mathbf{J}$ of a robot expresses the relation between operational-space velocities and joint velocities as follows:

$$\dot{\mathbf{p}} = \mathbf{J} \cdot \dot{\mathbf{q}} \quad (3.31)$$

The following method is taken from Codourey [27] and Guglielmetti [23]. Taking the derivative with respect to time of the closed loop position equation Eq.3.7:

$$\dot{\mathbf{p}} = l_a \dot{\mathbf{v}}_i + l_b \dot{\mathbf{w}}_i, \quad i = 1, 2, 3 \quad (3.32)$$

The loop closure equation in the reference frame Eq.3.8 can be rewritten as:

$$\mathbf{w}_i^T \cdot \mathbf{w}_i - 1 = 0 \quad (3.33)$$

Taking the derivative with respect to time yields:

$$\mathbf{w}_i^T \cdot \dot{\mathbf{w}}_i + \dot{\mathbf{w}}_i^T \cdot \mathbf{w}_i = 0 \implies \mathbf{w}_i^T \cdot \dot{\mathbf{w}}_i = 0 \quad (3.34)$$

Isolating $\dot{\mathbf{w}}_i$ from Eq.3.32 and substituting in Eq.3.34 gives:

$$\mathbf{w}_i^T \cdot \frac{1}{l_b} (\dot{\mathbf{p}} - l_a \dot{\mathbf{v}}_i) = 0 \quad (3.35)$$

$$\iff \mathbf{w}_i^T \cdot \dot{\mathbf{p}} = l_a \mathbf{w}_i^T \cdot {}^\perp \mathbf{v}_i \dot{q}_i \quad (3.36)$$

Where:

$${}^\perp \mathbf{v}_i = \frac{\partial \mathbf{v}_i}{\partial q_i} = {}^i \mathbf{R} \cdot \begin{bmatrix} -\sin q_i \\ 0 \\ -\cos q_i \end{bmatrix} \quad (3.37)$$

is a vector perpendicular to $\mathbf{v}_i$. Writing Eq.3.36 in matrix form gives:

$$\mathbf{J}_p \cdot \dot{\mathbf{p}} = \mathbf{J}_s \cdot \dot{\mathbf{q}} \quad (3.38)$$

Where:

$$\begin{aligned} \mathbf{J}_s &= l_a \begin{bmatrix} \mathbf{w}_1^T \cdot {}^\perp \mathbf{v}_1 & 0 & 0 \\ 0 & \mathbf{w}_2^T \cdot {}^\perp \mathbf{v}_2 & 0 \\ 0 & 0 & \mathbf{w}_3^T \cdot {}^\perp \mathbf{v}_3 \end{bmatrix} & \mathbf{J}_p &= [\mathbf{w}_1 \mid \mathbf{w}_2 \mid \mathbf{w}_3]^T \\ &= l_a \begin{bmatrix} {}^1 \mathbf{w}^T \cdot {}^\perp {}^1 \mathbf{v} & 0 & 0 \\ 0 & {}^2 \mathbf{w}^T \cdot {}^\perp {}^2 \mathbf{v} & 0 \\ 0 & 0 & {}^3 \mathbf{w}^T \cdot {}^\perp {}^3 \mathbf{v} \end{bmatrix} \end{aligned} \quad (3.39)$$

Therefore, the Jacobian matrix is computed as follows:

$$\mathbf{J} = \mathbf{J}_p^{-1} \cdot \mathbf{J}_s \quad (3.40)$$

Where:

$$\mathbf{J}_p^{-1} = \frac{1}{\det(\mathbf{J}_p)} [\mathbf{w}_2 \times \mathbf{w}_3 \mid \mathbf{w}_3 \times \mathbf{w}_1 \mid \mathbf{w}_1 \times \mathbf{w}_2] \quad (3.41)$$

$$\det(\mathbf{J}_p) = \mathbf{w}_1^T \cdot (\mathbf{w}_2 \times \mathbf{w}_3) = \mathbf{w}_2^T \cdot (\mathbf{w}_3 \times \mathbf{w}_1) = \mathbf{w}_3^T \cdot (\mathbf{w}_1 \times \mathbf{w}_2) \quad (3.42)$$

While the inverse Jacobian matrix takes the following form:

$$\mathbf{J}^{-1} = \mathbf{J}_s^{-1} \cdot \mathbf{J}_p \quad (3.43)$$

Where $\mathbf{J}_s^{-1}$ is trivial.

3.2 Collision modelling

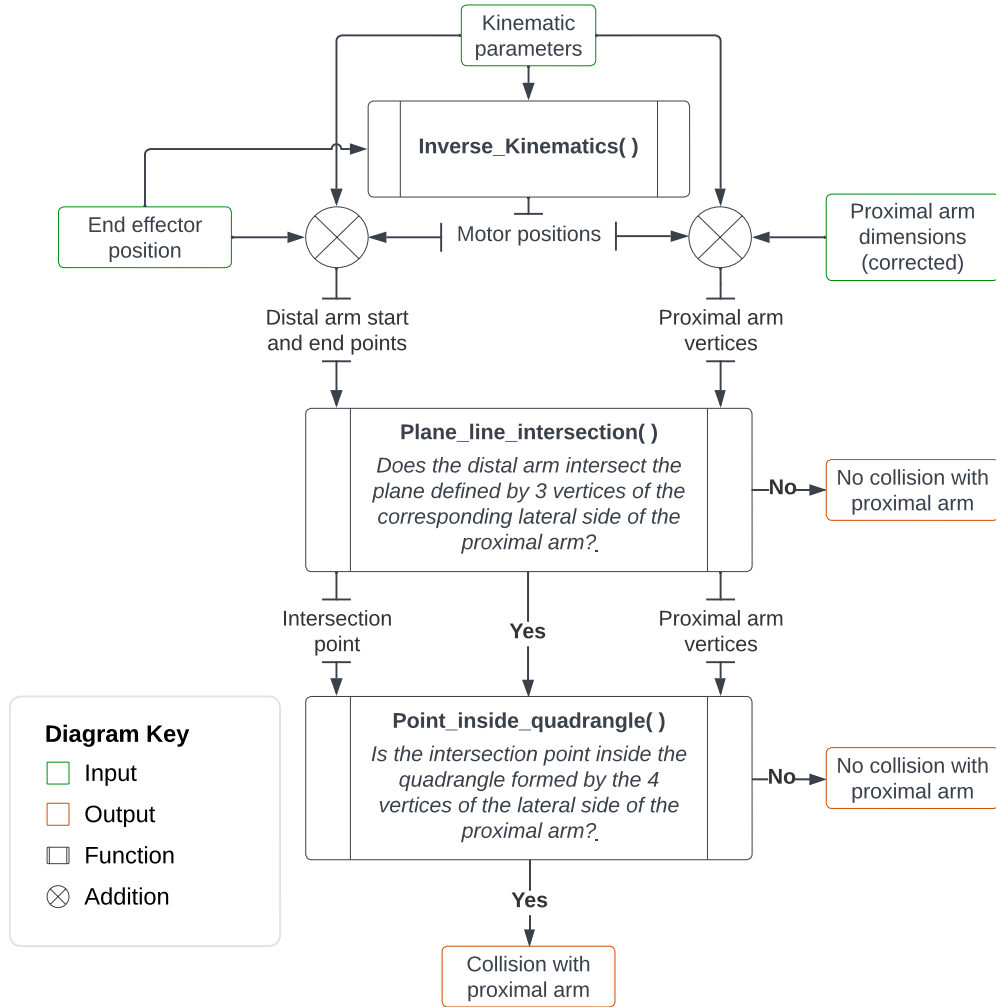


Figure 3.4: Collision Detection Algorithm

The delta robot being a parallel mechanism, a particular attention should be given to the potential collision between its components. The collision model is used to verify if a given configuration of the delta robot, meaning end effector position as well as link dimensions, induce a collision between the proximal link and the distal links. The algorithm that details the collision model can be seen on Fig.3.4. The collision model takes as input the kinematic parameters of the delta robot found in section 4, the position of the end effector in the workspace, as well as the outer dimensions of the distal links (outer diameter) and proximal links (width

and height). In the algorithm, the proximal link dimensions are corrected to take into account the distal link's outer diameter plus a margin of about $4[mm]$. It should be noted that, thanks to the azimuthal symmetry of the delta robot, only one kinematic chain has to be taken into account. More precisely one proximal arm and one distal arm. for simplicity, the proximal arm aligned with the x-axis ($\phi_1 = 0$) is considered. The distal arm considered is on the positive y axis side of proximal arm (Fig.3.5a).

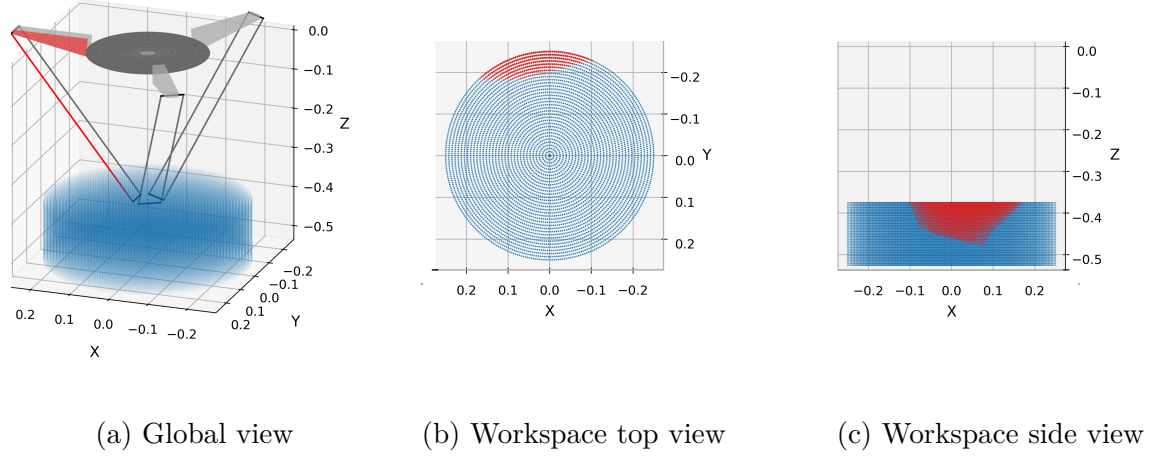


Figure 3.5: Highlighted in red is (a) proximal arm face and distal arm taken into account, (b)&(c) workspace points inducing a collision for a given margin and given dimensions of the proximal arm and distal arm taken into account (a)

The algorithm uses three functions. First the inverse kinematics (section 3.1.2) is used to get the motor positions, which is used to compute the distal arm extremities and the position of the proximal arm vertices. The distal arm starting and ending point are computed as follows:

$$\mathbf{w}_{1s} = \begin{bmatrix} r_a \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} l_a \cos q_1 \\ d_s/2 \\ -l_a \sin q_1 \end{bmatrix} \quad \mathbf{w}_{1e} = \mathbf{p} + \begin{bmatrix} r_b \\ d_s/2 \\ 0 \end{bmatrix} \quad (3.44)$$

The proximal arm vertices positions are computed directly from the corrected proximal arm dimensions, but they are further rotated and translated to the correct configuration:

$$\begin{bmatrix} r_a \\ 0 \\ 0 \end{bmatrix} + R_y(q) \mathbf{n}_k \quad \forall \quad k = 1, 2, 3, 4 \quad (3.45)$$

Where $\mathbf{n}_k$ are the 4 vertices of the lateral side of the proximal arm taken into account.

Secondly the "plane line intersection" function takes as input 3 of the vertices of the side of the proximal arm shown in Fig.3.5a, with the distal arm start and end point and figures out if the distal arm intersect the plane formed by these 3 vertices. The exact workings of the function will not be detailed here. The function outputs a vector with the intersection point if it exists, or a NaN vector otherwise.

Thirdly, if the previous function returns a valid intersection point, the "point_inside_quadrangle" function checks if that intersection point lies inside the 4 vertices of the functional side of the proximal arm. If the intersection point lies inside the quadrangle, there is a collision between the proximal arm and the distal arm, otherwise there is no intersection. Fig.3.5b & 3.5c show, for a certain proximal arm dimensions, distal arm outer diameter and margin, the points of the discretized workspace that have a delta robot configuration that induces a collision between the proximal arm and distal arm taken into account.

3.3 Elastic modelling

The contribution of the elasticity of the mechanical parts to the deflection of the end effector of a manipulator is defined by an elastic model. This elastic model is quite complex because of the different kinematic chains having an influence on each other and on the pose dependency of the robot. There are different approaches in the literature to model the delta robot elastically. The methods that are most frequently discussed are:

- Finite Element Analysis (FEA)
- Virtual Joint Method (VJM)
- Matrix Structural Analysis (MSA)

The Finite Element Analysis is well known and does not need to be presented. It's big advantage is its accuracy with a trade off of big computational cost. This method is not suitable for dimensioning, but is very good to verify the dimensioning step. This is also how FEA is used in our detail design (section 6.3.2).

The virtual joint method (also called lumped-parameter method), first introduced by Salisbury [28], then elaborated by Gosselin for parallel manipulators [29], assumes the links are rigid but the joints are flexible. Initially, the elasticity was modeled using one-dimensional virtual springs concentrated in the actuated joints, but later, additional translational and rotational virtual springs were included to account for the flexibility of the links. The VJM has been used for evaluating

and identifying industrial manipulator stiffness parameters and has been implemented on both serial and parallel robots, but it can be challenging for complex geometries like those found in parallel manipulators with internal loops or parallelogram links. Thus, this method will not be used as our elastic model for the delta robot. An example that uses this method for a delta robot can be found in [30].

The Matrix Structural Analysis is similar to Finite Element Analysis (FEA), but instead of dividing the physical model into a large number of small elements, each part of the robot, such as links and joints, is treated as a beam. The stiffness matrix of the entire structure is then obtained by combining the stiffness matrices of each beam and minimize the elastic potential energy of the whole system.

The main advantage of MSA is that it can obtain the stiffness matrix of the structure in parametric form, which is important when optimizing the stiffness of a manipulator. Matrix Structural Analysis is especially useful in the realm of parallel robots with π -joints [31], which are parallelogram four-bar linkages and are present in the three kinematic chains of the delta robot.

MSA is seen as a compromise between the low computational cost of VJM and the preciseness of FEA. This method reduces computational expenses that are quite acceptable for robotics but requires some non-trivial actions to include passive and elastic joints in the mathematical model. Besides, displacements of each node (manipulator's active or passive joints) have a physical interpretation, which can be useful in some applications. A description of the fundamentals of the MSA method can be found in [32].

3.3.1 MSA Model

The MSA Model used in this thesis is the model from Deblaise's PhD thesis [26]. In his thesis, Deblaise incorporates an elasto-geometric model in the calibration of a Delta robot. He argues that to ensure that the identified parameters are realistic in relation to the actual behavior of the calibrated structure, the model used during identification must consider all significant sources of imprecision, whether geometric or not. Previous studies have shown that errors in identifying geometric parameters can lead to physical interpretation problems. The author suggests that elastic deformations of the structure under its own weight and at passive joints also have a significant effect on parameter identification errors.

Deblaise proposes two elastic models for the Delta robot. The first model does not take the compliance of the joints into account, while the second model does take it into account.

The models are very well detailed in Deblaise's thesis, and more succinctly in Deblaise et al. [33]. Nevertheless, a short overview will be written here. The

approach to determine the deformation of the Delta robot as a whole in response to a given external load can be summarized as follows:

1. Get the stiffness matrix of each beam in it's local frame.

a) The proximal arm is modelled by a cantilever beam fixed at the motor side and is defined by one node corresponding to it's other side (parallelogram side). The stiffness matrix of such a beam, neglecting shear forces, is a 6x6 square matrix:

$${}^L\mathbf{K}_p = \begin{bmatrix} \frac{E_1 S_1}{L_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12E_1 I_{z1}}{L_1^3} & 0 & 0 & 0 & \frac{-6E_1 I_{z1}}{L_1^2} \\ 0 & 0 & \frac{12E_1 I_{y1}}{L_1^3} & 0 & \frac{6E_1 I_{y1}}{L_1^2} & 0 \\ 0 & 0 & 0 & \frac{G_1 J_1}{L_1} & 0 & 0 \\ 0 & 0 & \frac{6E_1 I_{y1}}{L_1^2} & 0 & \frac{4E_1 I_{y1}}{L_1} & 0 \\ 0 & \frac{-6E_1 I_{z1}}{L_1^2} & 0 & 0 & 0 & \frac{4E_1 I_{z1}}{L_1} \end{bmatrix} \quad (3.46)$$

b) The distal arms and half of the connecting links are modelled by a beam defined by two nodes, the stiffness matrix is then a 12 dimensional square matrix.

$${}^L\mathbf{K}_d = \begin{bmatrix} \mathbf{K}_{11} & \mathbf{K}_{12} \\ \mathbf{K}_{21} & \mathbf{K}_{22} \end{bmatrix} \quad (3.47)$$

Where $\mathbf{K}_{22}$ is equal to the 6x6 matrix above, $\mathbf{K}_{11}$, $\mathbf{K}_{12}$, $\mathbf{K}_{21}$ are of the same shape, but are not completely equal to the 6x6 matrix.

2. Express the stiffness matrix of the proximal link, the 2 distal links and the 2 half upper connecting links in the reference frame and assemble them together as a stiffness matrix of one kinematic chain. This matrix can be found in [26].
3. Assemble the kinematic constraints of a kinematic chain. They are used to model the passive revolute joints, which are also the point of contact of the nodes of the different beams of the kinematic chain.

$$\mathbf{A}_C \Delta \mathbf{X}_C = \mathbf{0}$$

Matrix $\mathbf{A}_C$ is expressed in the reference frame and regroups all the kinematic relations, $\Delta \mathbf{X}_C$ is the vector of nodal displacements.

4. Take the boundary conditions into account for each kinematic chain.
5. Assemble the stiffness matrices of the 3 kinematic chains.

$$\mathbf{K}_T = \begin{bmatrix} \mathbf{K}_{C_1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{C_2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K}_{C_3} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$

6. Assemble the kinematic constraints between the 3 kinematic chains. They are used to model the passive revolute joints between the kinematic chains and the end effector/platform and the platform itself which is considered as a rigid body.

$$\mathbf{A}_T \Delta \mathbf{X}_T = \mathbf{0}$$

7. Minimize the potential energy of the whole structure to get the solutions of the structure displacements which satisfy the equilibrium conditions. This gives the global system of equations containing both the assembly of stiffness matrices and the kinematic constraints.

$$\begin{bmatrix} \mathbf{K}_T & \mathbf{A}_T^\top \\ \mathbf{A}_T & \mathbf{0} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{X}_T \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_T \\ \mathbf{0} \end{bmatrix}$$

Which can be rewritten as:

$$\mathbf{K}_G \Delta \mathbf{X}_G = \mathbf{F}_G$$

Where $\mathbf{K}_G$ is the global stiffness matrix of the Delta robot, $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers corresponding to the kinematic constraints.

8. Invert the global stiffness matrix to get the displacement as a function of the forces acting on the structure.

$$\Delta \mathbf{X}_G = \mathbf{K}_G^{-1} \mathbf{F}_G$$

It should be noted that the type of Delta robot used in Deblaise's thesis uses only revolute joints and no spherical joints (3-R(RPaR)), which is not the same as our type of Delta robot (3-R(2SS)). We assume here that the two models have the same elastic behavior.

The second model proposed by Deblaise takes the compliance of all the revolute joints into account. This means that all the revolute joints are not kinematic relations anymore, but are replaced by stiffness matrices. This difference makes the second model paradoxically slightly less complex than the first one.

Both models proposed by Deblaise have been implemented. To verify our implementation of the models, we will compare the results shown in [26] versus the results obtained from the implemented models. The following table shows the displacements obtained for a force vector

$$\mathbf{F} = [100 \text{ N} \quad 50 \text{ N} \quad -200 \text{ N} \quad 3 \text{ Nm} \quad -5 \text{ Nm} \quad 9 \text{ Nm}]^T$$

at the articular configuration resulting from the following motor positions:

$$[\theta_1 = 15^\circ \quad \theta_2 = 45^\circ \quad \theta_3 = 75^\circ]$$

	Displacements					
	$dP(\mu m)$			$\delta (10^{-6}\text{rad})$		
	X	Y	Z	θ_x	θ_y	θ_z
Deblaise's results	-73, 1	-418, 4	-875, 4	367, 7	-1369, 7	286, 5
CASTEM Model results	-73, 1	-418, 4	-875, 5	367, 7	-1369, 8	286, 5
Our results	-72, 8	-417, 8	-874, 0	366, 8	-1368, 0	286, 0

As seen in the table above, our results are accurate at 10^{-6} , which is sufficiently close. The slight differences are hypothesised/thought to be coming from the difference in geometric model used for the direct dynamics. Overall it can be said that the models are well implemented.

3.4 Dynamic modelling

Dynamic modelling is used to identify the forces on the different components of the delta robot, and the torques required to drive the robot. These forces and torques are used for the dimensionning of the delta robot. Our dynamic model has been done using a multi body model called ROBOTRAN. Two models have been implemented in ROBOTRAN, a rigid model and an elastic model. Both models are described in the next subsections.

3.4.1 Rigid multi body model

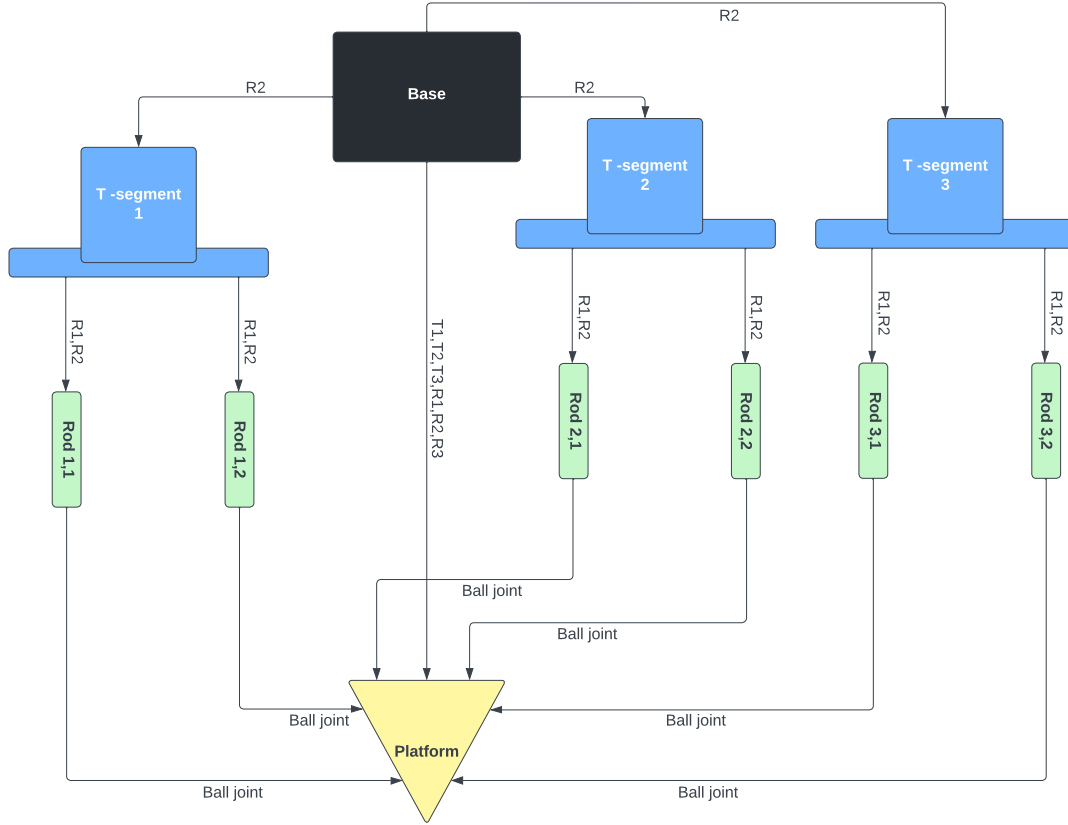


Figure 3.6: Multi body model of the delta robot

In the rigid model, all static components are modelled by one base body. Each delta robot moving component is modelled by one rigid body. The different bodies are connected by one or more degrees of freedom also called joints. Fig.3.6 shows a diagram of the modelled delta robot with all rigid bodies and degrees of freedom.

First, the platform is modelled to be free and given 6 degrees of freedom. Then, the three kinematic chains of the delta robot are constructed starting from the base with the motors modelled with a simple rotational degree of freedom. That rotational degree of freedom connects to the proximal link, which is itself rigidly connected to the connecting link.

The distal links are connected to the connecting link via the two necessary rotational degrees of freedom. Finally each kinematic chain is closed by 2 "ball cuts" connecting the distal links and the platform, forming a kinematic loop. Cuts are

necessary in multi-body systems presenting loops. The cuts break the loops and convert the constrained systems into unconstrained ones for further processing. Ball cuts act as an ideal ball joint and imposes three position constraints: the position vectors of the two connecting point must coincide at any time:

$$h(q, t) \triangleq x^Q(q, t) - x^P(q, t) = 0$$

The total degrees of freedom of the whole system can be computed by subtracting the total number of constraints from the total number of d.o.f. Each kinematic chain has 5 rotational d.o.f and 6 position constraints. Taking the 6 d.o.f of the platform into account, we have a total of $3 \times 5 + 6 - 3 \times 6 = 3$ degrees of freedom.

Of each body, the mass, center of mass and inertia matrix needs to be specified.

3.4.2 Joint forces and torques

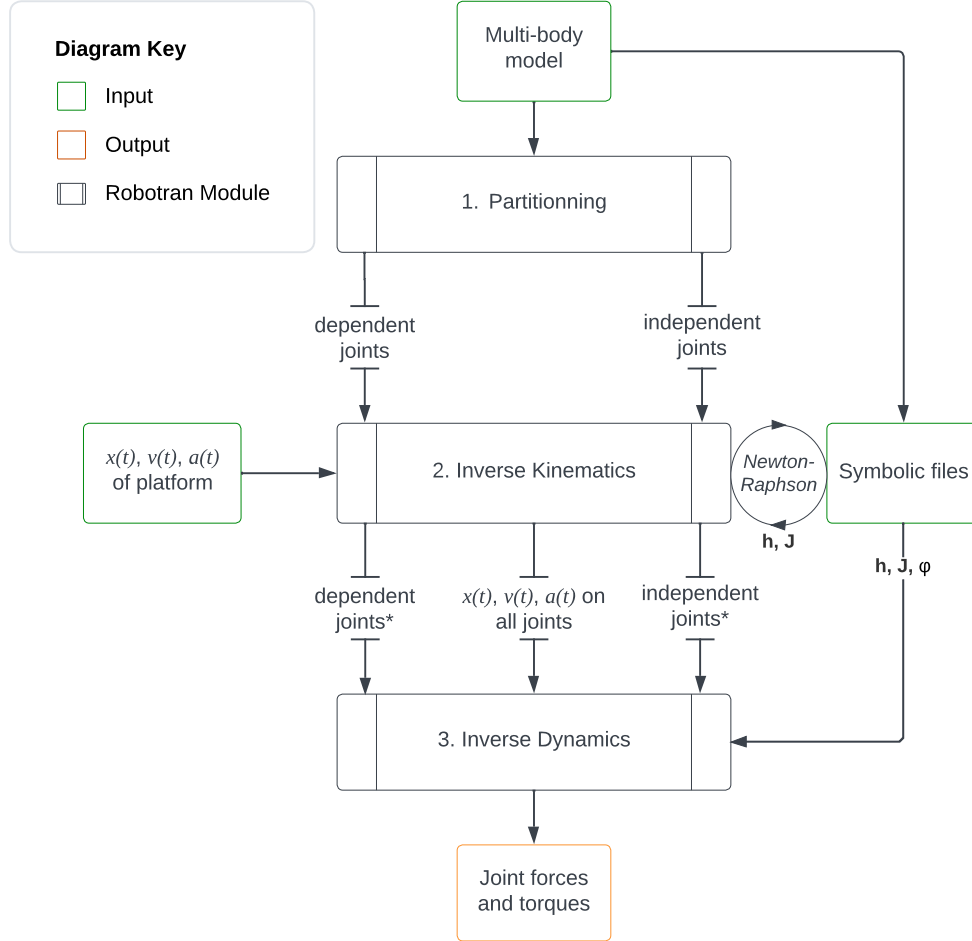


Figure 3.7: Dynamic model algorithm

The above diagram explains the dynamic model algorithm. The multi-body model indicates all the joints and generates the symbolic files. First, we have a partitioning of the joints into independent joints, and dependent joints denoted with subscript u and v respectively in the following. At this stage the independent joints are the 3 translational joints of the platform. All the other joints are dependent joints. From the trajectory planning (Section 2.3) we impose the position, velocity and acceleration of the 3 independent joints at all time.

The inverse kinematics module consists of closing the kinematic loops such that the ball cut constraints are satisfied and this way, get the position, velocity and

acceleration of all the joints of the model. This is done by iteratively calling the symbolic file that computes both the constraint jacobian matrix $J(q) = \frac{\partial h}{\partial q^i}$ and $h(q)$ which, as a reminder, should satisfy the following condition:

$$h(q) = 0 \quad (3.48)$$

The constraints are solved numerically by iterating with Newton/Rhapson to estimate q_v that satisfies $h(q) \leq \epsilon$:

$$q_v^{k+1} = q_v^k - (J_v)^{-1} h \Big|_{q_v=q_v^k} \quad (3.49)$$

When Newton/Rhapson has converged, q_v is equal to the relative position (in rotation or translation) of the dependent joints needed to have a closed configuration of the delta robot.

Finally, now that the final value of q_v and J are known, the velocity and acceleration of the dependent joints can be computed from the imposed velocities $\dot{q}_u$ and accelerations $\ddot{q}_u$ and the coupling matrix $B_{vu}(q)$:

$$B_{vu} = - (J_v)^{-1} J_u \quad (3.50)$$

$$\dot{q}_v = B_{vu} \dot{q}_u \quad (3.51)$$

$$\ddot{q}_v = B_{vu} \ddot{q}_u + b \quad (3.52)$$

$$b = - (J_v)^{-1} \dot{J} \dot{q} \quad (3.53)$$

Where $\dot{J} \dot{q}(q, \dot{q})$ is the quadratic term of the constraints at acceleration level and is computed with another symbolic file given by the multi-body model.

Before using the inverse dynamics module, a re-partitioning of the joints needs to be done. The 3 actuator joints become independent, while the 3 translation joints from the platform become dependent. Then, using the position, velocity and acceleration of all the joints previously computed, the symbolic files are used to compute both the constraint jacobian matrix $J = \frac{\partial h}{\partial q^i}$ and ϕ_i which contains the dynamics of the multi body system induced by the desired trajectory:

$$Q(q, \dot{q}) = \phi_i(q, \dot{q}, \ddot{q}, \delta?, g) \quad (3.54)$$

Finally, the coupling matrix is computed with the following equation:

$$B_{v^*u^*} = - (J_{v^*})^{-1} J_{u^*} \quad (3.55)$$

And is used to compute the torques needed at the actuators to comply with the wanted end effector trajectory as follows:

$$Q_a = \phi_{i,u^*} + B_{v^*u^*}^T \phi_{i,v^*} \quad (3.56)$$

3.4.3 Elastic multi body model

The goal of the dynamic elastic model is to compute the total elastic deflection of the end-effector while taking into account the dynamics for a given trajectory. Besides being interesting in itself, the model will mostly act as a validation tool for the dimensioning of the delta robot. In particular it will check that the distal links are not too flexible, as the static elastic model does not seem to vary greatly with the distal link dimensions.

The elastic model takes the rigid model and cuts every body other than the base and the platform into n sub-bodies. Like the static elastic model, the elastic elements are thus the proximal links, the connector links and the distal links. The degrees of freedom between the sub-bodies act as very stiff springs, to mimic the elasticity of the bodies. Ideally, there should be 6 degrees of freedom between each sub-body (3 translational and 3 rotational). In practice, only the relevant degrees of freedom are kept.

For all sub-bodies, the 3 translational degrees of freedom are neglected, as the corresponding stiffnesses are orders of magnitude bigger than the stiffness of the rotational degrees of freedom. Apart from being intuitive, this can be seen in the stiffness matrix of a cantilever beam (see the 3 first diagonal entries of Eq.3.46 vs the last 3 diagonal entries). Additionally, the rotational d.o.f along the axis of the link is only kept for the proximal arm. The way the delta robot behaves, there should be no elastic deflection along the axis of the connector and distal links, modelling elasticity is thus unnecessary.

The stiffness of the degrees of freedom k , is a function of the link's length, cross sectional shape and material and is found with the following formula:

$$k = \frac{EI}{\frac{L}{n}} \quad (3.57)$$

where E is the Young's Modulus, I is the second moment of area, L is the length of the link.

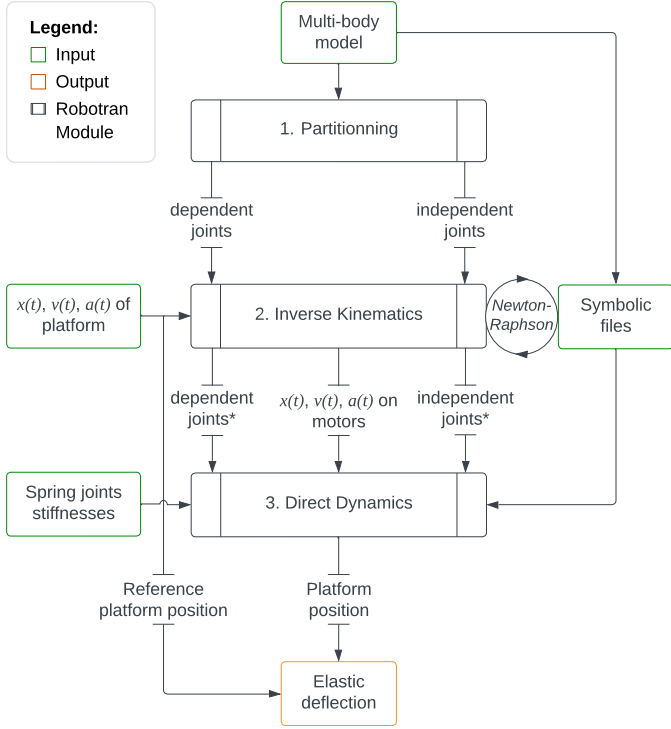


Figure 3.8: Dynamic model algorithm

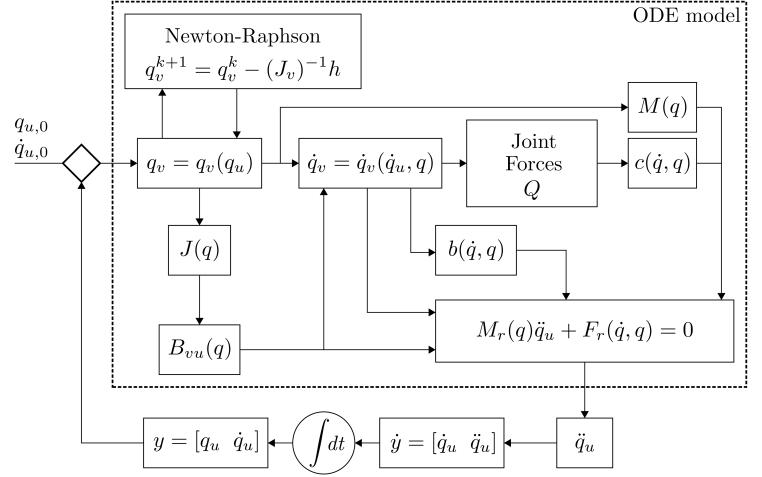


Figure 3.9: Direct dynamics from [34]

The algorithm of the elastic dynamic model shown on Fig.3.8 is similar to its rigid counterpart. The key difference is that the third step involves the direct dynamics module instead of the inverse dynamics module. The values of position, velocity and acceleration of the actuators found with the inverse kinematics are now imposed on the independent joints that are the motors. This simulates in a way the functioning of the delta robot for a the given trajectory.

The direct dynamics module (Fig.3.9) consist of finding the acceleration from the previously computed position and velocity and integrate for each time step. The accelerations are obtained by solving the following linear system for $\ddot{q}_u$:

$$M_r(q_u) \ddot{q}_u + F_r(\dot{q}_u, q_u) = 0 \quad (3.58)$$

Which is nothing more than Newton's third law. Where M_r is the (reduced) mass matrix and F_r the (reduced) force vector of the multi-body system. The way this system of equation is constructed is represented schematically on Fig.3.9 and is explained in detail in [34]. From the diagram we can see that M_r and F_r are constructed from $B_{vu}(q)$, $b(\dot{q}, q)$, $M(q)$ and $c(\dot{q}, q)$. The expression of $B_{vu}(q)$ and $b(\dot{q}, q)$ can be found in equation 3.50 and 3.53 respectively, $M(q)$ and $c(\dot{q}, q)$ are computed with a symbolic file stemming from the multi-body model.

As stated before, the joints between the sub-bodies act as very stiff springs. More precisely, the springs are modelled by joint forces $Q(q, \dot{q})$ with the following formula:

$$Q = kq + d\dot{q} \tag{3.59}$$

With k the stiffness of the joints as explained above. Some damping is introduced by the term $d\dot{q}$ and acts as a low pass filter to ease the numerical integration.

The numerical integrator used is a Rosenbrock integrator, which is stable for the stiffness of the system.

Chapter 4

Geometric synthesis of the Delta robot

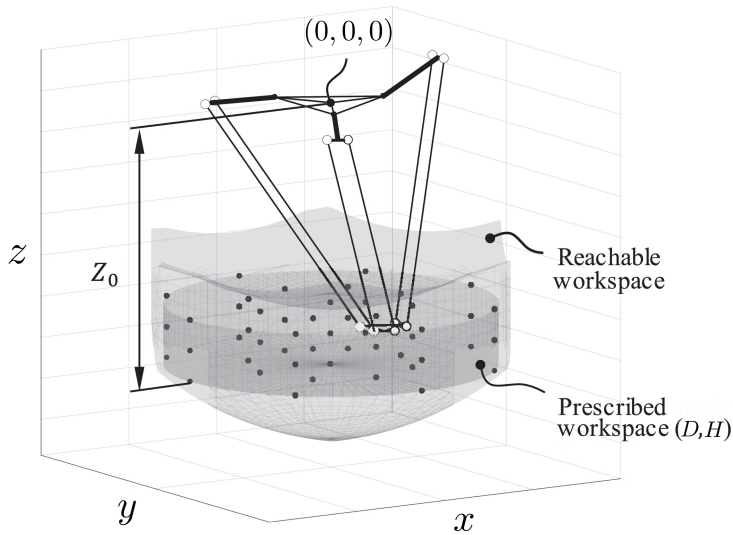


Figure 4.1: Workspace position Z_0 from [16]

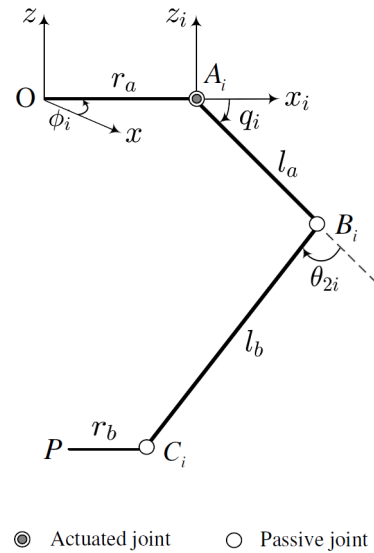


Figure 4.2: Link kinematic parameters

This chapter deals with the first dimensioning step, which is the geometric synthesis of the delta robot. The goal is to identify the optimal kinematic parameters of the Delta robot such that the prescribed workspace responds to a set of constraints and has optimal behaviour following performance indices. The kinematic parameters to be dimensioned are found in the table below and can be seen on Fig.4.1, 4.2 and 4.3.

Parameter	Description	Unit
r_a	radius of base platform	[m]
l_a	proximal link length	[m]
l_b	distal link length	[m]
r_b	radius of moving platform	[m]
d_s	connecting link length	[m]
Z_0	z position of the middle of the workspace	[m]

Clavel in [12] gives a design plan to work out these parameters considering singularities, link collisions, accuracy, dynamics, etc. In this thesis, an original synthesis plan is proposed. However, to reduce the number of parameters, some constraints dictated by Clavel are used.

1. $r = r_a - r_b$: Only r appears in the kinematic models.
2. $d_s = l_a/4$: Clavel states that, for medium robots, it is a good compromise between stability of the end effector, total mass of the manipulator and stiffness.
3. $r_b = d_s/2$: this constraint is obvious considering the assembly of the Delta robot. Indeed, $r_b < d_s/2$ is impossible, $r_b > d_s/2$ does not provide good stiffness.

With these constraints, the number of parameters have been reduced to 4. The geometric synthesis concerns the parameters: r , l_a , l_b , Z_0 .

The structure of the chapter is as follows, first the singularities of the delta robot will be identified and discussed. Then, the performances indices on which the geometric synthesis is based are presented. After a presentation of the design method, the results are shown.

4.1 Delta robot singularities

As Gogu beautifully states in [35, 36]:

"In a general mathematical sense, a singularity is a point at which a given mathematical model is not defined or fails to be well-behaved in some particular way. In engineering, a singularity is a configuration of a system in which the subsequent behaviour cannot be predicted. In a singular configuration, the underlying equations of the mechanical model exhibit a mathematical singularity. The corresponding motions, forces, or other physical parameters modelled by these equations become undetermined."

Identifying singularities is thus crucial to have a predictable behavior of the robot and be able to control it. A lot of effort has been made to identify and classify these singularities. Consequently a lot of different classifications have emerged. Gogu [35] gives an overview of the different classifications of singularities for parallel robots. The following subsections will treat two of these classifications and the application on the Delta robot.

4.1.1 Analysis of the two part Jacobian

One of the common methods for singularity analysis of parallel manipulators is using the Jacobian matrix. In section 3.1.4, the Jacobian matrix got developed to the following expression:

$$\mathbf{J}_p \cdot \dot{\mathbf{p}} = \mathbf{J}_s \cdot \dot{\mathbf{q}} \quad (4.1)$$

Where $\mathbf{J}_p$ is called the parallel Jacobian matrix or direct kinematic matrix and $\mathbf{J}_s$ is called the serial Jacobian or inverse kinematic matrix [35, 37]¹. The advantage is that a two-part Jacobian allows, in a natural way, the identification as well as classification of various types of singularities.[38]

In 1990, Gosselin and Angeles [39] addressed the analysis of singularities of parallel mechanisms from a two-part Jacobian and classified the singularities into three types.

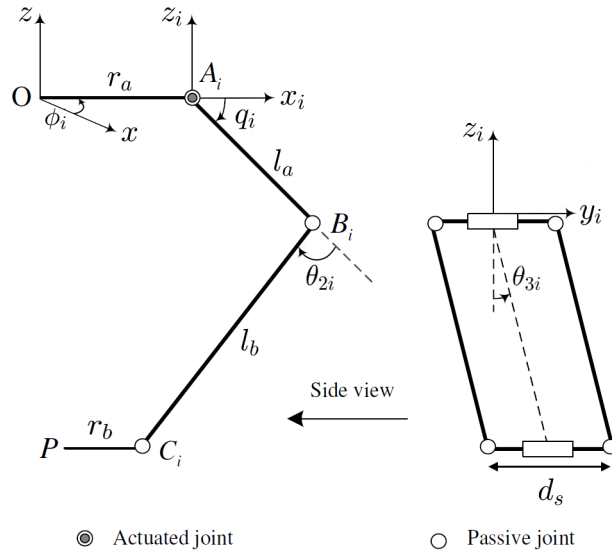


Figure 4.3: Kinematic angles of a kinematic chain from [40] (modified)

¹It seems like Gogu in [35] swaps the name of the inverse and direct kinematic matrix

A) Type I singularities

Type I singularities, also called inverse kinematic singularities or serial singularities occur when $\mathbf{J}_s$ is singular, so when its determinant is zero. In a serial singular configuration, the input links can have a nonzero velocity while the output link (platform) is at rest. In these configurations, the robot loses the ability to generate certain velocities $\dot{\mathbf{p}}$ at the output, and thus loses one or more degrees of freedom. This implies that the output link can resist one or more forces or moments without exerting any torque or force at the powered joints. This can be understood more intuitively by rewriting Eq.4.1 as:

$$\dot{\mathbf{q}} = \mathbf{J}_s^{-1} \mathbf{J}_p \cdot \dot{\mathbf{p}} = \frac{\text{adj}(\mathbf{J}_s)}{\det(\mathbf{J}_s)} \mathbf{J}_p \cdot \dot{\mathbf{p}} \quad (4.2)$$

Where $\dot{\mathbf{p}}$ is forced to be zero because $\dot{\mathbf{q}}$ cannot be infinite.[38] To visualize these singularities, we express $\det(\mathbf{J}_s)$ as a function of the kinematic angles θ_{2i} and θ_{3i} (4.3).

$$\det(\mathbf{J}_s) = \prod_{i=1}^3 (l_a^i \mathbf{w} \cdot {}^{\perp i} \mathbf{v}) = l_a^3 \prod_{i=1}^3 \sin \theta_{2i} \cos \theta_{3i} \quad (4.3)$$

$${}^i \mathbf{w} = \mathbf{R}_y(q_i + \theta_{2i}) \mathbf{R}_z(\theta_{3i}) \mathbf{e}_x = \begin{bmatrix} \cos(\theta_{3i}) \cos(q_i + \theta_{2i}) \\ \sin(\theta_{3i}) \\ -\sin(q_i + \theta_{2i}) \cos(\theta_{3i}) \end{bmatrix} \quad {}^{\perp i} \mathbf{v} = \begin{bmatrix} -\sin q_i \\ 0 \\ -\cos q_i \end{bmatrix} \quad (4.4)$$

Inverse kinematic singularities happen when any of the kinematic chain has either:

- $\theta_{2i} = 0$ or $\theta_{2i} = \pi$, which corresponds to the configuration where for kinematic chain i , both distal links are in the same plane as the proximal link.
- $\theta_{3i} = \pm \frac{\pi}{2}$, which corresponds to the configuration where for kinematic chain i , one of the proximal links is perpendicular to the distal link in the proximal link's xy-plane.

These singularities occur at the boundary of the Delta robot's reachable workspace.

B) Type II singularities

Type II singularities, also called direct kinematic singularities or parallel singularities occur when $\mathbf{J}_p$ is singular. In a parallel singularity, output link velocities can be non-zero while input link velocities remain zero, a situation documented as particularly undesirable due to the manipulator's inability to withstand any force, leading to a loss of control [37]. Type II singularities occur within the

workspace. Similar reasoning to Eq. 4.2 can be applied. In cases of direct singular configurations, non-zero vectors $\dot{\mathbf{p}}$ result in zero vectors $\dot{\mathbf{q}}$, indicating that the manipulator is incapable of withstanding forces even with locked actuators, and introducing additional degrees of freedom at the end-effector. The implications on the delta robot are addressed by analysing the determinant of $\mathbf{J}_p$:

$$\det(\mathbf{J}_p) = \mathbf{w}_1^T \cdot (\mathbf{w}_2 \times \mathbf{w}_3) = \mathbf{w}_2^T \cdot (\mathbf{w}_3 \times \mathbf{w}_1) = \mathbf{w}_3^T \cdot (\mathbf{w}_1 \times \mathbf{w}_2) \quad (4.5)$$

A type II singularity happens in configurations where a distal link from any kinematic chain is linearly dependent with a distal link from another kinematic chain. Explained in a more geometric way, the delta robot is in a parallel singularity if any distal link is parallel to another distal link (distal link from the same kinematic chain excluded of course)[41]. Lopez et al [38] worked out some configurations for this type of singularity by forcing the last column of $\mathbf{J}_p$ to be equal to zero:

$$\mathbf{J}_{p_{i,3}} = \begin{bmatrix} \sin(q_1 + \theta_{21}) \cos \theta_{31} \\ \sin(q_2 + \theta_{22}) \cos \theta_{32} \\ \sin(q_3 + \theta_{23}) \cos \theta_{33} \end{bmatrix} = \vec{0} \Rightarrow \begin{cases} \theta_{3i} = \pm\pi/2 & \forall \quad i = 1, 2, 3; \\ q_i + \theta_{2i} = 0 & \forall \quad i = 1, 2, 3; \\ q_i + \theta_{2i} = \pi & \forall \quad i = 1, 2, 3 \end{cases}$$

Some of these configurations are purely mathematical, as they would not be physically possible due to collisions between linkages.

C) Type III singularities

Type III singularities, also called combined singularities, arise when both $\mathbf{J}_s$ and $\mathbf{J}_p$ matrices have zero determinants. This category encompasses simultaneous situations of the first two types, yet these type of singularity is different than the first two types[39], and has been redefined many times in the literature [35]. It corresponds to configurations where the manipulator can exhibit finite motion despite locked actuators or no motion despite finite motion of the actuators. Zhao [41] states that the delta robot exhibit combined singularities if the following two conditions are satisfied simultaneously: (i) The geometry of the moving platform is identical to that of the base platform and (ii) all the three input links are perpendicular to the fixed base.

4.1.2 Undetected singularities & closeness measure

The analysis of the two part Jacobian gives some great geometrical insights about the singularities of the delta robot. However, this is not the end of the story. Indeed, in 2002 Han et al. [42] identified a new type of singularity in lower mobility parallel manipulators that failed to be detected by the two part Jacobian. This

new type of singularity was later named constraint singularity by Zlatanov et al. [35, 43]. Constraint singularities occur when the limbs of a limited-DOF parallel manipulator lose their ability to constraint the moving platform to the intended motion, gaining at least one additional DOF [44].

Additionally, there also exist architectural singularities that fail to be detected by the two part Jacobian. In the delta robot this type of singularity happens when the dimensions of the moving and fixed platforms are comparable [38]. Some methodologies are proposed to identify the constraint and architectural singularities of limited DOF parallel robots. An example among others is by Joshi and Tsai [44] who introduces a "global Jacobian" by using the theory of reciprocal screws.

The point of singularity analysis in this thesis, besides gaining understanding of the manipulator, is to design the delta robot's kinematic parameters such that it operates in a workspace far from singularities. In this regard, Liu et al. [45] propose a new approach for singularity analysis of parallel manipulators by taking into account motion/force transmissibility. Such an approach is able to not only identify all possible singularities but also explains their physical meanings in terms of motion/force transmission.

The paper classifies the singularities of a limited-DOF parallel manipulator into three types: input transmission singularities, output transmission singularities and constraint singularities. Each singularity is associated with (introduces) a performance index that is configuration dependent, frame free and with a value between $[0, 1]$:

- Input transmission index (ITI) : measures closeness to input transmission singularities
- Output transmission index (OTI) : measures closeness to output transmission singularities
- Constraint transmission Index (CTI) : measures closeness to constrain singularities

It should be noted that these indices do not measure the distance to the singularities but are proportional to the distance. In fact there exists no mathematical metric defining the distance between a prescribed pose and a given singular pose for parallel robots.[46]

In the following section, these performance indices will be applied to the delta robot following the extended work of Brinker et al. [16, 47, 48].

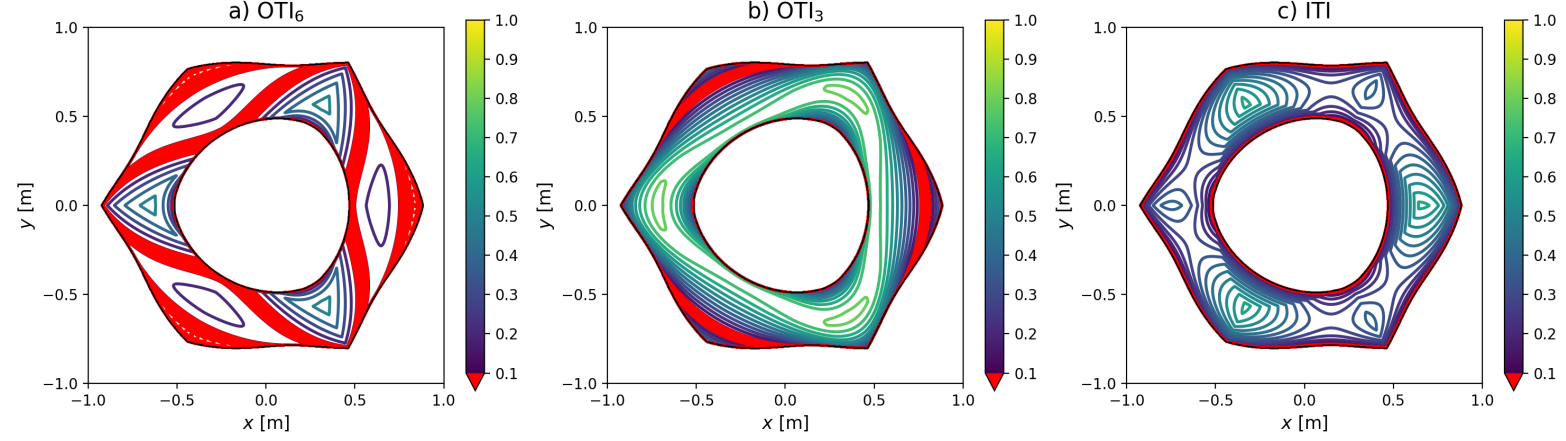


Figure 4.4: Distribution of OTI_6 , OTI_3 and ITI for the plane $z = -0.24[m]$ where l_a, l_b, r_a, r_b, d_s is equal to 0.4, 0.8, 0.2, 0.05, 0.1[m] respectively. The Delta robot parameters used is the same as in [16] where we can observe the same results, showing the good implementation of the transmission indices.

4.2 Performance indices

4.2.1 Input Transmission Index (ITI)

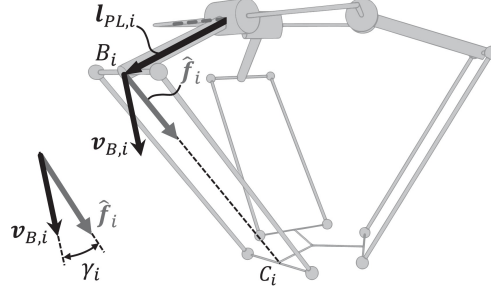


Figure 4.5: Input transmission index from [16]. $l_{PL,i}$ is the i th proximal arm vector, $\hat{f}_i$ is the unit vector in the direction of the i th distal link (equivalent to $\mathbf{w}_i$) and $\mathbf{v}_{B,i}$ is the velocity of the i th distal arm at point B_i

As said previously, the ITI measures closeness to input transmission singularities. The input transmission index for the delta robot has been covered plenty in the literature [16, 47–50]. It's expression is:

$$ITI = \min(|\cos \gamma_i|) \quad \forall i = \{1, 2, 3\} \quad (4.6)$$

Where:

$$\cos \gamma_i = \frac{\hat{\mathbf{f}}_i^T \mathbf{v}_{B,i}}{\|\mathbf{v}_{B,i}\|} = \mathbf{w}_i^T \cdot {}^\perp \mathbf{v}_i = {}^i \mathbf{w}^T \cdot {}^\perp {}^i \mathbf{v} \quad (4.7)$$

$$\cos \gamma_i = \sin \theta_{2i} \cos \theta_{3i} \quad (4.8)$$

Which is exactly the minimum of the diagonals of the inverse kinematic matrix $\mathbf{J}_s$ (Eq.3.39). Looking at Eq.4.8, the link with the inverse singularities is also obvious. The angle γ_i can be interpreted as the pressure angle of the input transmission. This is the angle between the velocity of point B_i (along ${}^\perp \mathbf{v}_i$), and the driving force (along $\mathbf{w}_i$) imposed by the proximal link to the distal link at the same point.[50] A high ITI, means a good force/motion transmission and a long "distance" from transmission singularity. The best transmission happens when the velocity of the proximal arm at point B_i is aligned with the distal link, thus when $\gamma_i = 0$.

4.2.2 Output Transmission Index (OTI)

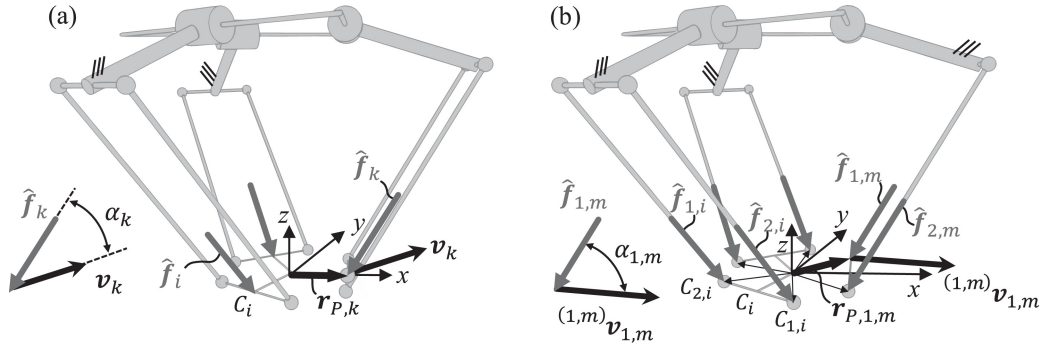


Figure 4.6: Output transmission index from [16]. (a) OTI_3 with 3 supporting links. (b) OTI_6 with 6 supporting links. $\hat{\mathbf{f}}$ is the unit force vector in the direction of distal the link (equivalent to $\mathbf{w}$) and $\mathbf{v}$ is the output velocity of the platform.

The output transmission index measures the closeness to an output transmission singularity. Brinker et al.[16] proposes two types of output transmission indices for the delta robot. The first index is called OTI_3 and as the name suggest, models the system with three supporting links (see 4.6(a)). This index is computed as follows:

$$\text{OTI}_3 = \min(|\cos \alpha_k|) \quad \forall k = \{1, 2, 3\} \quad (4.9)$$

Where:

$$\cos \alpha_1 = \left(\frac{\mathbf{w}_1^T (\mathbf{w}_2 \times \mathbf{w}_3)}{\|\mathbf{w}_2 \times \mathbf{w}_3\|} \right) \quad \cos \alpha_2 = \left(\frac{\mathbf{w}_2^T (\mathbf{w}_3 \times \mathbf{w}_1)}{\|\mathbf{w}_3 \times \mathbf{w}_1\|} \right) \quad \cos \alpha_3 = \left(\frac{\mathbf{w}_3^T (\mathbf{w}_1 \times \mathbf{w}_2)}{\|\mathbf{w}_1 \times \mathbf{w}_2\|} \right)$$

Again, we recognize the similarities with the determinant of the corresponding direct kinematics matrix $\mathbf{J}_p$. The angle α_k can be interpreted as the pressure angle of the output transmission. As an example, α_1 represents the angle between the driving force (along $\mathbf{w}_1$) imposed by the distal link 1 at point C_1 , and the velocity (along $\mathbf{w}_2 \times \mathbf{w}_3$) at point C_1 (4.6(a)) [50]. The problem with OTI_3 is that the constraint singularities are not taken into account. To take the constraint singularities into account, the CTI can be computed. Another possibility is to use OTI_6 .

Brinker et Al. [16] propose a physically meaningful measure, which aggregates the transmission and constraint characteristics into a single index for a 2R(2SS) Delta robot. The second output transmission index OTI_6 models the system with six supporting links (see 4.6(b)). The virtual coefficient is given by the dot product of the pure force and the linear velocity at the respective spherical joint.

$$\text{OTI}_6 = \min(|\cos(\alpha_{k,m})|) \quad \forall k = \{1, 2, 3\}, \forall m = \{1, 2\} \quad (4.10)$$

With:

$$\cos(\alpha_{k,m}) = \frac{{}^{(k,m)}\mathbf{v}_{k,m}^T \hat{\mathbf{f}}_{k,m}}{\|{}^{(k,m)}\mathbf{v}_{k,m}\|} \quad (4.11)$$

Where the linear velocity $\mathbf{v}_{k,m}$ at connecting joint (k, m) is found by solving the following system of 6 equations for $i = \{1, 2, 3\}$ and $j = \{1, 2\}$:

$$\begin{cases} \left[\begin{array}{c} (\mathbf{r}_{p,i,j} - \mathbf{r}_{p,k,m}) \times \hat{\mathbf{f}}_{i,j} \\ \hat{\mathbf{f}}_{i,j} \end{array} \right]^T \cdot \begin{bmatrix} \mathbf{w}_{k,m} \\ \mathbf{v}_{k,m} \end{bmatrix} = 0 & \forall (i, j) \neq (k, m) \\ w_{x_{k,m}} + w_{y_{k,m}} + w_{z_{k,m}} + v_{x_{k,m}} + v_{y_{k,m}} + v_{z_{k,m}} = 1 \end{cases} \quad (4.12a)$$

$$\quad \quad \quad (4.12b)$$

The higher OTI_6 , the better the kinematic performance.

4.2.3 Workspace ratio

The workspace ratio is defined as follows:

$$\rho = \frac{V_{\text{PW}}}{V_{\text{RW}}} = \frac{\pi H D^2}{4 V_{\text{RW}}} \quad (4.13)$$

Where V_{PW} is our prescribed workspace volume, and V_{RW} is the volume of the reachable workspace for an arbitrary motor range big enough to encompass the prescribed workspace (here chosen to be from -50° to 100°). H and D are the height and the diameter of the prescribed cylindrical workspace respectively.

This index is introduced to constrain the size of the robot. Because the bigger the links, the bigger the reachable workspace thus the better the behavior of the robot for a given volume.

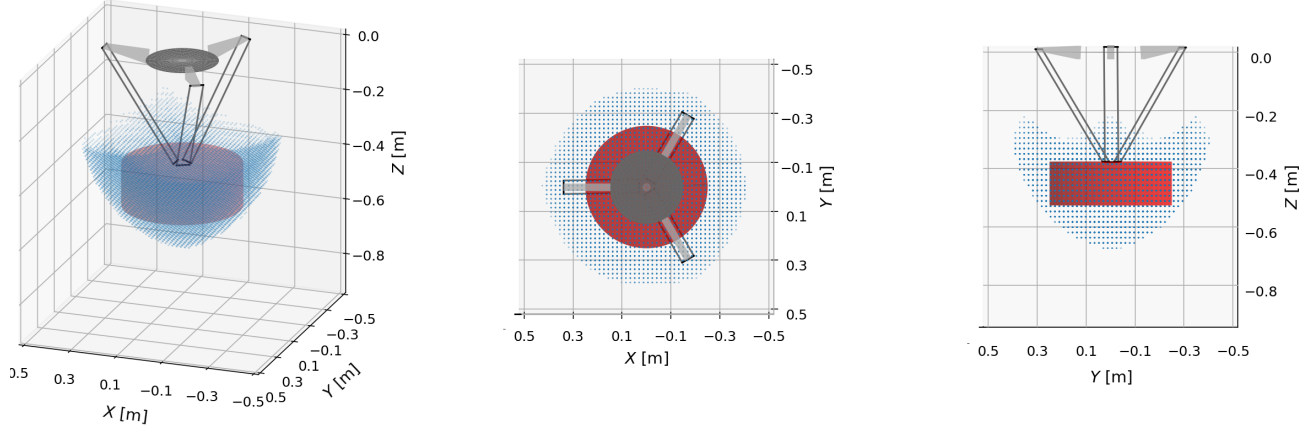


Figure 4.7: Prescribed cylindrical workspace vs reachable workspace for motor ranges from -50° to 100°

4.2.4 Tilt angle

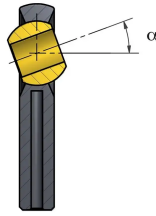


Figure 4.8: Tilt angle of a rod end spherical joint

The 3-R(2-SS) variant of the Delta robot uses a total of 12 spherical joints to give the delta robot its mobility. In reality, these spherical joints do not have infinite rotational motion range. They are limited in two of the three DOF by the tilt angle, which is represented on figure 4.8 for a rod end spherical joint. This tilt angle is equivalent to the kinematic angle θ_{3i} from 4.3, which can be computed from Eq.4.4:

$$\theta_{3i} = \arcsin {}^i w_y \quad (4.14)$$

It is thus important to constrain this tilt angle appropriately to be able to translate the design in the real world. Clavel [12] mentions a limit of $\pm 40^\circ$. For rod-end

spherical joints a limit of $\pm 30^\circ$ is more realistic. Restricting the tilt angle also helps avoiding collisions between the distal links and the proximal links.

4.2.5 Resolution/positioning error

The resolution of the end effector for a given resolution of the actuators, or the relative error of the end effector due to a relative error of the actuators is directly found with the Jacobian:

$$\Delta \mathbf{p} = \mathbf{J} \Delta \mathbf{q} \quad (4.15)$$

The index is the maximum end effector displacement of the 2^3 possible displacements of the actuators $\Delta \mathbf{q}$ for a certain point in the workspace.

The resolution has a direct impact on the accuracy of the manipulator and can be compared to the condition number in the sense that it expresses the position error amplification factor. In fact, Merlet in [51] concludes that the most appropriate accuracy indices for parallel robots are the determination of the maximal positioning errors, their average values and their variance.

4.2.6 Torque Index

The kinematic behavior of the robot in the prescribed workspace is important, but dynamics should not be neglected. Introducing the dynamics in the early design phases will lower the required torques significantly. The dynamic model presented in section 3.4 will be used together with the reference pick and place trajectory from section 2.3.1. The index are the RMS torque and the peak torque of the trajectory for a time t .

There is also the possibility to use a torque index without having to compute a dynamic model. Zhang et al. [50] proposes an inertial torque index based on the the pressure angles γ_i and α_i from ITI and OTI₃ respectively:

$$\tau_{ai} = I_A \sqrt{\frac{\eta^2 l_a^2 \cos^2 \gamma_i}{\cos^2 \alpha_i} + \frac{1}{l_a l_b \cos^2 \gamma_i} + 2\eta} \quad \eta = \frac{m}{I_A} \quad (4.16)$$

Where m is the equivalent mass of the movable platform and I_A is the equivalent moment of inertia of the proximal link about the axis of rotation, including the contributions from the active proximal link, the motor rotor and the lumped mass of the distal links. The particularity of this index is that the torque index can be evaluated on the whole workspace and not only for a given trajectory.

4.3 Design method

Traditionally, the geometric synthesis of parallel manipulators has been approached as an optimization problem, as discussed by Merlet and Gosselin in [46]. Each performance requirement, whether related to workspace dimensions, accuracy, or rigidity, is quantified through a performance index. The combination of these indices into a weighted cost function forms the basis for the optimization. The aim is to minimize this cost function by adjusting the geometric design parameters, culminating in what is referred to as optimal design. However, this approach is not without its challenges. The determination of weight factors for the cost function, the nuanced definition of performance indices, and the numerical optimization methods used present complexities that can hinder the effectiveness of the optimization process.

As an alternative to this optimization paradigm, the notion of appropriate design emerges. This concept, diverges from the optimization-driven path and instead focuses on ensuring that specified requirement constraints are met. This approach uses a parameter space, where each dimension corresponds to a design parameter. Successive consideration of performance indices allows for the computation of regions within this parameter space that correspond to robots fulfilling those requirements.

The design approach for the geometric synthesis, is mostly based on the appropriate design method. However, some optimization of the performance indices will be taken into account.

The parameters to dimension are : $[r, l_a, l_b, Z_0]$. Before starting the process, a constraint is imposed on r by defining an non dimensional parameter δ .

$$\delta = \frac{D}{2(r + l_a)} \implies r = \frac{D}{2\delta} - l_a \quad , \quad \delta \in [0.8; 1.2] \quad (4.17)$$

If δ is greater than 1, the proximal arm will always remain within the limits of the prescribed cylinder diameter. Similar to the workspace ratio concept, the aim is to ensure the robot's dimensions are consistent with its prescribed workspace. This newly introduced parameter serves to normalize r and simplify its interpretation, thereby enabling the imposition of a specific range on the parameter.

Algorithm 1 Geometric synthesis algorithm

Input: δ, l_a, l_b, D, H

Output: Values of performance indices for the restricted parameter space

```
for all  $\delta$  do
  for all  $l_a, l_b \in [l_{a_{\min}}; l_{a_{\max}}] \times [l_{b_{\min}}; l_{b_{\max}}]$  do
    if Dimensional/Workspace ratio constraints are not met then
      break
    else
      for all  $Z_0 \in [-(l_a + l_b); 0]$  do
        Discretize the prescribed cylindrical workspace  $W(D, H)$ 
        if Some points of  $W$  are not reachable then
          break
        else
          Compute the performance indices of all points  $\mathbf{p} \in W$ 
          if One of the performance constraints is not satisfied then
            break
          else
            Return the performance indices for further processing
          end if
        end if
      end for
    end if
  end for
end for
```

Algorithm 1 shows the process of finding the restricted parameter space that fulfills the set of constraints found in table 4.1. The constraints are evaluated on the set of all possible solutions. If the constraints are satisfied, the solution is added to the restricted parameter space.

In table 4.1 the workspace evaluation indicates how the performance indices are evaluated in the workspace. For example, the characteristic value of ITI for the whole workspace is it's minimum value. The optimization criteria indicates how the performance index is evaluated on the parameter space $\mathbf{k} = [\delta, l_a, l_b, Z_0]$. The optimum value of ITI is it's maximum value in the parameter space.

The constraint values are either chosen as appropriate bounds, or found in the literature. For example, $r_a > 50[mm]$ is chosen to have enough space for the mounting of the actuators, the maximum absolute value of $\theta_{3i_{\max}}$ is discussed in section 4.2.4. The limit values of OTI₃ and ITI are found in the literature [16, 50].

Finally, the resolution constraint comes from the specifications of the robot.

Dimension/ Performance index	Workspace evaluation	Constraint	Optimization criteria
r_a	/	$r_a > 50[mm]$	/
Workspace ratio	/	$\rho > 0.2$	$\max_{\mathbf{k}}(\rho)$
Tilt angle	$\theta_{3i_{\max}} = \max_{\mathbf{p} \in W}(\theta_{3i})$	$\theta_{3i_{\max}} \leq 30^\circ$	/
OTI ₃	$\text{OTI}_{3,\min} = \min_{\mathbf{p} \in W}(\text{OTI}_3)$	$\text{OTI}_{3,\min} > \cos 70^\circ$	/
ITI	$\text{ITI}_{\min} = \min_{\mathbf{p} \in W}(\text{ITI})$	$\text{ITI}_{\min} > \cos 50^\circ$	$\max_{\mathbf{k}}(\text{ITI}_{\min})$
Resolution	$\Delta p_{\max} = \max_{\mathbf{p} \in W}(\Delta p)$	$\Delta p_{\max} < 0.6 [\text{mm}]$	$\min_{\mathbf{k}}(\Delta p_{\max})$
OTI ₆	$\text{OTI}_{6,\min} = \min_{\mathbf{p} \in W}(\text{OTI}_6)$	/	$\max_{\mathbf{k}}(\text{OTI}_{6,\min})$
τ_{ai}	$\tau_{aG} = \max_{\mathbf{p} \in W}(\tau_{ai})$	/	$\min_{\mathbf{k}}(\tau_{aG})$

Table 4.1: Constraints and optimization criteria

Dimension	Value	Performance index	Evaluated workspace value	Mean workspace value
r_a	0.15 [m]	Workspace ratio	$\rho = 0.285$	/
l_a	0.19 [m]	Tilt angle	$\theta_{3i_{\max}} = 30^\circ$	/
l_b	0.5 [m]	ITI	$\text{ITI}_{\min} = 0.644$	0.861
d_s	0.055 [m]	OTI ₆	$\text{OTI}_{6,\min} = 0.426$	0.619
r_b	0.0275 [m]	Resolution	$\Delta p_{\max} = 0.574 [\text{mm}]$	0.415 [mm]
Z_0	-0.45 [m]	τ_{ai}	$\tau_{aG} = 0.227$	0.212

Table 4.2: Values obtained for the geometric synthesis of the Delta robot

4.4 Results

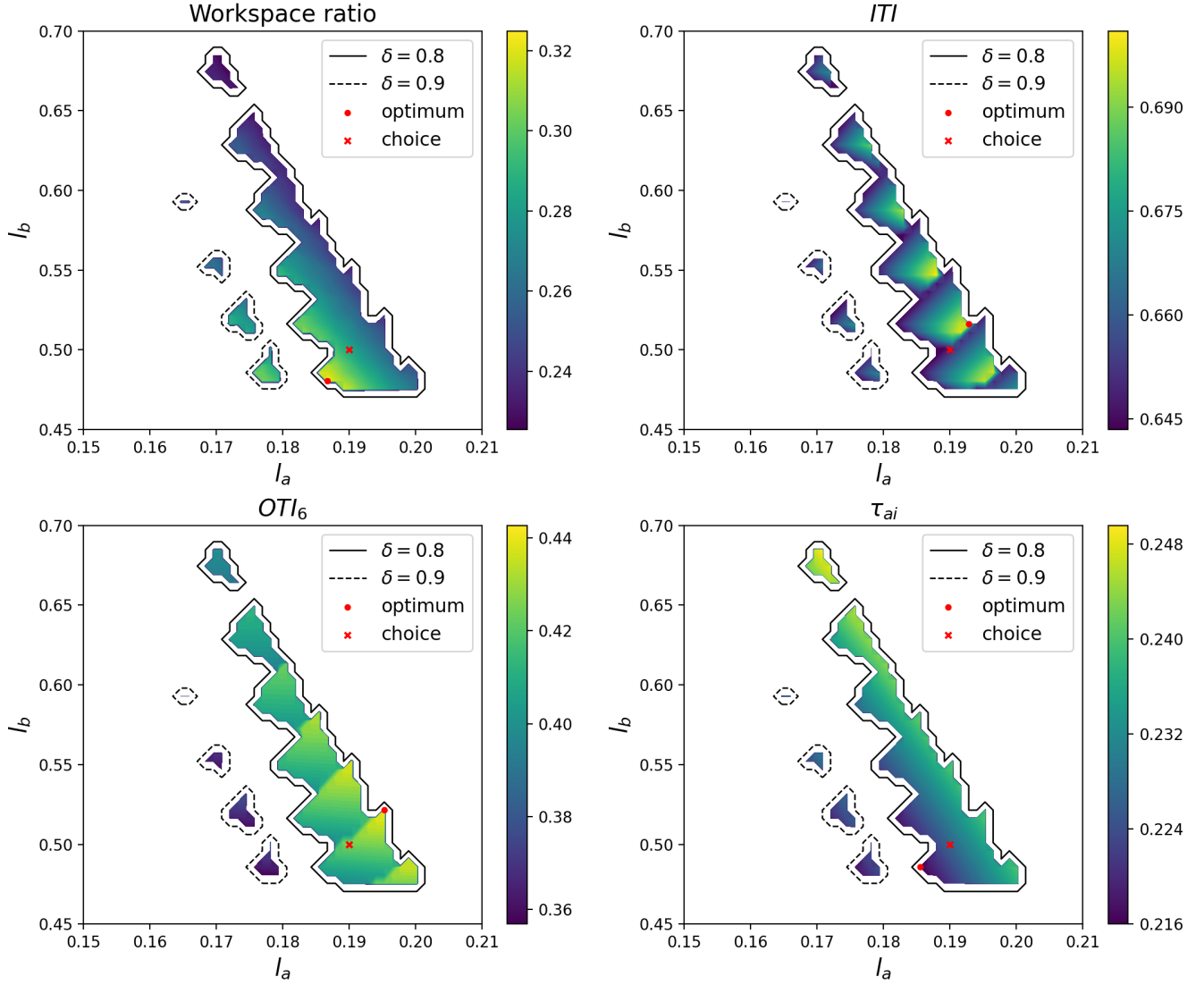


Figure 4.9: Restricted parameter space of Workspace ratio, ITI, OTI₆ and τ_{ai} for $\delta = [0.8, 0.9, 1.0, 1.1, 1.2]$

Fig.4.9 presents the restricted parameter space for different performance indices. As can be observed, the space is quite small after satisfying all constraints. For $\delta = [0.8, 0.9, 1.0, 1.1, 1.2]$, only 0.8 and 0.9 are defined on the restricted parameter space. The lower δ the bigger the the restricted parameter space. Fig.4.10b) shows that the lower δ , the better the performance indices. Consequently, $\delta = 0.8$ is taken.

The choice of l_a and l_b is done by trying to optimize the different performance indices. It is not surprising to see that the optimum of the different performance indices are on the boundary of the restricted parameter space. A certain margin needs to be taken into account to ensure that the constraints on the prescribed workspace are always satisfied, even with the tolerance errors on the different components of the Delta robot. The final choice of $l_a = 0.19[m]$ and $l_b = 0.5[m]$ has been taken as the centroid of the optimum points of the different performance indices. This choice is a good compromise between the performance indices. Only ITI is on the lower side, but the values of ITI are already satisfying and do not vary much on the restricted workspace.

Taking l_b in the lower range reduces the cost of the Delta robot, as some common materials used for the distal links like carbon fiber can be expensive per unit length.

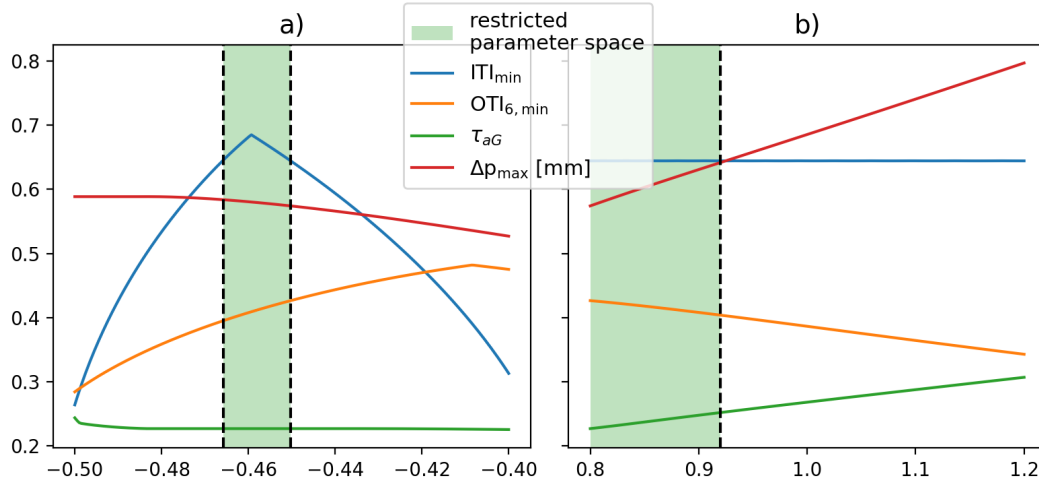


Figure 4.10: a) Variation of the workspace evaluation of the performance indices with Z_0 for $\delta = 0.8$. b) Variation of the workspace evaluation of the performance indices with δ for $Z_0 = -0.45[m]$

The definitive value of Z_0 is chosen by looking at the behavior of the performance indices with δ , l_a , l_b fixed previously. Fig.4.10a) indicates that $Z_0 = -0.46$ optimizes ITI, while $Z_0 = -0.45$ optimizes OTI₆ and the resolution. Both choices are valid, but the latter value of Z_0 is chosen.

Table 4.2 summarizes the values obtained for the geometric synthesis of the Delta robot. It should be noted that the value of d_s in the table is not equal to $l_a/4$. This is because the final value of d_s is found during the proximal link synthesis, because it impacts the potential collisions between the proximal and distal links.

The value of $l_a/4$ is only temporary. However, it should also be noted that all the evaluated performance indices in the workspace are the same with both value of d_s . This is because r and r_b/d_s do stay the same.

Chapter 5

Link dimensional synthesis of the Delta robot

In this chapter, the dimensions of the different components of a kinematic chain are synthesised.

A kinematic chain is composed of the following elements:

- 1 proximal link
 - 4 spherical joints
 - 2 connecting links
 - 2 distal links
- } parallelogram

The dimensions of the elements of the kinematic chain are intrinsically linked. Figure 5.4 explains the design/dimensioning process for the kinematic chain. The forces on the different elements are identified using the dynamic model explained in section 3.4.2.

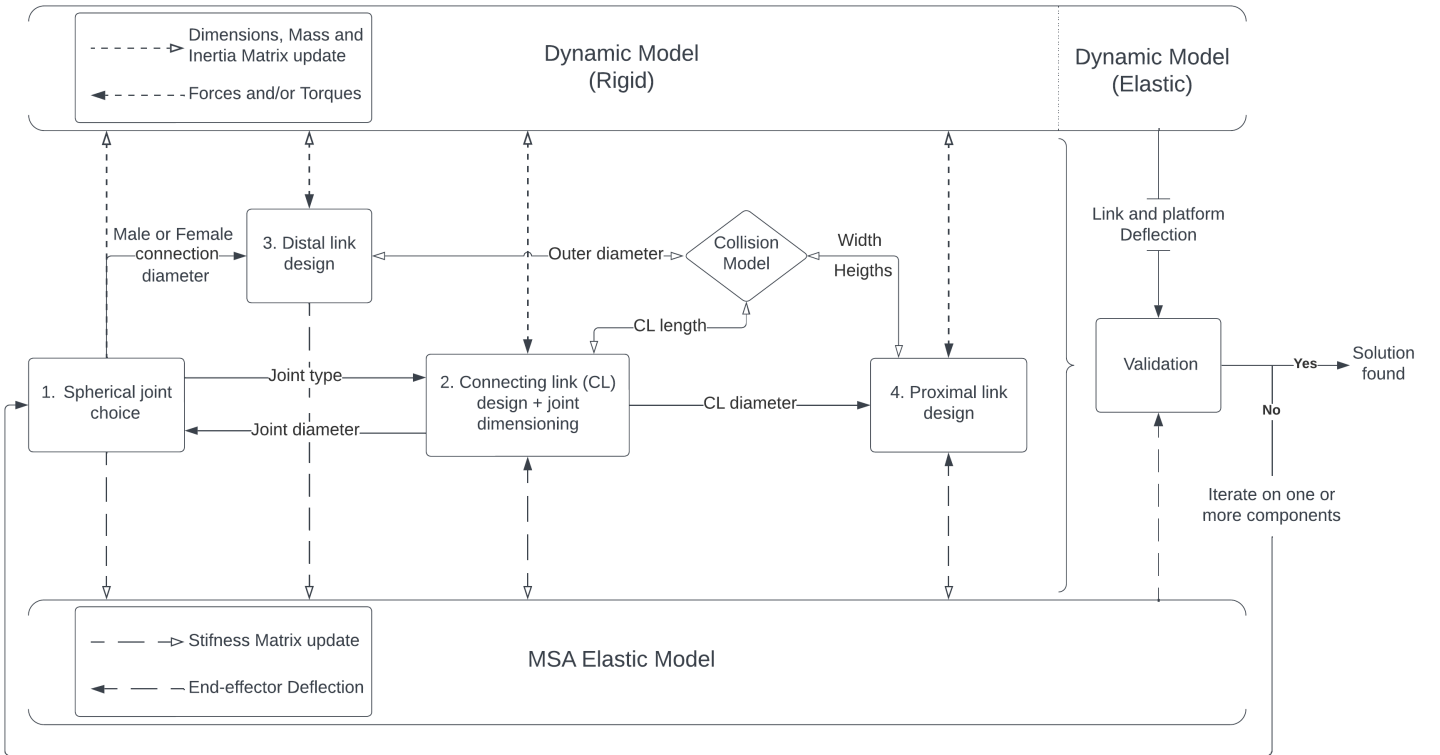


Figure 5.1: Kinematic chain design diagram

5.0.1 Spherical joints

The design of a delta robot presents two distinct approaches to implementing spherical joints.

The first approach involves the use of a "ball and socket" design. This particular design is predominantly employed in industrial-grade Delta robots, providing a substantial workspace due to its extended tilt angle capacity. The design is typically custom developed by the delta robot manufacturers themselves as it is not readily available for purchase in the open market. The "ball and socket" joints demand meticulous design and manufacturing processes to achieve low clearance and friction. Installation of these joints on the connector link is mostly conducted using a spring tension mechanism.

The second approach entails the utilization of a "rod-end" design (Fig.4.8). This design primarily allows for rotational movement along the hole axis, while also offering two additional side degrees of freedom to cater for misalignments. Rod-end spherical joints are broadly available commercially and are relatively inexpensive.

However, their tilt angle capacity is less than that of the "ball and socket design," as it is originally intended to adjust for misalignments. This type of joint is often found in amateur-built, and low-cost Delta robots.

In the context of our Delta robot design, we have chosen to incorporate the rod-end spherical joint. The maximum tilt angle provided by this design suffices for our workspace requirements while also mitigating unnecessary complexity and cost in the robot's design.

The spherical joint serves as a recurrent and critical component in the delta robot design. Furthermore, it is often the primary (if not the sole) component subject to replacement. Hence, selecting a cost-effective and lightweight option is crucial. Our preference gravitated towards the solution offered by IGUS, with their Igubal rod ends. Composed of plastic, these rod-ends offer a lightweight yet remarkably load-resilient solution with acceptable clearance. Additionally, IGUS offers a combination of a steel tube and a double spherical joint, a design option that we will explore further in section 5.0.3.

5.0.2 Connecting link

The sizing of the connecting link of the delta robot is directly influenced by the sizing of the spherical joints. This is due to the assembly of these two components, where the connecting link is compelled to align with the choice of the spherical joint. Given the use of a rod end spherical joint design in our project and our method of assembly, the connecting link is constrained to have a circular cross-section with a diameter equivalent to the joint's diameter. However, it is worth noting that alternate assembly techniques could afford greater flexibility in these parameters, allowing for the decoupling of the connecting link and spherical joint dimensions and/or shape. For instance, employing a connecting link with a square cross-section and machined tips tailored to the spherical joints could be an alternative, though this may have implications such as limiting the effective tilt angle or increasing the complexity and cost of assembly.

Upon reviewing the IGUS catalogue (Appendix C), we identified two viable options for the spherical joint's diameter: 6[mm] and 8[mm]. Both diameters can comfortably bear the operational loads and provide a sufficient tilt angle of 35 and 40 degrees respectively. Given our requirement for a tilt angle of 30[°], the 6[mm] option offers a larger margin.

Table 5.1 presents various combinations of the connector link's diameter (6 or 8[mm]), material (aluminum or steel), and configuration (hollow or plain). These

options are evaluated based on the maximum elastic deflection of the end effector in the workspace for a load of $1[kg]$, along with their impact on the torques required for the reference pick-and-place trajectory with a payload of $250[g]$.

It is important to highlight that the variations in material and configuration primarily affect the torques due to alterations in the mass of the connector link only. On the other hand, alterations in diameter have a more significant impact on the total moving mass, and consequently on the required torques. This stems from the fact that the connector link's diameter is not only closely tied to the size of the spherical joint, but also influences the minimum height of both the end effector and the proximal arm to ensure structural integrity.

Material	Aluminum				Steel			
Cross section	Plain		Hollow		Plain		Hollow	
Diameter [mm]	6	8	6	8	6	8	6	8
Elastic deflection	0.93	0.24	1	0.27	0.25	0	0.27	0.01
Torques	0.03	0.62	0	0.57	0.23	1	0.15	0.86
Total	0.96	0.86	1	0.84	0.48	1	0.42	0.87

Table 5.1: Selection of the material, cross section type and diameter of the connecting link and fitting joint

The Elastic deflection δ and torques τ have been normalized then added per the following function:

$$\text{Total} = \frac{\delta - \delta_{\min}}{\delta_{\max} - \delta_{\min}} + \frac{\tau - \tau_{\min}}{\tau_{\max} - \tau_{\min}}$$

The table suggests that the optimal solution is a $6[mm]$ hollow steel shaft, closely followed by a $6[mm]$ plain steel shaft.

The length of the connecting link has already been dimensioned in section 4, where the value was first set to $l_a/4 \approx 0.05[m]$. It was mentioned that this value is temporary. Indeed, the final value is computed during the proximal link dimensioning (section 5.0.4). The length of the connecting link is the smallest possible length $> l_a/4$, that yields no collisions between the proximal links and the distal links in the prescribed workspace. For the dimensions of the proximal link found in section 5.0.4, and a margin of $4[mm]$, the collision model returns a minimum value for $d_s = 0.055[m]$.

5.0.3 Distal links

There is no real discussion needed to know that the optimal material and cross section for the distal links is carbon fiber tubes. They are widely available on the market and have a stiffness to weight ratio that far outweighs aluminum or steel. The circular cross section is optimal to minimize the collision potential with the proximal arms. They are also overwhelmingly used on Delta robots. Some Delta robots feature aluminum or steel solutions, mostly for cost or environmental reasons (corrosion, high heat,...)

Figure 5.2 shows that the principal forces on the distal links are traction and compression. The possible failure modes are thus either buckling or tensile failure.

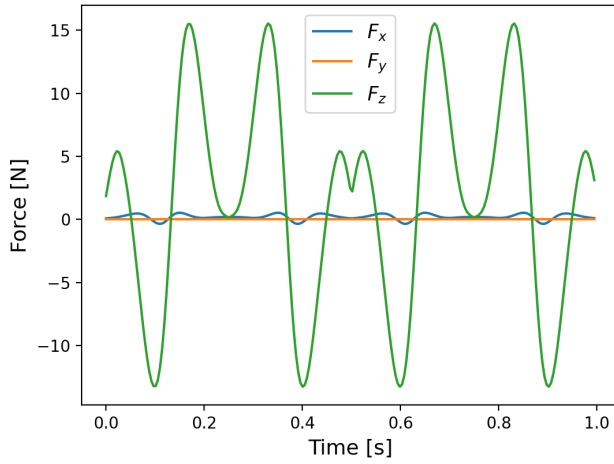


Figure 5.2: Forces on one distal link for the reference pick and place trajectory. F_x is the force along the link axis

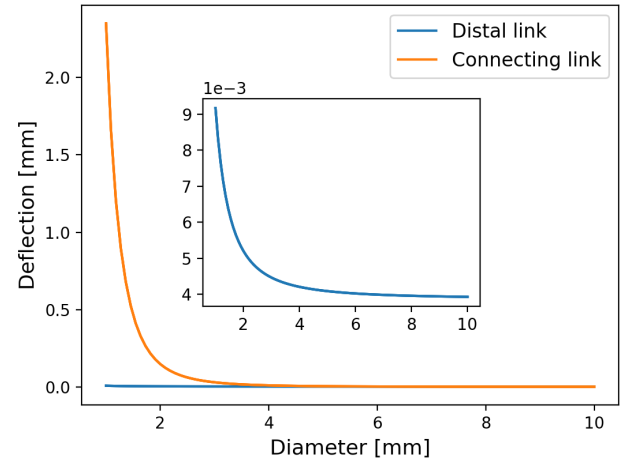


Figure 5.3: Deflection of the end effector with a mass of $1[kg]$ for an increasing diameter of the distal links vs the connecting links.

According to the MSA elastic model, the impact of the distal links diameter on the end effector deflection is close to none (fig.5.3). However, the MSA elastic model does not account for dynamical effects, it is thus important to dimension the distal link rigidly enough. The elastic dynamic model has been primarily created to look for the dynamical effects on the distal links and their impact on elastic deflection of the end effector.

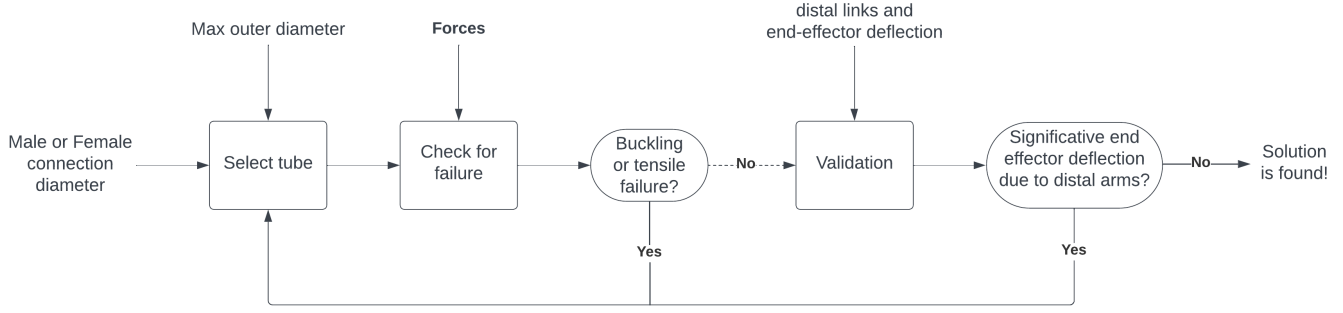


Figure 5.4: Distal links design diagram

Overall the dimensionning of the distal links is mostly done based on availability of tube dimensions and their possible connection design with the spherical joints. The tube dimensions should be minimized, both for mass and for collision considerations. The dimensionning steps are the following:

1. Select the smallest carbon fiber tube available with dimensions that are assemblable with the spherical joints, and that is not suspected to buckle or fail with operational loads.
2. Check for failure of the tube with operational loads. The failure can be either by buckling due to the compression forces or tensile failure due to the traction forces.

a) Buckling is checked with Euler's column formula, with a case of a column pivoted in both ends:

$$F_{\text{crit}} = \frac{\pi^2 EI}{l_a^2}$$

b) Tensile failure is checked with:

$$F_{\text{crit}} = \frac{\sigma}{A}$$

Where σ can be the yield strength or the tensile strength depending on the material. A big safety factor is recommended ($SF \approx 4..5$) for the critical loads, to already ensure enough rigidity.

3. During the validation step at the end of the kinematic chain design (see diagram fig.5.4), the dynamic elastic model is used to check the impact of the distal links deflections on the end effector deflection. If the deflection of the distal links is reasonable, the selected tube is a valid choice. Otherwise, the dimensionning procedure is iterated.

Although carbon fiber tubes are the optimal choice due to their exceptional properties, a more pragmatic approach led to a solution proposed by igus mentioned in section 5.0.1. The solution, called KDGM (see Appendix C), features two KARM CL spherical joints connected by a steel tube with inner diameter 4,6[mm] and outer diameter 6[mm] and successfully complies to the design procedure above. This choice is motivated first by budget constraints. Opting for carbon fiber tubes, despite offering superior performance, includes a substantially higher cost. Additionally, temporal constraints have played a crucial role; the integration of carbon fiber tubes would likely extend the project timeline.

Furthermore, it is pertinent to acknowledge that the initial iteration of the delta robot serves as a foundational prototype. This underlines the importance of starting with a practical and cost-effective solution. By opting for the igus KDGM solution, the primary focus is on efficiently validating the core functionalities and intended design of the delta robot.

However, this choice isn't intended to be the ultimate solution and should be considered the first upgrade to be made on the Delta robot.

5.0.4 Proximal link

The proximal link is the main part to be dimensioned, as it is entirely designed and machined. The length of the proximal link is already known from section 4. The dimensioning will be divided in two parts. The first part will decide the cross section and the material that will be used. The second part, based on the elastic model, will decide the cross section dimensions.

A. Material and cross section

The material selection process is based on stiffness to weight ratio, cost and machinability. The candidate materials for the proximal link were narrowed down to two choices: aluminum or carbon fiber.

Carbon fiber boasts an exceptional stiffness-to-weight ratio, yet it comes with a significant price tag and proves challenging to machine. This complexity in design and assembly, alongside the elevated cost, makes it more suitable for commercial delta robots, where weight reduction takes precedence and cost and complexity are more manageable.

Aluminum, on the other hand, offers a favorable balance with its commendable stiffness-to-weight ratio, superior machinability, and cost-effectiveness. This renders aluminum an appealing choice not only for commercial delta robots but also for hobbyist and amateur delta robots.

Ultimately, the decision leaned toward aluminum over carbon fiber. The ease of machinability, simplified assembly process, and cost-effectiveness outweighed the benefits of weight reduction. Since the proximal link maintains close proximity to the actuators, the impact of weight on the required torque isn't as significant as for elements positioned farther from the actuators, such as distal links, spherical joints, and the end-effector.

When it comes to selecting the cross section of the proximal arm of a delta robot, 3 possibilities have been identified: circular, rectangular and I-shape. The square cross section is seen as a subset of the rectangular cross section. The following table, compares and ranks constraints for each possible choice of material and cross section.

Cross Section	Aluminum			Carbon Fiber	
	Rectangular	Circular	I-Beam	Rectangular	Circular
Stiffness/mass ratio	5	4	3	2	1
Cost	1	2	3	4	5
Complexity	2	3	1	4	5
Collision Potential	5	2	3	4	1
Total	13	11	10	14	12

Table 5.2: Ranking for material and cross section selection

Table 5.2 presents the ranking of stiffness-to-mass ratios based on the static elastic model. The evaluation of cost encompasses material selection, an approximation of machining time, and assembly component expenses. Complexity is quantified by considering the potential quantity of components necessary for assembly, encompassing connections with the motor and connecting link. The ranking related to collision potential factors in the shape and essential dimensions of the cross section, while also accounting for tapering possibilities.

The optimal solution appears to be the Aluminum I-shaped configuration in our specific context. Importantly, this ranking is context-dependent and tailored to our circumstances. For instance, our approach involves machining the I-shaped cross section entirely from an available aluminum plate, with an end taper. The convenience of accessing the material within the university lab brings down costs, further supplemented by special machining rates for educational projects. The finalized design of the proximal link is showcased in figure 6.14, revealing a singular-piece construction that eliminates assembly, thereby minimizing complexity.

The integration of the taper brings multiple advantages. Notably, it mitigates

the potential for collisions with the distal links without necessitating a significant reduction in width of the proximal link, which could adversely impact elastic deflection. Additionally, the taper contributes to substantial reductions in overall mass and rotational inertia of the arm. This reduction is particularly impactful as the influence of mass on the moment of inertia scales with the square of the distance.

Besides tapering, another approach to avoid collision with the distal links is by integrating some curvature in the proximal link. This design characteristic is commonly observed in the aluminum proximal links of various delta robots.

B. Width, height and thickness

In this section, we further delve into the dimensioning of the proximal arm of the delta robot, focusing on the parameters of width, initial height, tapered height, and thickness of the I-beam. It is important to note that the web thickness is mandated to be equal to the flange thickness and is collectively referred to as the "thickness". The overarching objective of this dimensioning process is to minimize the elastic deflection for optimal accuracy, as well as minimizing the mass moment of inertia due to its impact on the required torques. Additionally, we aim to prevent any collision between the proximal link and the distal links. We also consider the constraint of using the material available in the university stock.

Dimension	Description	Unit
b	Width	[m]
h_i	Initial height (motor side)	[m]
h_t	Tapered height (connector link side)	[m]
t	Flange and web thickness	[m]

The first step in the dimensioning process involves addressing the constraint of available material, which subsequently determines the width of the proximal arm. The university stock provides at the moment either 25[mm] or 30[mm] aluminum plates. Upon examining the technical drawing of the motor (Appendix.B), we observe that the dimension from the "start of key" to the "end of shaft" is already 25[mm]. Given our design, using a 25[mm] thickness is not optimal as it would not fully utilize the key to transmit the motor's torque to the proximal arm. Consequently, the width b of the proximal arm is fixed at 30[mm].

The thickness, initial height, and tapered height of the proximal arm are determined by analyzing the elastic deflection and the required torques for a range of the two extremity heights, and this is done for several different thicknesses. Two models are employed in this process: the entirely parametric MSA elastic model

and the parametric version of the rigid dynamic model. The MSA model takes the Young's modulus, second moment of area, and dimensions of the kinematic chain elements as inputs, and it calculates the maximum elastic deflection of the end effector for a static load of 1kg across the entire workspace. The dynamic model, on the other hand, computes the torques required for the reference pick-and-place trajectory with a load of 250 grams.

Fig.5.5 shows the behavior of each model over the height domain for different values of the thickness t . The behavior of the elastic model decreases exponentially for an increasing thickness, the behavior of the required torques increases linearly with increasing thickness.

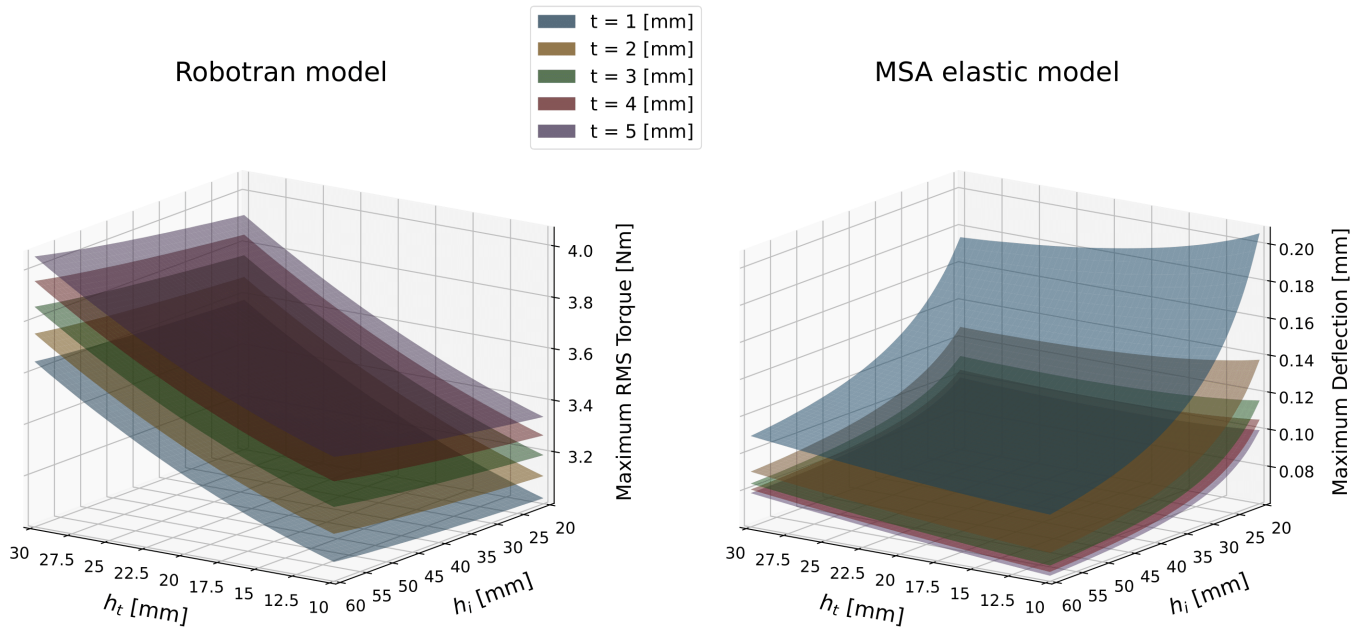


Figure 5.5: Model Behavior over the 2D height domain

To identify the optimal thickness, a cost function is created . This function is the sum of the normalized and weighted results of the elastic model and the dynamic model over the 2D domain of heights (see fig. 5.5).

The norming is graph dependent and is done with respect to the overall maximum and minimum values of each respective graph of figure 5.5. This is done to keep the same difference between each graph and make the comparison between the different thicknesses possible. The overall maximum/minimum of a graph is denoted by $f_{\max}^*$ and $f_{\min}^*$ respectively.

The weighting is done to account for the change over the domain of each individual

thickness. The weights are thus thickness dependent and are determined by dividing the maximum value by the minimum value for each respective thickness $\frac{f_{\max}}{f_{\min}}$.

$$C\left\{f_{\delta}(t, h_i, h_t), f_{\tau}(t, h_i, h_t)\right\} = \frac{\frac{f_{\delta, \max}}{f_{\delta, \min}} \left(\frac{f_{\delta} - f_{\delta, \min}^*}{f_{\delta, \max}^* - f_{\delta, \min}^*} \right) + \frac{f_{\tau, \max}}{f_{\tau, \min}} \left(\frac{f_{\tau} - f_{\tau, \min}^*}{f_{\tau, \max}^* - f_{\tau, \min}^*} \right)}{C_{\max}^*} \quad (5.1)$$

Where the division by $C_{\max}^*$ is done to have a result between $[0,1]$. For each thickness, the mean and median of the cost function over the domain are computed and compared, the results are found in table 5.3.

	Thickness [mm]				
	1	2	3	4	5
Mean [%]	52,87	35,48	33,91	35,63	38,42
Median [%]	51,56	35,21	33,31	34,76	37,46
Actual heights [%]	31,49	18,62	18,07	20,88	24,05

Table 5.3: Mean and median of the cost function for different thicknesses. The evaluation of the cost function at the actual dimensions of the proximal arm is also shown.

Based on the data presented in the table, it has been determined that a thickness of 3[mm] provides the lowest mean and median, making it the preferred option. While the Cost function values for 2[mm] and 4[mm] thicknesses are similar to 3[mm], 2[mm] sacrifices low deflection and possibly structural integrity for low required torques, while 4[mm] prioritizes low end-effector deflection over low torques. This reinforces the conclusion that 3[mm] is the optimal choice. It is hypothesized that a thickness of 3[mm] is sufficient to prevent any risk of local web and/or flange buckling, although this hypothesis will be tested using finite element analysis.

To determine the initial and tapered heights, the normalized and weighted result surfaces of the two models are plotted for a thickness of 3[mm] (Fig.5.6). The intersection between the two surfaces is identified and then projected onto the 2D height domain. Several constraints are plotted on the 2D domain to indicate which pairs of values are not permissible. These constraints include the collision constraint, the maximum RMS torque of 3.4[Nm] (actuator limit), and the minimum heights necessary to avoid stress concentration due to the presence of a hole in the proximal arm at both extremities. For a lack of references, these minimum heights have been fixed to two times the respective inner hole diameter. (Fig.5.7).

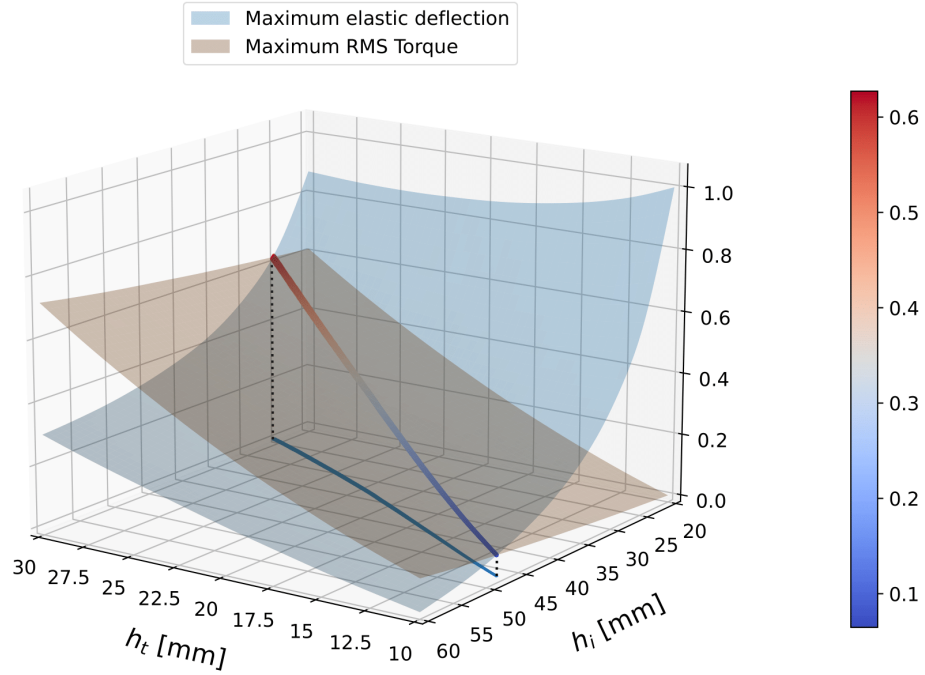


Figure 5.6: Intersection between the maximum elastic deflection surface and the maximum RMS torque surface for a thickness of 3[mm]

As seen on fig.5.6, minimizing the tapered height h_t , minimizes the intersection line. The minimum value of h_t is thus the limiting value and will be chosen as design value. The intersection between the minimum tapered height and the projected intersection line is selected as the pair of values, as it minimizes the "Z value" of the intersection line. This results in an initial height value of 46[mm] and a tapered height of 12[mm]. The minimal value of 12[mm] for a hole diameter of 6[mm] has not been found in any reference, and has thus been verified using an FEA software to ensure there is no local deformation or stress concentration.

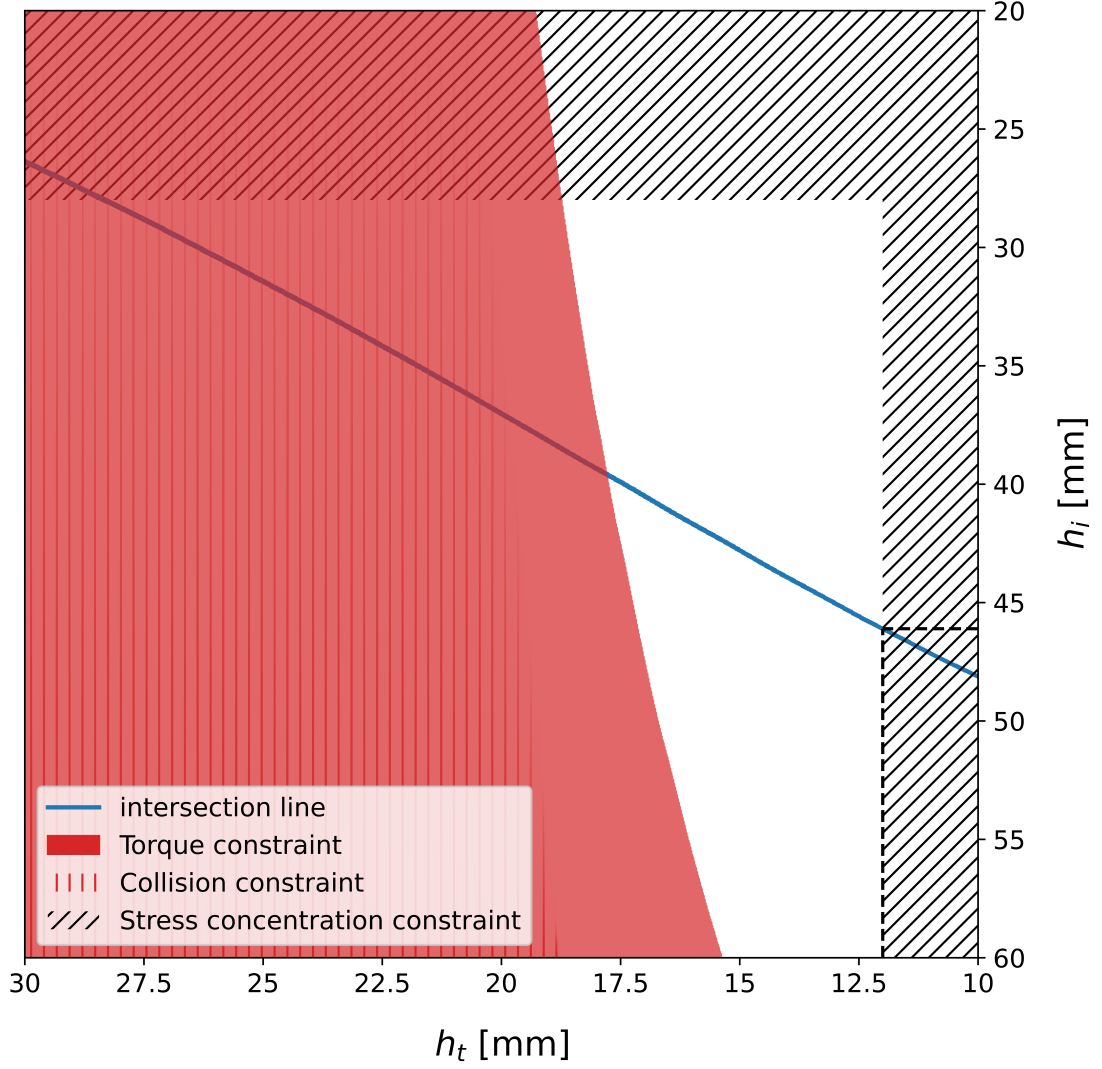


Figure 5.7: 2D domain with constraints and projected intersection line

5.0.5 Validation

In this section the static and dynamic elastic model is used to check the end-effector deflection. Figure 5.8 shows the deflection computed by both models for the reference pick and place trajectory with a load of $1[kg]$. The static elastic deflection

curve is computed by taking the forces acting on the end effector at each timestep and feed it to the static elastic model.

The maximum value of $0,1[mm]$ for a load of $1kg$ is more than acceptable, and indicates a probable over-dimensionning of the Delta robot links.

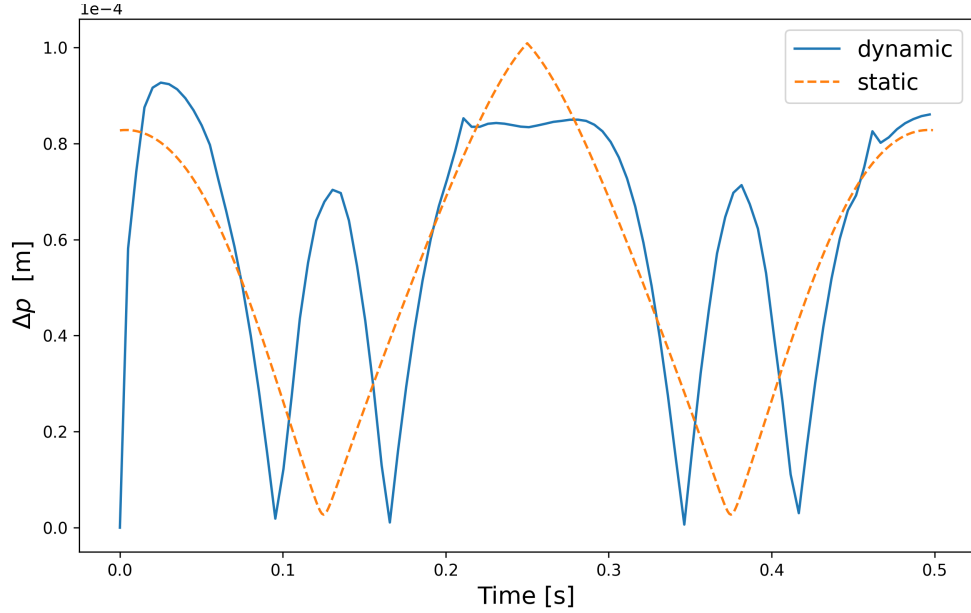


Figure 5.8: Total deflection of the end effector for the reference pick and place trajectory with a load of $1[kg]$. The static model takes the forces at each time t from the rigid dynamic model to compute this pseudo-dynamic deflection.

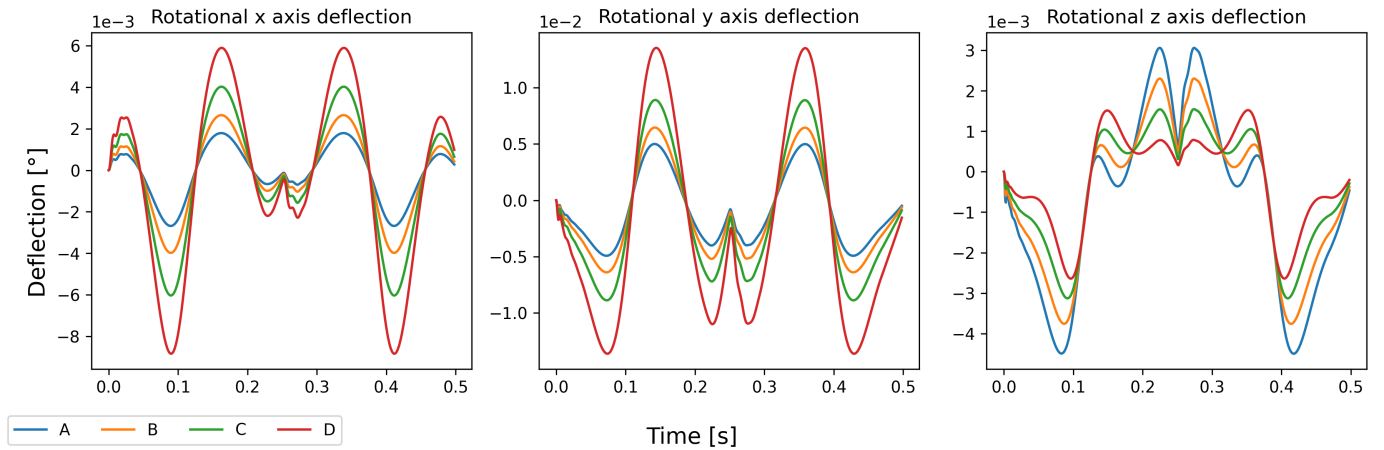


Figure 5.9: Deflection of the intermediate rotational degrees of freedom of a proximal arm during the reference pick and place trajectory with a load of $1[kg]$.

Chapter 6

Detail design



Figure 6.1: Render of the complete delta robot made on SOLIDWORKS

The detail design has been carried out with the values determined during the dimensioning phase. This design process back and forth through several design loops between the dimensioning and the detail design. Fig.6.2 shows the whole detail design process of the delta robot. All the technical drawing of the machined parts can found in the section D.

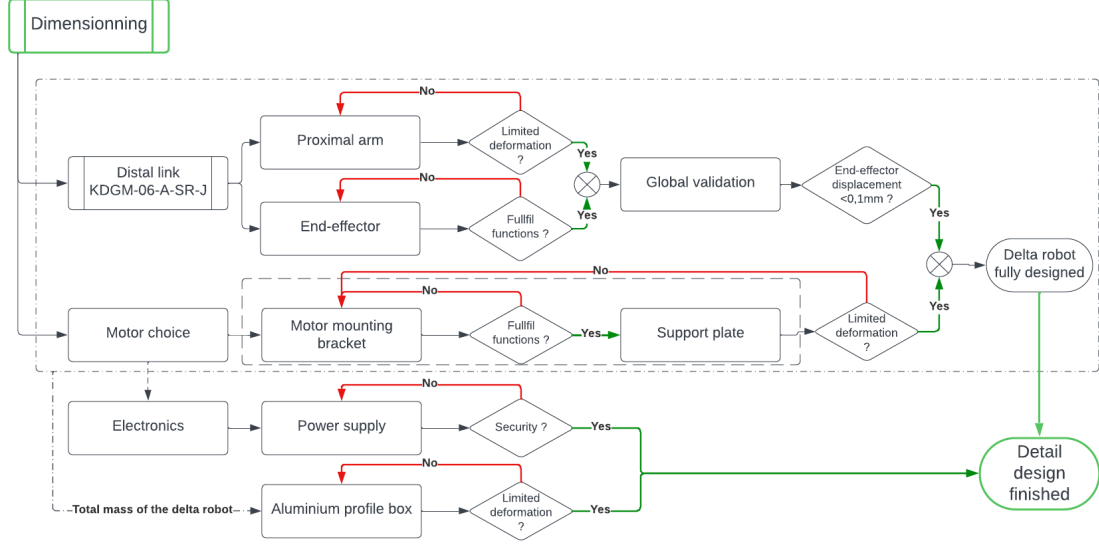


Figure 6.2: Diagram of the detail design process of the delta robot.

The first step in the detail design is to choose the motors. These motors must produce the required torque and have the right resolution as calculated in the dimensioning phase. With the motors selected, the electronics can be determined. In fact, the power electronics and the electronics of command must be chosen to properly control the motors. These electrical components have been placed in a safety box with a dedicated emergency stop circuit.

In a second step, as mentioned in section 5.0.3, after the third iteration during the design loop between the detail design and the dimensioning, the KDGM-06-A-SR-J from IGUS is chosen to be used as distal link. Subsequently, the end effector is designed. The goal of this part is to increase resistance and, above all, to enable different attachments to be used to carry out the various tasks that will be developed in the future on this robot. Next, The proximal arm can be designed too. This part will be considered as "well designed" if its maximum deformation stays close from $0.1[mm]$ as explained in section 5.0.4. Finally, to validate the whole kinematic chain design, the end effector center displacement must be under $0.1[mm]$ to achieve the $0.6[mm]$ resolution in the workspace.

Finally, the design of the fixed part needed to hang the robot can be carried out. It begins with the conception of the motor mounting bracket. Initially, the unique function of this part was to fix the motors to the support plate. However, progressively the bracket will get new functions to simplify the whole design of the

fixed parts and to lower the total mass. Now the bracket also provide mechanical stop and microswitches. This prevents the robot to exceed the workspace and and get damaged. The support plate has been design to hang the robot and fix it to a box. The box has been made out of aluminium profile furnished by MISUMI. This box had to be able to support the entire mass of the robot.

6.1 Motors selection

The choice of the motors for the delta robot depend on many factors including the torque, the resolution, the repeatability, etc. All these parameters depend on the type of the motor and how the transmission between the motor and the mechanical system is built.

To begin with, one could make a direct drive implementation or use a gearbox. The accuracy of the delta robot will be greater and the response time will be quicker if a direct implementation is used. However, the direct drive solution requires the motors to be capable of developing high torques. Motors that can develop high torque and be precise are in general very expensive. With a gearbox, smaller motors with a lower output torque can be chosen. However, this device will introduce friction and play between the proximal link and the motor, which subsequently can affect the precision of the robot. In the case of the Delta robot the direct drive seems to be the best option to achieve the targeted resolution.

Next, the type of motor must be chosen. Currently, there are three kinds of motors that are mainly used in Delta robot:

- **Stepper motors:** the advantages of such motors are that they can be accurate depending on the discrete step angle and they are less expensive. However, stepper motor have a major issue: for a high torque motor, the step angle is around $1,8[^\circ]$ which is much higher than the required resolution of the motor. Stepper motors with less than $0,05[^\circ]$ exist but will deploy less than $0,1[N.m]$.
- **Brushless DC motors:** these motors are highly efficient and have a long lifespan. They can be purchased at reasonable prices for the required torque (around 500 – 700€). They provide the versatility of controlling more precisely the motor than a stepper motor for a high torque. However, to use these motors a controller must to be implemented from scratch.
- **Servo motors:** Its advantages over stepper motors are that they can be fast and develops more torque. They are equipped with an on-board motor

controller and can be tuned to the mechanics attached to it. However, these kind of motor are very expensive compared to the BLDC motors.

The BLDC and the servo motor are evenly good choice, each one of them have their pros and cons. During the research, the two types motors were considered with a preference for the servo motor since its implementation is simpler in order to reach the required specifications.

The CPM-MCPV-3441S-ELS motors from TEKNIC (Fig.6.3a) were acquire. These are integrated servo motor costing 547€ each. They satisfy to the specifications determined in the section ?? in term of resolution and torque as shown in the table 6.1. The motor's speed never goes beyond $200[RPM]$, the maximum peak torque is around $11.8[N.m]$ at this speed as shown in the Fig.6.3b. The peak torque determined in the dimensioning is textcolorredrajouter valeur is thus below the peak torque of the motor. The same observation is applicable for the RMS torque. To verify that the direct drive implementation is possible, the radial and thrust load applied on the motor must be lower than the maximum that the motor supports. To find the forces applied to the motor's shaft, a ROBOTRAN simulation of the delta robot for the three trajectories described in the section 2.3 has been use. The maximal axial radial load is obtain for the pick and place trajectory and is equal to $71,4[N]$. The maximal thrust load is obtain for the circular trajectory and is equal to $26.14[N]$. These two value are below the limit loads of the the motor.

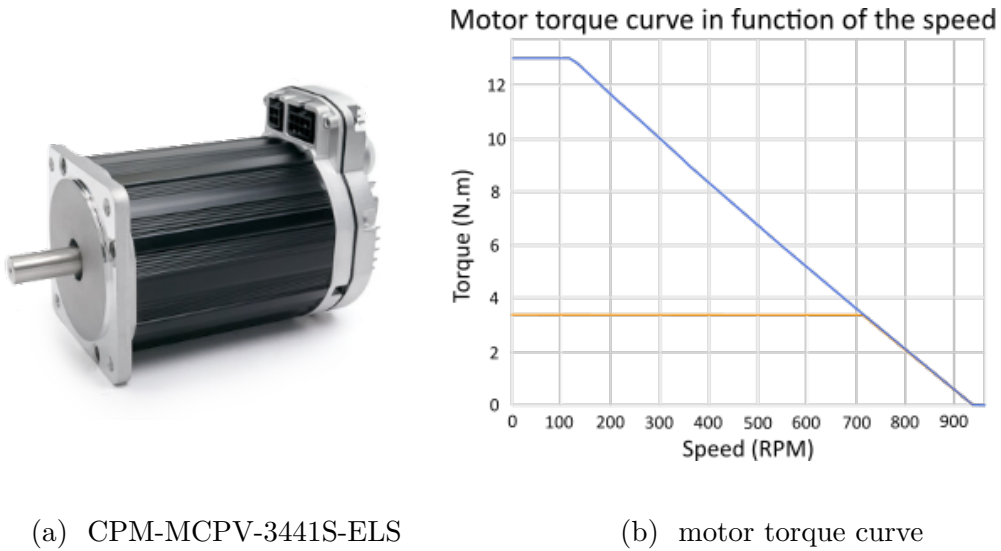


Figure 6.3: ClearPath - Integrated Servo System CPM-MCPV-3441S-ELS made by TEKNIC is shown in (a). The motor torque curve in function of the speed in RPM is shown in (b).

	Value targeted by dimensioning and specifications	Motor specifications
Peak torque [N.m]	11	13
RMS torque [N.m]	3.4	3,4
Max speed [RPM]	250	840
Peak power [W]	/	354
RMS power [W]	/	251
Achievable Resolution [°]	0,057	0,057
Repeatability [°]	/	0,03
Weight [Kg]	/	3,3
Maximum Radial Load [N]	71.37	222,4
Maximum Thrust Load [N]	26.14	44,5

Table 6.1: Table of the specifications of the CPM-MCPV-3441S-ELS and the specifications determined during the dimensionning.

6.2 Electronics: Electronical scheme

The electrical system has been designed to communicate with the servo-motors and to supply them. TEKNIC provides a power supply and a programmable controller especially made for the Clearpath motors. The controller board need also to be supplied but by another power source. To complete the electrical scheme, there is a conventional emergency stop circuit which cuts the motors power supply. The global electrical scheme of the delta robot is illustrated in the Fig.6.4.

6.2.1 Clearcore board

As stated before, to communicate with the motors the choice has been made to use the I/O motion controller Clearcore developed by TEKNIC (Fig.6.5). This board was chosen for the following reason:

- The board has been especially designed to communicate with the motors developed by TEKNIC. This will make the communication with the motor much easier than if a FPGA board is used for example.
- All the three motors of the delta robot can be controlled with this board.
- TEKNIC has developed a C++ library to easily program the 32-bit ARM Cortex M4F processor on the Clearcore board. The control of the motor is

thus easier as the library is documented and has a lot of example. The library is tailor-made for the motors.

- The card offers a lot of port: digital, analog, I/O, Ethernet,... This allows a great flexibility for future improvements to the delta robot.

Currently, the board is used to communicate with the three motors and is connected to six micro-switches used as limit switches for the proximal arm.

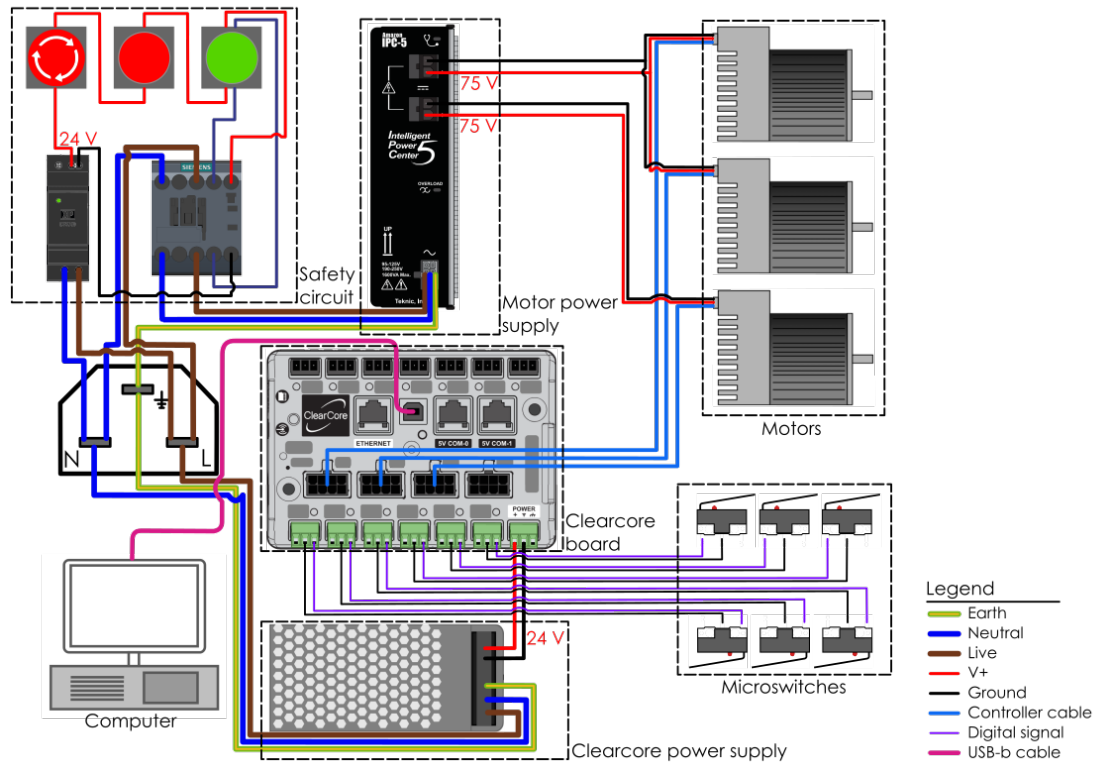


Figure 6.4: Global electrical scheme of the robot with the power supply, the motors, the programmable controller, the micro-switches, and the safety circuit

6.2.2 Power management

The Clearcore and the motors need to be supply separately. Thanks to this, when the emergency button is engaged, only the power supply of the motor is cut and the Clearcore board is still usable. The supply circuit is illustrated on the Fig.6.6



Figure 6.5: Clearcore - industrial I/O and motion controller made by TEKNIC

The power supply used for the motor is the IPC-5 Power Supply made by TEKNIC (Fig.6.7a). The power source takes $240[V_{AC}]$ as input and outputs $75[V_{DC}]$. Each output can go up to $500[W]$ and the peak power is $900[W]$ RMS, which is sufficient for the output with the two motors connected to it. Indeed, the two motors will need $502[W]$ RMS and $708[W]$ peak (table 6.1)¹.

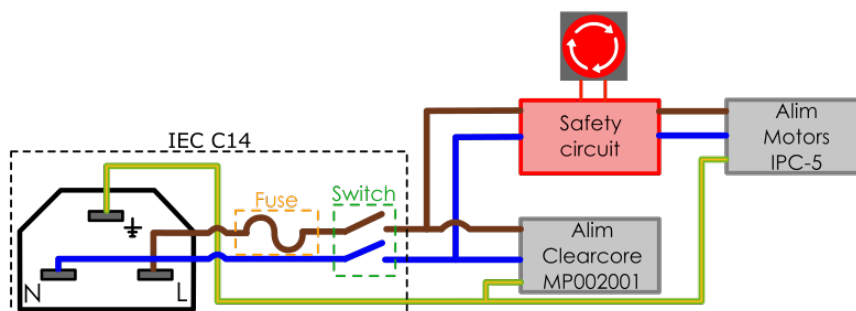


Figure 6.6: Power supply scheme representing the connection of the power supply

The Clearcore power supplied is the MP002001 power supply $24V\ 6,5A$ from MULTI-COMP PRO (Fig.6.7b). Therefore, the card can consume up to $156\ W$. Currently, this power for communicating with the three motors and for 6 micro-switches is oversized. This leave room for improvement in the future for a vacuum pump for example.

¹The peak power (1 sec) of the motor and the IPC-5 (3 sec) are limited in time. However the robot will never be in this situation.

In order to shut down the Clearcore and the safety circuit a switch is needed between the socket and them. To prevent the circuit from overloading, a fuse can be used to. The IEC C14 socket (Fig.6.7c) contains both of them. The fuse and the connector can handle up to 6[A] at 250[VAC] and thus up to 1500[W]. The theoretical maximum power needed by the system is 1218 W².



(a) IPC-5 - TEKNIC (b) MP002001 - MULTICOMP (c) IEC C14 - RS PRO PRO

Figure 6.7: (a) is the power supply of the motor, (b) is the power supply of the Clearcore and (c) is the socket with the fuse and the switch that connects the whole circuit

6.2.3 Electrical box

To ensure that all electrical components are neatly stored, an electrical box has been specially designed. The emergency button and the start and stop buttons have been fixed on the door of the box. The power supplies, the Clearcore and the safety circuit fit all in the box and all cable emerge from the underside of the box. The Fig.6.8 shows the complete electrical box built.

²This could only happen if the motors and the clearcore card go to the maximum power, which should not happen during the normal use of the delta robot

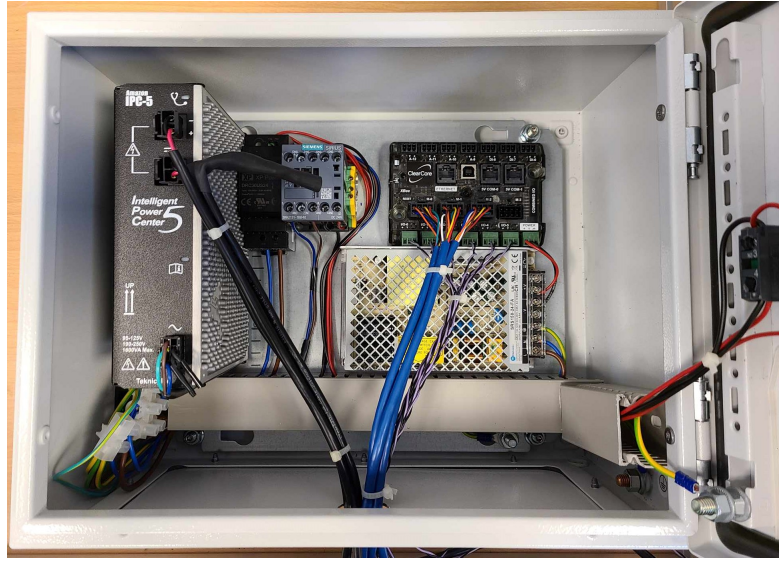


Figure 6.8: Complete built electrical box

6.3 Mechanics: moving parts

The next step is the detail design of the mechanical parts. All values determined 5 will be used at this stage. For the sake of simplicity, the notation introduced in the section 4 will be re-used here too (Fig.6.9).

The moving parts design correspond to the design of the end-effector and the kinematic chain composed of the proximal arm, the connecting link and the distal arm. For the latter, the KDGM-06-A-SR-J will be used. The proximal arm design will be validate through SOLIDWORKS FEM simulations for specific trajectories. The whole kinematic chain will be validated through a FEM simulation of the complete assembly of all moving parts. In order to make the simulations, the forces applied on the parts have been extracted from a ROBOTRAN of the delta robot.

6.3.1 End effector

The proposed design of the end effector is shown in Fig.6.10. At this stage, no mouthpieces has been designed, the design proposed here is likely to be changed in the future. This first design will serve as a test piece and can serve as basis for the final design. To this end, we tried to use additive manufacturing for this piece and proposed solutions to attach the connecting link and the future mouthpieces.

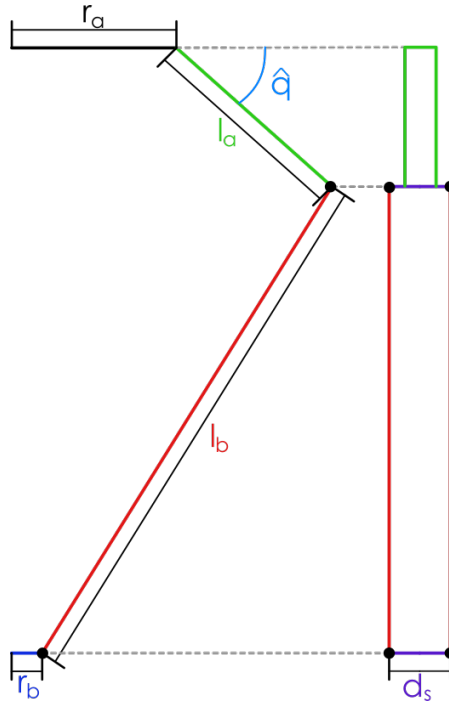


Figure 6.9: Scheme of geometrical notation used for the delta robot. With l_a : proximal arm length, l_b : distal arm length, r_a : radius of the circle composed of the three actuators, r_b : radius of the circle composed of the six parallelogram-to-platform connections, d_s : the distance between the two rods of the parallelogram and $\hat{q}$: the angle of the motor.

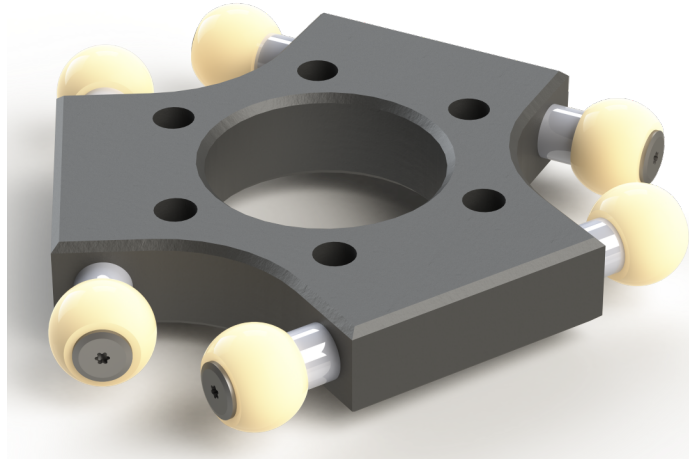
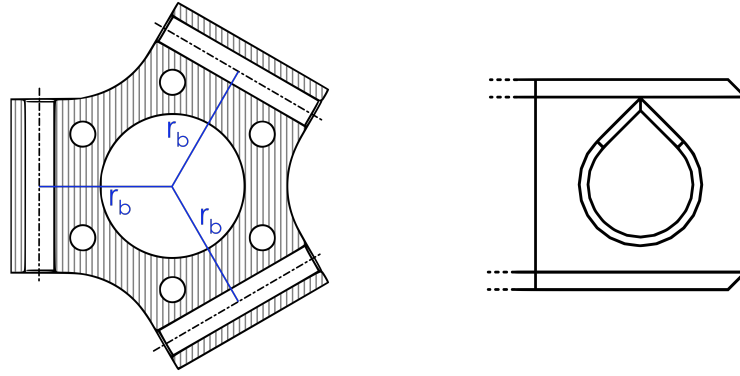


Figure 6.10: Render of the End-effector made on SOLIDWORKS

The design must ensure that the distance between the two distal link is respected. To do that, the center of spherical ball of the rod-end must be placed at the distance d_s ³. Another important dimension to keep in mind during the design of the end-effector is the distance r_b .

As explained in section 5.0.2, the connecting links are plain steel articulation pins. The centers of those axes must be at a distance r_b from the center of the end-effector (Fig.6.11a). The pieces will be 3D-printed and thus the positioning of the connecting link will be as precise as the precision of the 3D printer allows. In our case, the printer has a precision of $0,1[mm]$. However, there is an issue with the hole for the connecting link: the support. In fact, removing the support will roughen the surface of the hole. The pin could be perhaps out of alignment or could no longer pass through since the diameter of the hole is $6[mm]$. To prevent the use of support, a teardrop-shaped hole (Fig.6.11b) has been made.



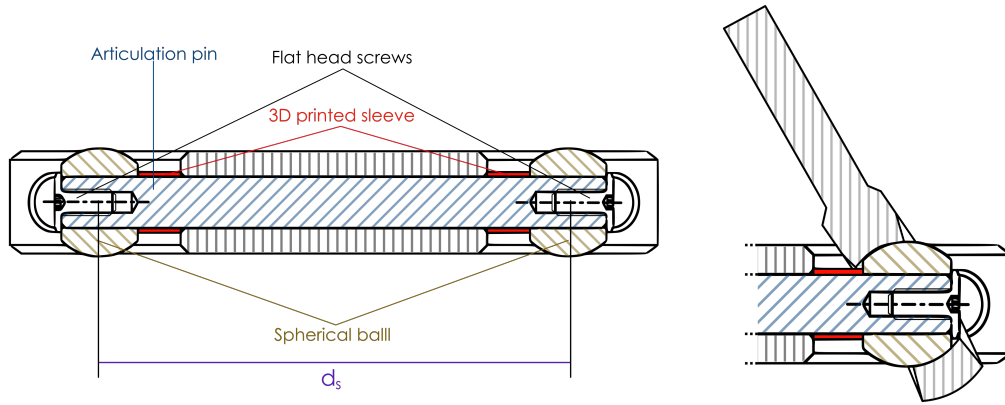
(a) End-effector sectional view (b) Teardrop-shaped hole

Figure 6.11: The center of the connecting link must be placed at a distance r_b from the center of the end-effector as shown in (a). To prevent the use of support, the shape of the through hole is a teardrop shape as shown in (b).

To maintain the center of the two spherical balls at a distance d_s away from each other, the translational movement of the balls along the connecting link has been constrained. The two extremities of the articulation pins are tapped. A flat head screw has been screwed against the spherical ball as shown in the Fig.6.12a). The other side of the ball cannot be put against the end-effector. Indeed, this will limit

³The design proposed here for the end-effector will work for the carbon distal link. As long as the spherical joint are KARM CL rod-end from IGUS, the carbon arm or the IGUS solution are interchangeable

the tilt angle of the rod-end. As a matter of fact, the sleeve must be thin so as not to interfere with the rod-end (Fig.6.12b). The choice has been made to 3-D print the sleeve to reach with the desired distance d_s . The advantages is that the spherical ball can be fixed at precise distance from the end-effector as the printer precision is less than $0,1[mm]$. The thickness of the sleeves can be chosen so that the maximum tilt angle can be 35° . The mouthpiece can be fixed to the end-effector through the six holes using nylon screws and bolts as shown in the figure 6.13. As it will be show in the section 7.4, an example of a 3D printed part has been made to make some experiment using this fixation method.



(a) Sectional view of the connecting link fixed to the end-effector (b) Rod-end maximum tilt angle

Figure 6.12: The fixation method of the connecting link and the ball of the rod-end is shown in (a). This is achieved by blocking the translation movement of the balls by wedging them between the 3D-printed sleeves and the flat head screws. The maximum tilt angle of the rod end is limited by the thickness of the sleeve as shown in (b).

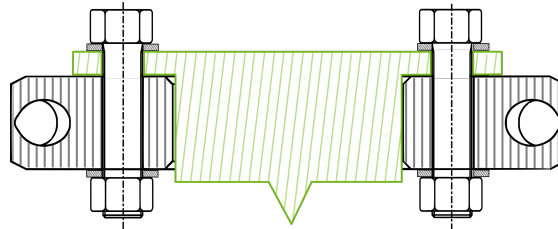


Figure 6.13: Drawing showing how to fix the mouthpiece to the end effector using screws and bolts in nylon.

As stated before, the end effector has been made with a specific 3-D printing technique. It has been printed on a MARKFORGED with the Onyx filament. It is a composite material composed of micro carbon fiber filled nylon. The printed part has the same strength as it has been made in aluminium. The printed pieces have also six layers of Kevlar positioned at 120° from each other, there are three layers on each side of the connector link holes. They are perpendicular to the articulation pins to reinforce the resistance to bending. The printed part mass is 19,24[g]. In comparison, the mass would have been 64,6[g] if the pieces had been made in aluminium 6061-T6.

6.3.2 Proximal arm

The proximal arm (Fig. 6.14) is the result of many loops of design between the dimensioning and the detail design. The choice of the cross section and its dimension has been done in the section 5.0.4. This part has been machined in aluminum 6061-T6 and its mass is 198,61[g]. The technical drawing of the proximal arm can be found in the appendix D.

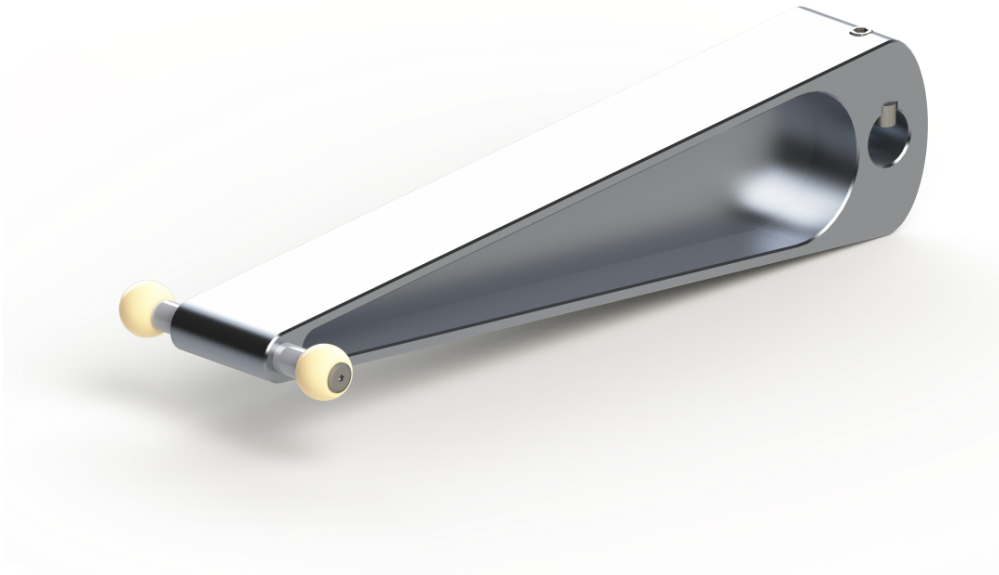
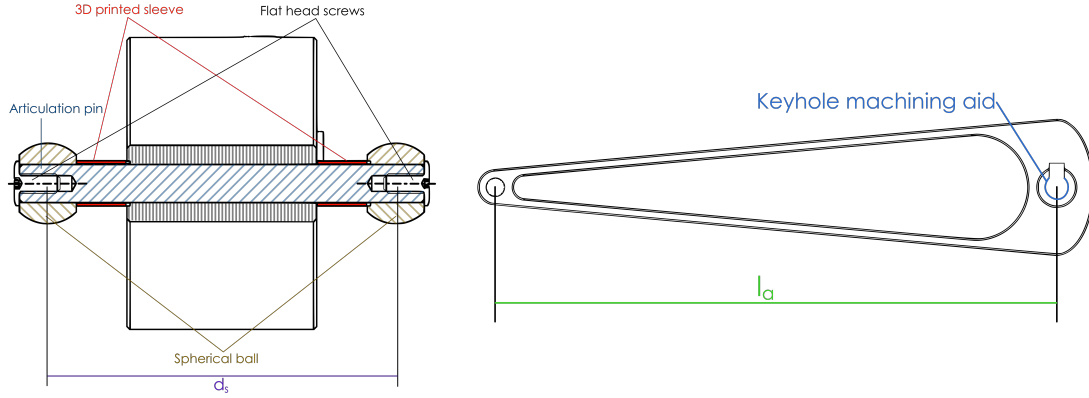


Figure 6.14: Render of the proximal arm made on SOLIDWORKS

The proximal arm has the same fastening system for the connecting link as the one from the end-effector(6.15a). The distance l_a is measured from the center of the motor shaft hole and the center of the articulation pin (Fig.6.15b). The proximal arm is fixed to the motor via a key and a pressure screw as shown in Fig.6.25. At the bottom of the shaft hole a smaller circle can be found. This has been done for the machining of the keyhole. Effectively, it has been done with electrical discharge machining and therefore the hole goal is to let the wire pass through.



(a) Sectional view of the connecting link fixed to the proximal arm

(b) Profile view of the proximal arm

Figure 6.15: The fixation method of the connecting link and the ball of the rod-end is shown in (a). This is achieved by blocking the translation movement of the balls by wedging them between the 3D-printed sleeves and the flat head screws. The figure (b) shows the length of the l_b and how the machining aid for the keyhole. The keyhole has been made by electrical discharge machining. The machining aid is a hole that let the wire pass through.

FEM validation

To validate the detail design of the proximal arm, a total of five simulations have been carried out. The piece has been fixed at its keyhole. The forces for all simulations have been taken from ROBOTRAN for the pick and place semi-elliptical trajectory described in the section 2.3.1. The forces applied on the proximal arm are the highest for this trajectory. The pick and place trajectory is a travel four times (two back and forth movement) in 1 second with a $1[kg]$ mass attached to the end-effector⁴. The forces obtained from ROBOTRAN were applied to the two ends

⁴In the section 5.0.4, the dimension has been determined for a $250[g]$ mass attached to the end-effector. For the FEM simulation, the choice has been made to increase it by a factor of 4 to

of the connector link over 9[mm] in SOLIDWORKS. This distance corresponds to the contact length of the spherical balls with the connecting link (the B length in appendix C). The forces have been applied in X-Y-Z reference frame as displayed in the Fig.6.16 and in Fig.6.18. The procedure to get the forces to apply is the following:

1. Determine the maximum forces in the z or x axis applied on the connecting link.
2. Find the precise moment at which this force has been applied.
3. Extract all the forces in X-Y-Z axis of the connecting link at this moment.

The five case studies are the following :

- The maximum force obtained in the z-axis for the arm aligned with the trajectory.
- The maximum force obtained in the z-axis for the arm at 120° from the trajectory.
- The maximum force obtained in the x-axis for the arm aligned with the trajectory.
- The maximum force obtained in the x-axis for the arm at 120° from the trajectory.
- The maximum delta of forces between the left and the right of the connecting link obtained in the z-axis for the arm at 120° from trajectory.

All the forces applied are shown in the table 6.3. Only the critical simulations obtained (cases 1 and 2) will be analyzed. The result of the other simulations can be found in the appendix E.1.

	Simu 1	Simu 2	
Forces [N]	left/right	left	right
X-axis	33, 45	42, 93	-17, 05
Y-axis	0, 0	9, 47	-2, 30
Z-axis	3, 79	11, 70	-10, 37

Table 6.2: Table of the force in the X-Y-Z direction applied on the extremities left and right of the connecting rod for each FEM simulation

be use as a safety factor.

Fig.6.16 and the Fig.6.18 shows the resulting displacement for the arm aligned with the trajectory and the arm at 120° from the trajectory respectively. The maximum deflection observed is on the edge of the proximal arm and is below $0.12[mm]$ in the two cases as shown in the charts A in Fig.6.17 and Fig.6.19. Therefore, the maximum deflection of the detail design is $0.02[mm]$ greater than the limit of $0.1[mm]$ determined in the dimensioning (section 5.0.4). However, to reach the targeted maximal deflection, the piece must be much thicker. The mass of the pieces will rise significantly and thus the torque that the motor must be able to deploy too. The gain in deflection was not considered sufficient to offset the loss in motor torque. The edge of the connecting link highlighted in Fig.6.17 and Fig.6.19 are where the deformation of this part is maximal. The deformations are below the $0.25[mm]$ computed in the dimensioning. This is mainly due to the fact that the connecting link is wrapped by a $3[mm]$ layer of aluminium. With this, the detail design of the proximal arm can be validate.

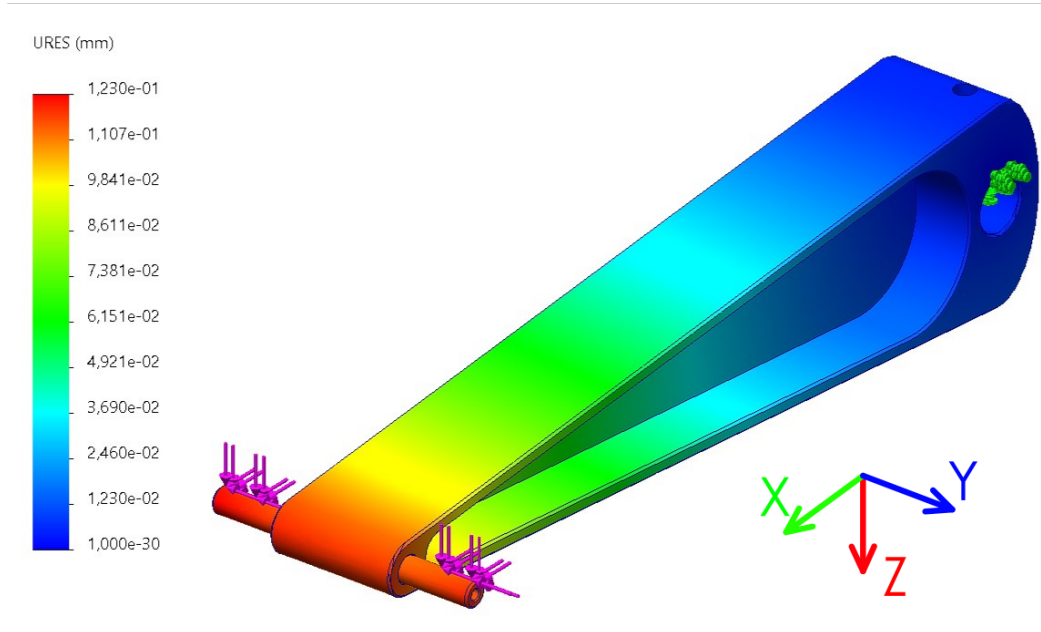


Figure 6.16: FEM simulation result of the deformation of the proximal arm for the maximum force obtained in the z-axis for the arm aligned with the trajectory.

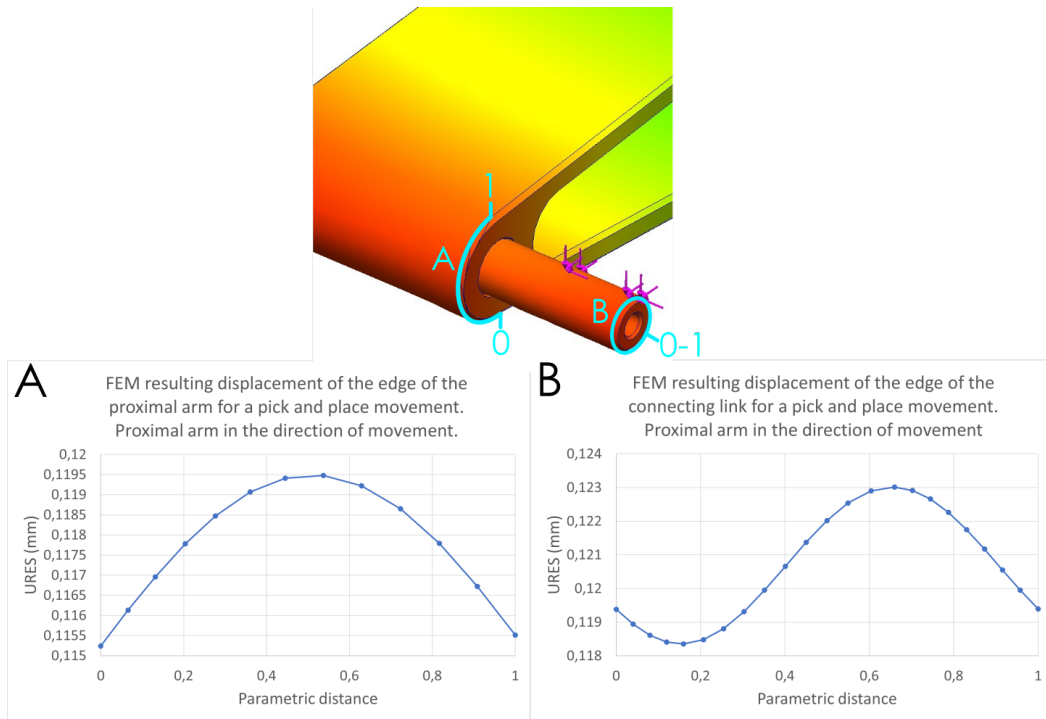


Figure 6.17: Charts of the displacement of the edge of the proximal arm (A) and the edge of the connecting link (B) for simulation 1. The ordinate axis are parametric distance of the edges. The picture shows what the 0 and 1 correspond to for each of the edges.

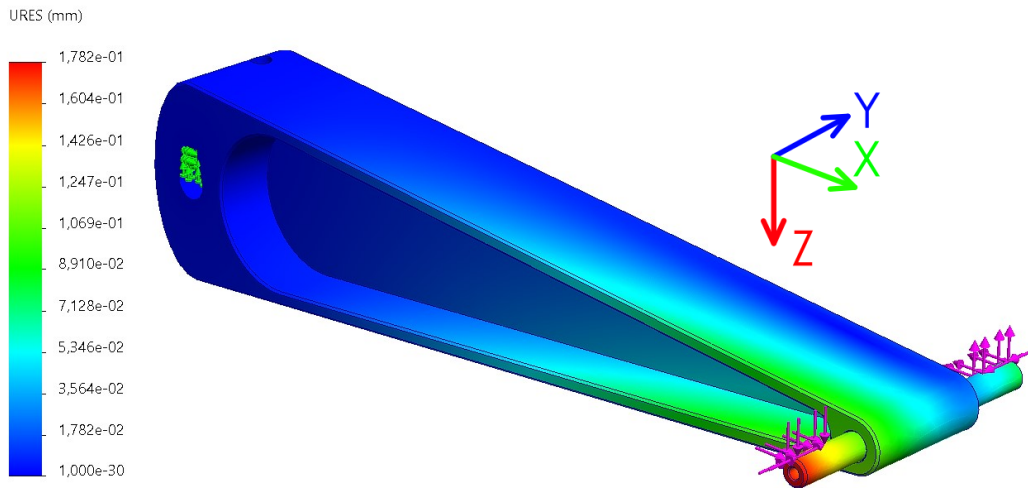


Figure 6.18: FEM simulation result of the deformation of the proximal arm for the maximum force obtained in the z-axis for the arm at 120° from the trajectory.

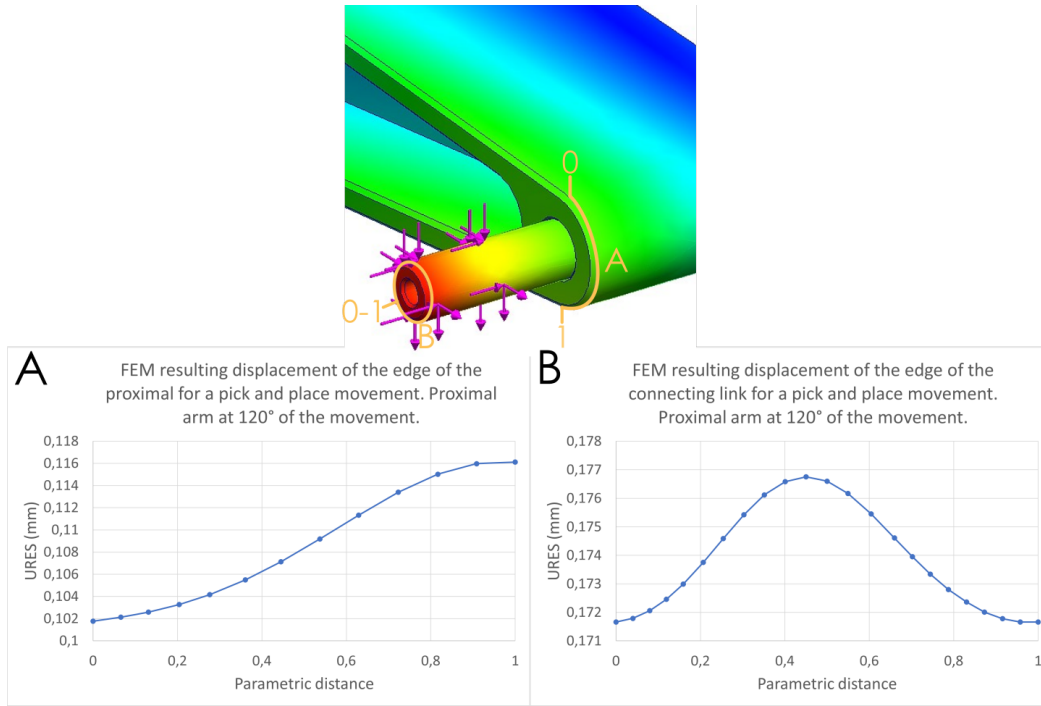


Figure 6.19: Charts of the displacement of the edge of the proximal arm (A) and the edge of the connecting link (B) for the simulation 2. The ordinate axis are parametric distance of the edges. The photo shows what the 0 and 1 correspond to for each of the edges.

6.3.3 FEM global validation of the moving parts

To validate all parts from the kinematic chain, FEM simulations of all moving part have been carried out. The goal is to validate the designed proximal link, the KDGM-06 from IGUS and the connecting link to achieve maximum deformation less than 1[mm]. Three simulation have been conducted for each trajectory presented in the section 2.3: the pick and place trajectory, the circle trajectory and the helix trajectory. For all simulations the keyholes and the angles of the proximal arms have been fixed. The forces have been applied on the end of the connecting links of the end effector over 9[mm]⁵. To obtain the forces applied on each link and the angle of the proximal arm in ROBOTRAN, one proceeds as follow:

1. Determine the maximum forces in the z axis applied to any of the connecting link.

⁵Corresponding to the B length in appendix C. It is the same length as the one used for the proximal arm FEM simulations

2. Find the precise moment at which this force is applied.
3. Extract all the forces in X-Y-Z axis of all the connecting link at this moment.
4. Do the same for the angle of the proximal link.

All forces found for the the pick and place trajectory applied on all the connecting links are shown in the table. Only the pick and place simulations will be analyzed as it is the most critical one. The other simulations can be found in the appendix E.2. For all simulation the spherical balls of the rod-end are rigid. Indeed, the material of those balls does not exist in SOLIDWORKS and no equivalent have been found as this material is very specific. In any case, the impact of the deformation of the spherical balls on the displacement of the end effector is negligible. The end effector is rigid in this simulation as well as the simulation in section 5. This is because the goal of the simulation is to determine the impact of the three kinematic chains on the end-effector displacement.

		Pick and place	
Forces [N]		left	right
Connecting link 1	X-axis	23,28	
	Y-axis	0,0	
	Z-axis	-19,95	
Connecting link 2	X-axis	-1,47	-2,24
	Y-axis	3,89	-17,58
	Z-axis	-6,61	29,84
Connecting link 3	X-axis	-1,47	2,24
	Y-axis	-3,89	17,58
	Z-axis	-6,61	29,84
Motor Angles	Motor 1	24.36	
	Motor 2	10.15	
	Motor 3	10.15	

Table 6.3: Table of the force in the X-Y-Z direction applied on the extremity left and right of each connecting rod for each FEM simulation. The corresponding connecting link can be found in the Fig.6.21

The result of the pick and place simulation can be found in the Fig.6.20. The maximum static displacement is 0,1044[mm] and is located on the distal arm aligned with the trajectory. The deformations in the three proximal arms are around 0,03[mm] which is different from the simulation result in section 6.3.2. This is due to the fact that the interaction forces are not the same in the two cases. For the simulation in this part, the force is not directly applied on the proximal arm.

Moreover, the force used here are the critical forces for the end effector and not the proximal arm. To validate the detail design of the whole kinematic chain, the displacement at the center of the end effector must be less than $0.1[mm]$ to reach the targeted precision. The deformation obtained at the center node (Fig.6.21) is $0,057[mm]$. The whole kinematic chain is thus validate.

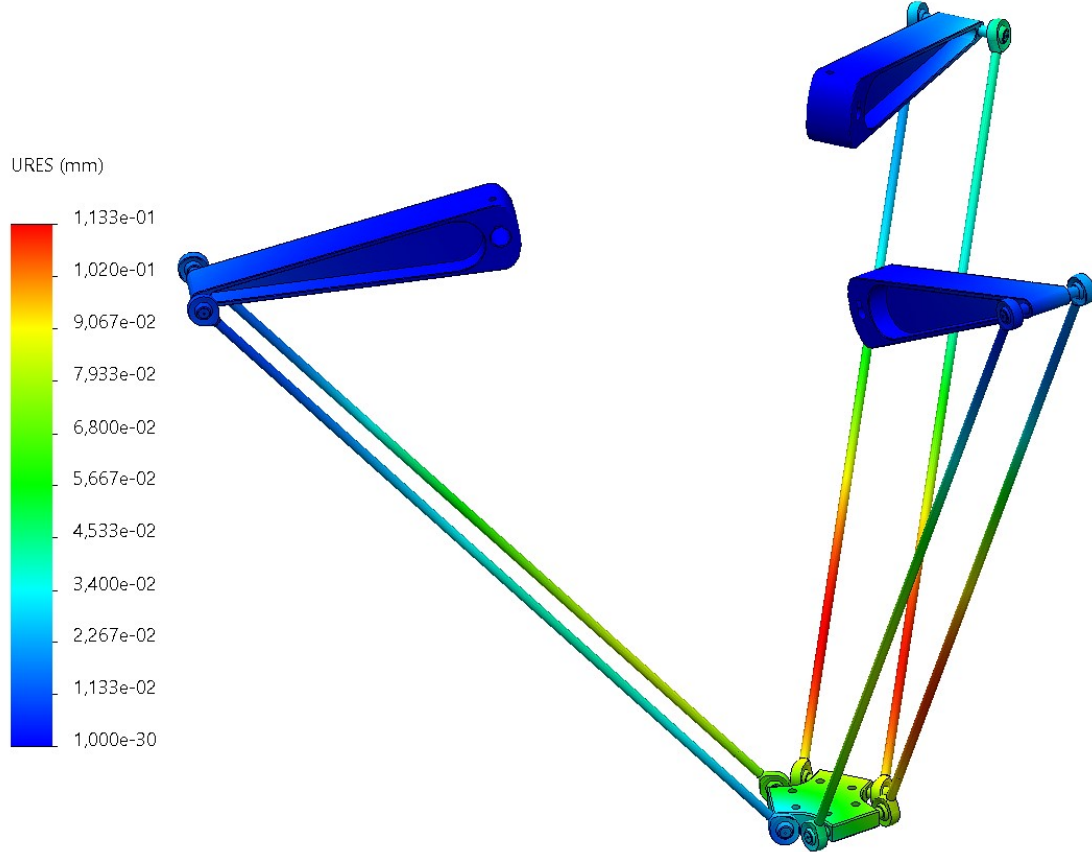


Figure 6.20: Complete FEM simulation of the whole kinematic chain for a pick and place movement. The maximum deformation are located in the distal arm. The displacement all over the end-effector is less than $8,35e^{-2}[mm]$.

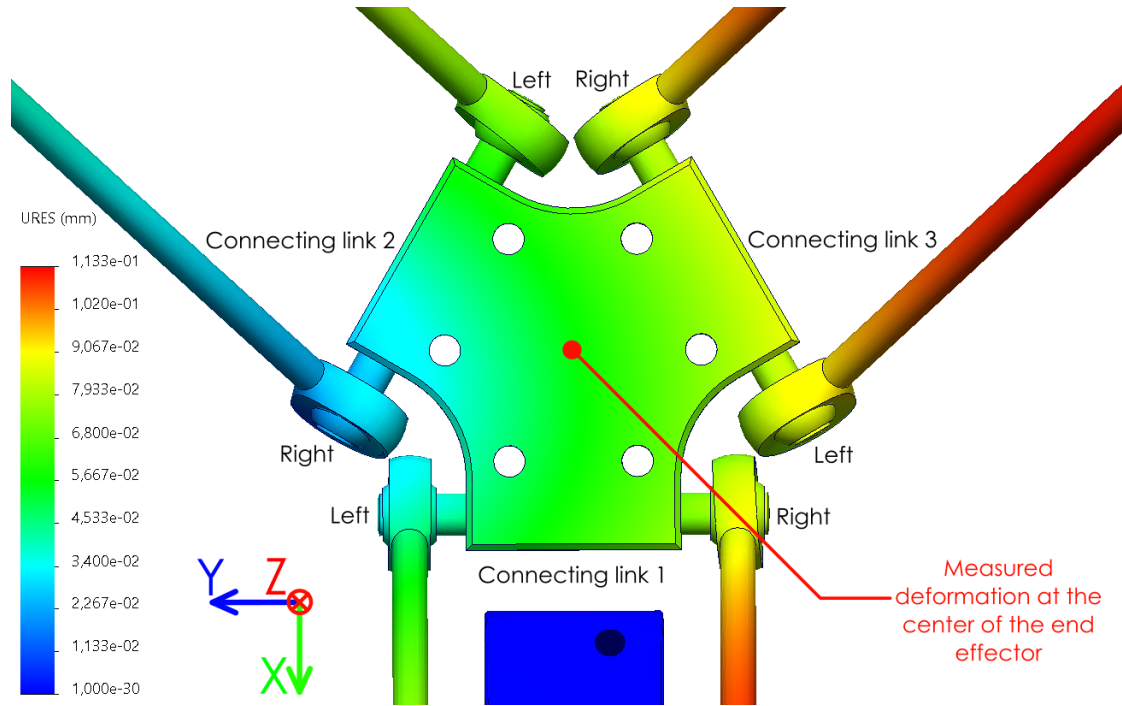


Figure 6.21: Deformation result of the end effector for the global simulation. The red dot is the node of the mesh where the deformation has been measured to validate the detail design of the kinematic chain.

6.4 Mecanics: fixed part

The main purpose of the fixed parts is to allow the robot to be suspended. The machined parts are limited first by the thickness of the aluminium plate available from the lab. The design of these parts requires that they do not have an impact on the precision of the end effector. Therefore, the deformation of those parts must not impact the distance r_a , the angle $\hat{q}$ or the orientation of the motor. The design of those parts must be done in displacement and not in buckling. In order to do that, FEM simulations have been conducted to validate the design. For all following simulations, distributed mass has been applied with the acceleration of gravity on SOLIDWORKS. The motors bracket and the mounting plate (Fig. 6.22) will be covered first and then the aluminium profile box will be presented.

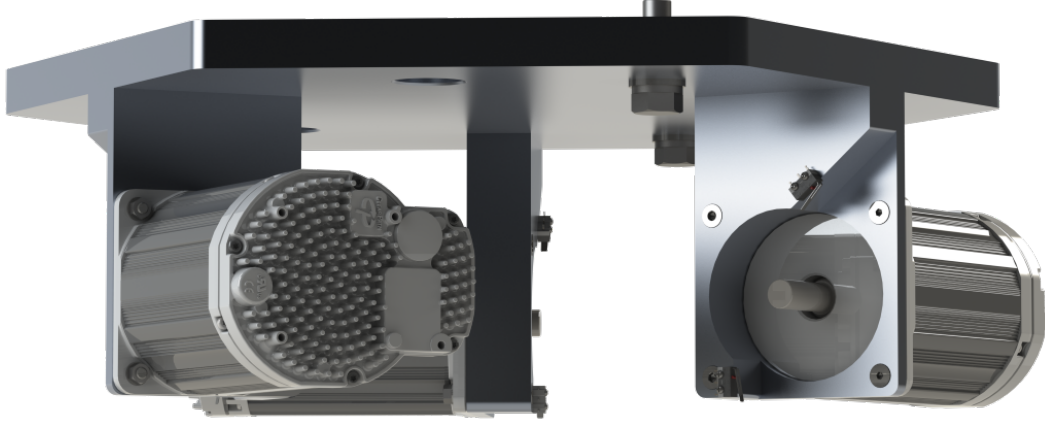


Figure 6.22: Rendering of the mounting plate with the motor brackets made on SOLIDWORKS

6.4.1 Motor mounting bracket

The motor mounting brackets must be able to fulfill 3 functions (Fig.6.23): suspend the entire robot and its motors, assure that the motor shaft rotation axis is tangent to the circle of radius r_a and serve as both mechanical and electrical stops. This part has been machined and is made from aluminium 6061-T6 from a 30[mm] thick plate. The orientation of the piece is assured by the positioning pins (Fig.6.24a). The brackets are fixed to the mounting plate thanks to the screw in the middle. The last function is made possible by the shape of the pieces and the use of microswitches. The thickness of the mounting bracket in the swing zone of the proximal arm is 7[mm] as shown in Fig.6.24b. The tolerances for this thickness is $\pm 0.1[mm]$. This allows 0.5[mm] between the proximal arm and the mounting bracket for the worst case scenario⁶.

⁶If the motor shaft length and the depth of the proximal arm hole are at their minimal tolerance (B and D

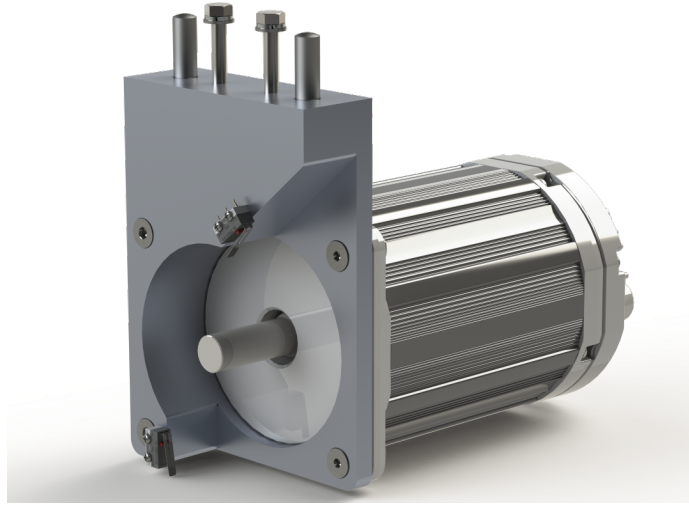
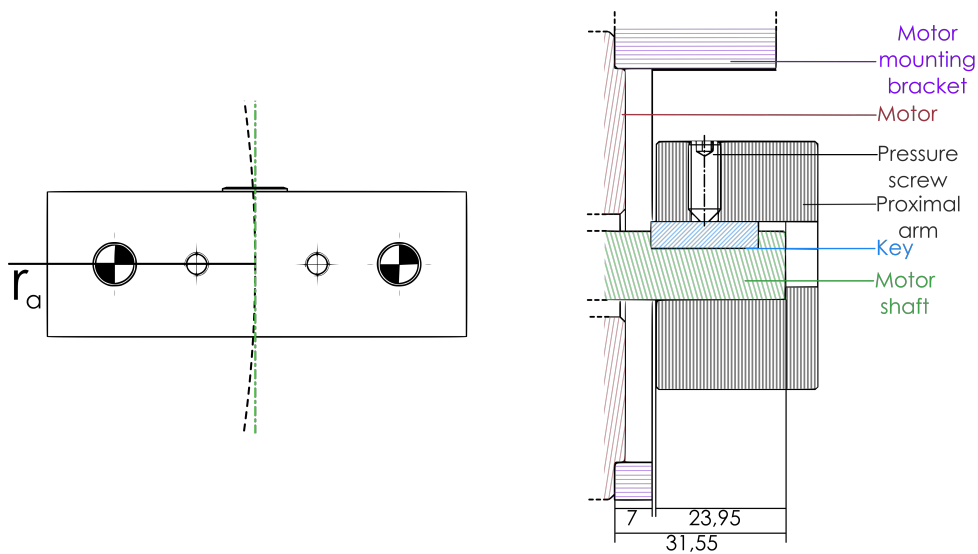


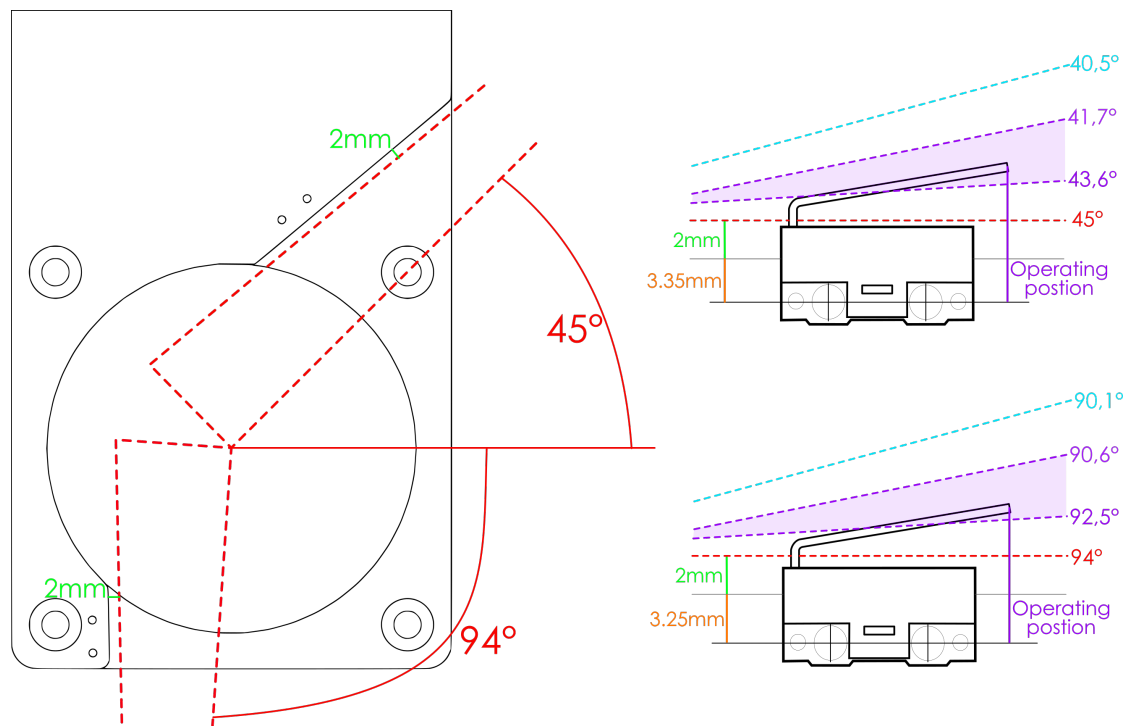
Figure 6.23: Rendering of the motor mounting bracket done on SOLIDWORKS



(a) Top view of the motor mounting bracket (b) Sectional view of motor mounting bracket

Figure 6.24: The motor mounting bracket orientation is precisely placed thanks to the positioning pins, and is fixed to the mounting plate via the screw in the middle (a). The drawing in b is a sectional view of the motor mounting bracket and the attached proximal link. The arm is fixed to the shaft with pressure screw and a key. The bracket thickness is $7[mm]$ and with the tolerances, the space between the proximal arm and this part is $0.5[mm]$ in the worst case scenario.

The mechanical stops are limiting the swing of the proximal arm between $45[^\circ]$ and $-94[^\circ]$ as shown in the Fig.6.25a. As presented in the section 4.2.3, the swing angles of the proximal arm will never go above $40,5[^\circ]$ and $-90,1[^\circ]$. Therefore, the proximal arm have a margin of around $4[^\circ]$ before hitting the proximal arm. To soften the contact between the proximal arm and the stops, a $2[mm]$ layer of rubber has been placed on the mechanical stop. The micro switches must be placed carefully as their operating position tolerances is $\pm 0,8[mm]$. Indeed, the angle range of the operating position must be bounded between the mechanical stop and the maximum proximal arm angle (Fig.6.25b). Thanks to this, the movement of the arm will not be stopped when it has not exceeded its limit positions and it will be detected before coming into contact with the bracket.



(a) limit angles of the proximal arm (b) Operating position of the microswitches

Figure 6.25: The motor mounting bracket limit angles of the proximal arm due to the motor mounting bracket are shown in (a). A $2[mm]$ space has been left to place a layer of rubber to soften the contact. The drawing in (b) shows the operating angle range of the microswitches. They have been placed at those distance from the mechanical stop so as not to unexpectedly cut the motion of the proximal arm and to be able to detect them before they enter in contact with the mechanical stops and prevent that to happen.

FEM validation

The FEM simulation (Fig.6.26) has been done by applying on the screw that fixes the motor to the bracket a distributed mass equal to a third of the total mass of the robot (including motors) which is equal to $3,635[kg]$. The top of the bracket has been fixed as it is directly in contact with the mounting plate. The layer of steel of the motor has been added to to get closer to reality. The maximum displacement observed on the piece is less than $1,3e^{-4}[mm]$ which validate the detail design of the mechanical stop. Indeed, the impact on the axis of rotation of the shaft of the motor is negligible.

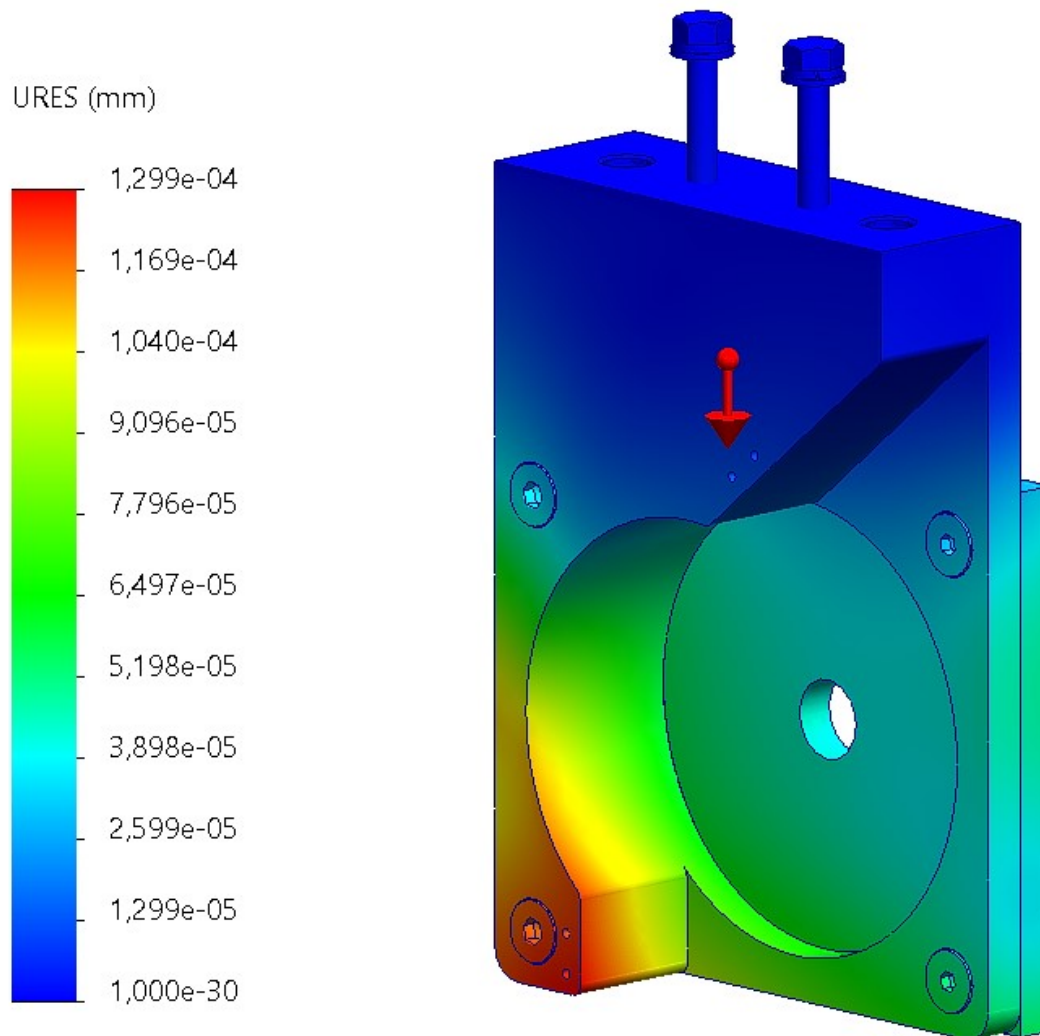


Figure 6.26: FEM simulation of the motor mounting bracket showing that the deformation in this piece are negligible.

6.4.2 Mounting plate

The mounting plate (Fig.6.27) goal is to fix the whole robot to the aluminium box structure while ensuring that the motor shaft rotation axis is at a distance r_a from the center of the plate. Three holes have been placed to let the cables through. This plate has been made out of aluminium 6061-T6 and is 20[mm] thick.

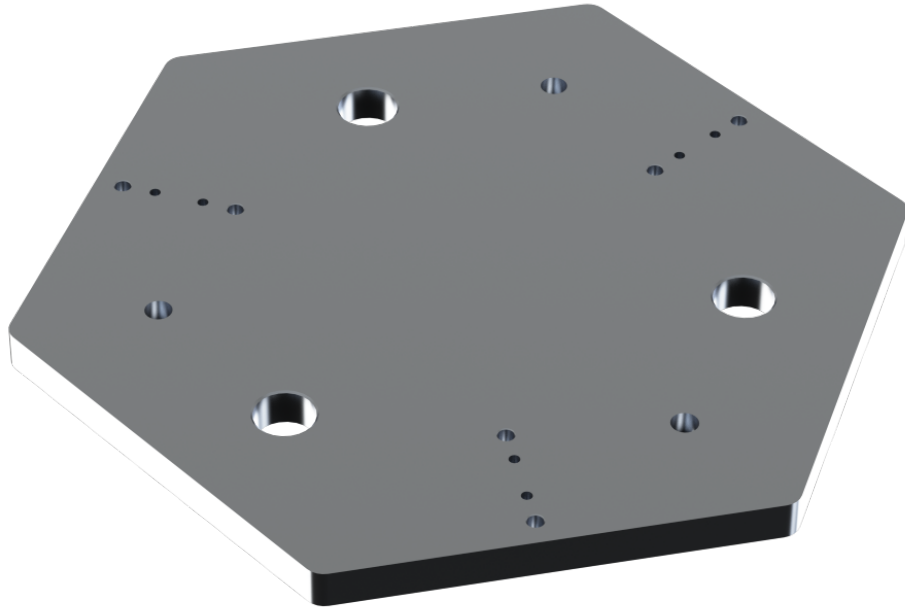


Figure 6.27: Rendering of the mounting plate made on SOLIDWORKS

FEM validation

The FEM simulation (Fig.6.28) has been made by applying on the screw that fix the brackets to the plate a distributed mass equal to the total mass of the robot (including motors) which is equal to 12,405[kg]. The screw fixing the plate to the aluminium profile box are fixed. Maximum displacement of the plate being lower than $2,287e^{-3}$ [mm], the detail design of the plate can be validate. Indeed, the impact on the geometrical parameter (and more specifically r_a) of the robot are negligible.

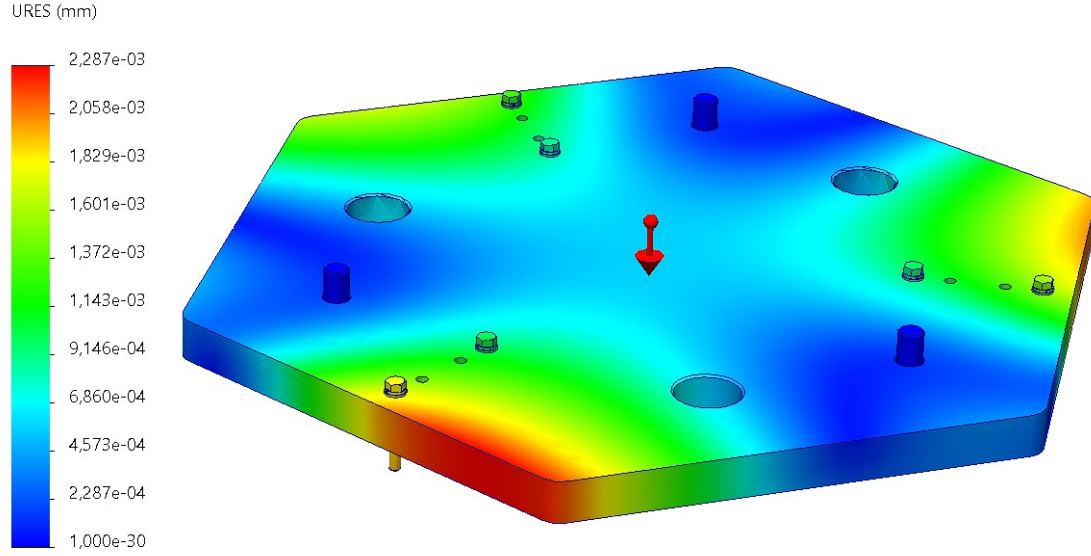


Figure 6.28: FEM simulation of the mounting plate showing that the deformation in this piece are negligible.

6.4.3 Aluminium profile box

To determine the total height required for the enclosure, the following lengths must be taken into account:

1. The length between the plane that intersects all the axes of rotation of the drive shafts and the bottom of the workspace: 525,3[mm].
2. The length between the plane that intersects all the axes of rotation of the motor shafts and the top of the enclosure: the length between the center of the motor mounting bracket and the top of this piece 86.5[mm], the thickness of the mounting plate 20[mm] and the aluminium profile linking the plate and the box 85[mm]. 191.5[mm] in total.
3. Allow space for the electrical box: 300[mm] the height of the box.
4. There will be 3 aluminium profiles placed horizontally : 135[mm]

The total length of the aluminium profiles placed vertically must be higher than 1151.8[mm]. Profiles with a length of 1200[mm] were already available in the laboratory and were thus used to reduce the overall cost of the robot.

The minimal length needed for the horizontal profiles is 599[mm]. This length corresponds to the side of the isosceles triangle whose vertices correspond to the

end of the proximal arms when they are at $0[^\circ]$ from the the plane that intersects all the axes of rotation of the motor shafts. The only available profile in the lab were $710[mm]$. By taking into account the width of the two vertical profiles on either side of the horizontal profiles, resulting in a total width of $800[mm]$, which is higher than the max width imposed in the constraints (section 2.2) and thus the profile should have been cut. However, The box has been left as it is if it is necessary in the future to completely rethink the box, for example if it needs to be reinforced as it will be discussed in the section 8.5.

To ensure that the profile box will be able to hold the robot, it has been validated by a FEM simulation shown in Fig.6.29. The box was fixed to its base. The entire mass of the suspended part of the robot was applied to the threaded surfaces of the aluminium profiles $85[mm]$. The deformation is less than one millimetre and the box can contain the total mass of the robot.

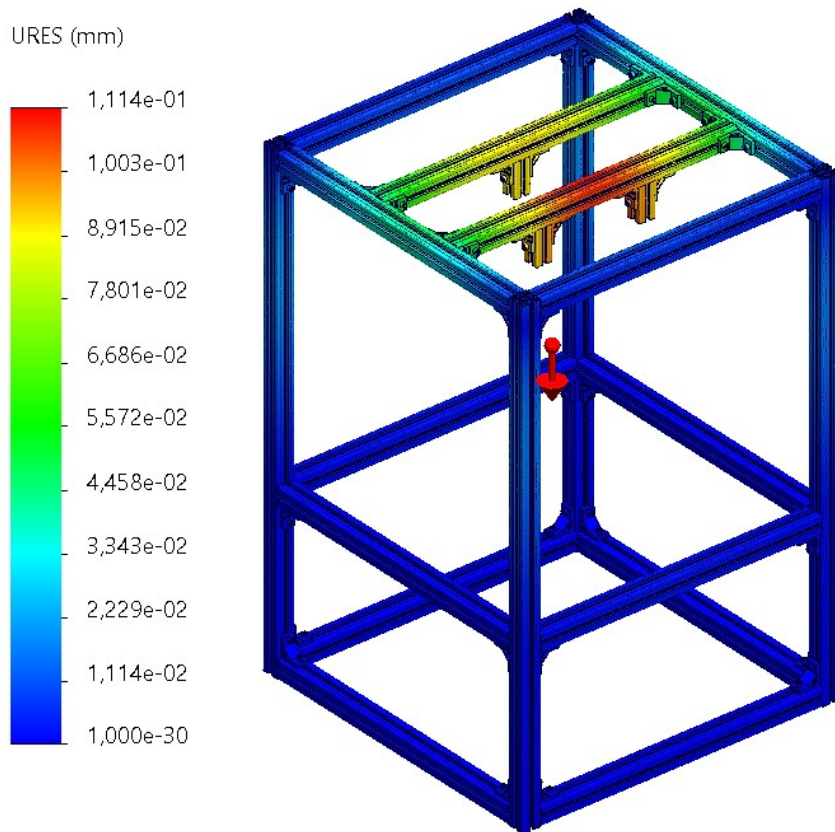


Figure 6.29: FEM simulation of the Aluminium profile box verifying that the box can hold the total mass of the robot.

6.5 Mechanics: Global validation

To validate the fact that the robot can hold the $1[kg]$ in static a global validation of the mechanical part has been carried out. The end effector has been placed On the edge of workspace. The right materials have been applied on each piece on SOLIDWORKS. A $1[kg]$ mass have been fixed to the end effector. The result is displayed on the Fig.6.30 and as the maximum deformation is less than $0.36[mm]$, the static payload function requirement of $1[kg]$ is validate.

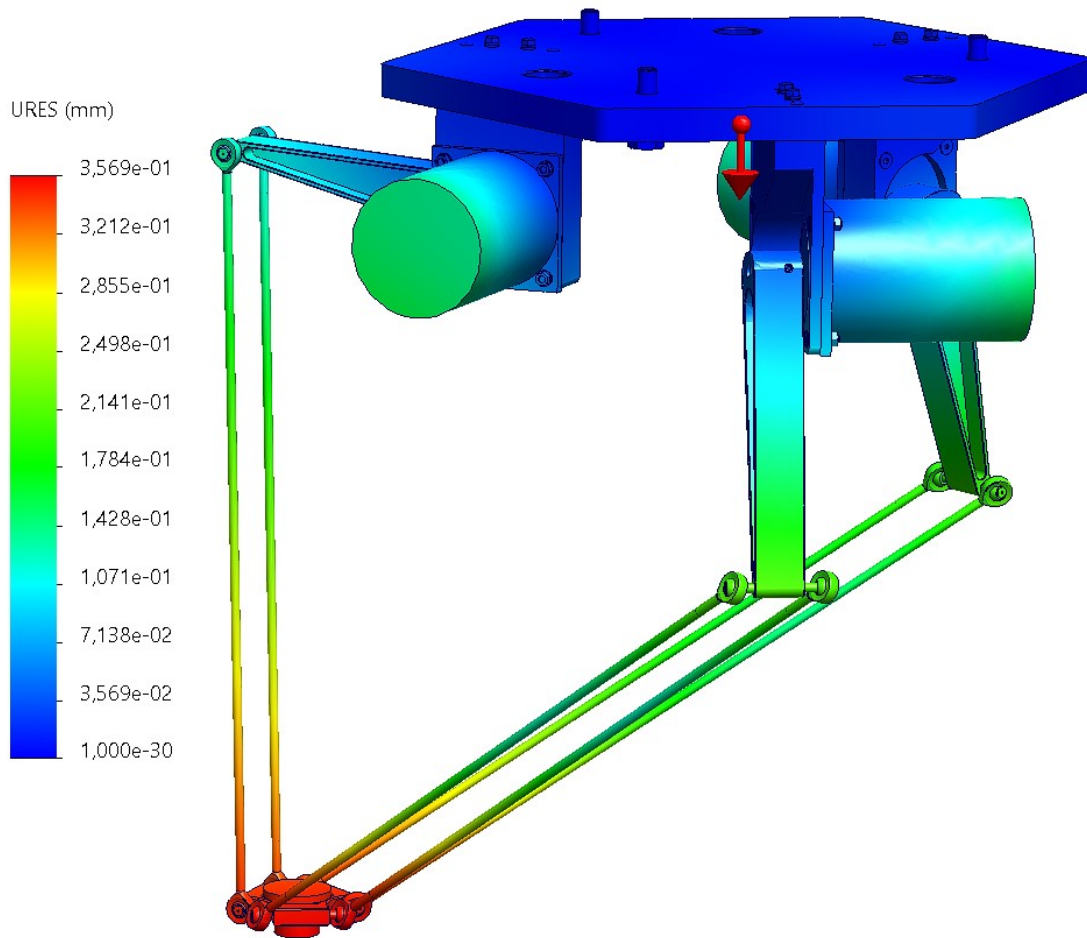


Figure 6.30: FEM simulation of the complete Delta robot at the edge of the workspace with a $1[kg]$ mass attached to the end effector.

Chapter 7

Manufacturing, implementation and validation



Figure 7.1: Delta robot mounted

With all the detail design steps complete, it was time to move on to materializing the Delta robot. The aluminium parts were machined at CREDEM as well as by 3D printing. The mechanical components were ordered from MISUMI and part of the electrical components were ordered from FARNELL and the other part from RS. Once the robot was fully assembled (Fig.7.1), the programming is then carried out. Finally, the robot was tested on the circle, pick and place and helix trajectories.

7.1 Assembly of the Delta robot

We didn't encounter any major problems during the construction of the robot. The parts were correctly sized and there were no problems during machining at CREDEM.

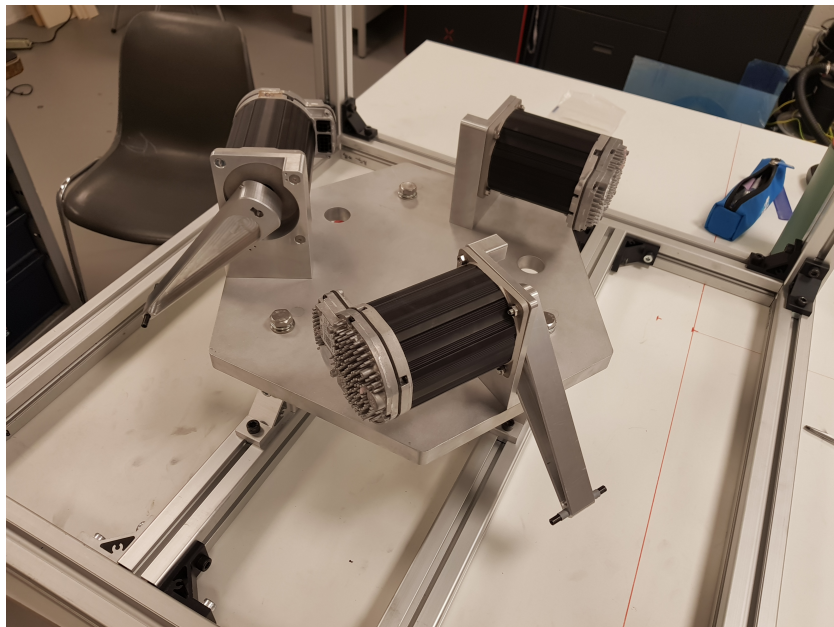


Figure 7.2: Plate mounted on the aluminium profile box with motor mounting brackets and proximal arms fixed to the motors.

For the 3D printed parts, the printing of the end effector went well (Fig.7.4), but we did notice an issue with the sleeves. Indeed, there is play between the spherical ball and the end effector. This is due to the chamfer on the tear-drop hole.



Figure 7.3: End effector 3D printed with the MAKEFORGED printer with Kevlar layers.

Another problem we encountered is the possible collisions between the robot and the aluminum profile. Indeed, the horizontal aluminum profiles, which are placed at the bottom of the workspace, could be included in the reachable volume of the Delta robot if it is not placed in the center of the box. This could be a problem in the future, when the width of the aluminum profile box is reduced to less than $750[mm]$.

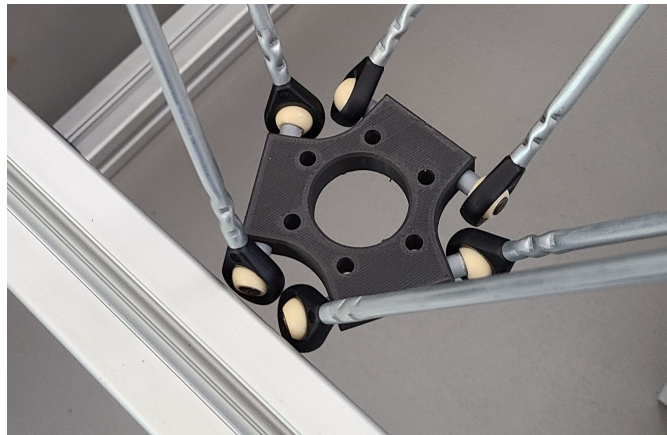


Figure 7.4: Collision between the end-effector and the horizontal aluminium profile.

In the section 3.2, it has been shown that the collision between the proximal arm and the distal arm were impossible. However, we did not study the collision between the motor mounting bracket and the distal arm. In some end effector configurations in the reachable volume, a collision can occur (Fig.7.5). If the robot stays in the workspace this collision is impossible, but another layer of security

need to be implemented to prevent this case from occurring.

As mentioned in the section 6.4.3, the structure of the profiles oscillates during the movement of the robot and need to be reinforced.



Figure 7.5: Collision between the distal arm and the motor mounting bracket.

7.2 Budgeting

The detailed budget of the Delta robot can be found in the appendix F. The total cost of the robot is 3560,68€, the budget of 4000€ has been thus respected. The biggest expense was for the motors with the cables (communication and power supply), the power supply, the control board and above all the motors themselves. The total cost of the motors represents nearly 64% of the robot's price. By taking into account the price of other electrical components such as the casing, the emergency stop circuit, etc., this represents almost 78% of the total price.

The rest of the expenditure is made up solely of mechanical parts. This low total cost is due to the hourly rate for machining the parts was only €15, as they were machined at CREDEM as part of a master thesis. If we hadn't benefited from the reduction for master's theses, the real cost of these parts would have been 440€ for the mounting plate, 580€ for the distal arms and 582,5€ for the motor mounting brackets.

7.3 Programming

As presented in the section 6.2.1, the motors can be controlled using the Clearcore card, thanks to the C++ library developed by Teknic. In the figure 7.6, the complete code used for the motors is summarised in a diagram form. For the moment, the code allows a PWM signal to be sent to the motor corresponding to a given position as a percentage of the motor's total range.

In order to provide a basis on which future work on the robot can relay, we have not hardcoded the positions of the motors for the three trajectories presented in section 2.3. Instead, the inverse kinematic model of the robot has been directly implemented in C++. Thus the user only need to implement its wanted trajectory for the end effector and the code compute itself the motors angles. For now, only the circle, pick and place, and helix trajectory has been implemented.

Currently, the programs compute the inverse kinematic each time a trajectory is uploaded upon the Clearcore board. This is not done in real time, the angles of the motor are pre-calculated before before the motors start moving and are all the stored in an array in percent of the total range of the motors. Thanks to this, the motors positions can be updated every 0.25 ms. The state of the micro switches is checked at each motor update. If they are activated, the motors are disabled and the arms return to the home position.

The motors must be set up once via the MSP software developed by TEKNIC. The motors can be auto-tuned to work with the mechanics attached to them. During the auto-tuning process, the maximum and minimum angles that the motors can reach can be define. To be able to communicate in PWM, it is also necessary to define the maximum position for a signal sent at 100% of the duty cycle and a minimum position for a signal at 0%. A homing sequence also can be defined on the software. This allows the motors to be calibrated each time they are enabled and placed at a desired position.

We encountered a problem during programming that need to be pointed out. The function developed to send a PWM signal does not allow values below unity to be sent. In fact, the function rounds all commas and we can't reach the maximum resolution of the motors with the current code. We did not manage to solve this issue in time but possible solutions will be discuss in the section 8.2.

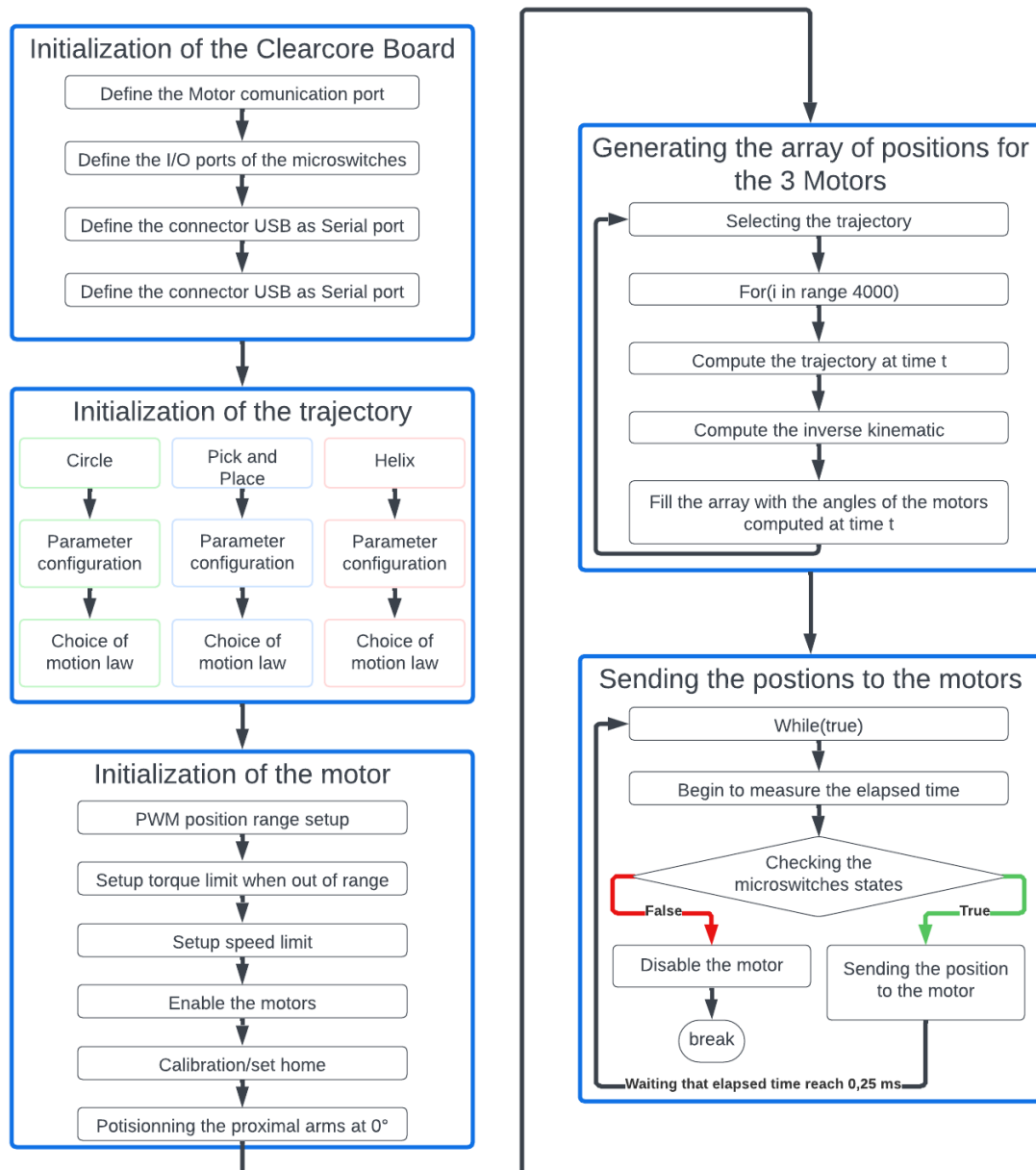


Figure 7.6: Diagram of the robots code explaining in detail its structure.

7.4 Validation through the trajectories

Experiments were conducted to test and validate some of the specifications of the robot. Those test were conducted through the circular, the pick and place and the Helix trajectories presented in the section 2.3.

Firstly, the accelerations at the end effector were measured and compared with the values obtain via the derivative of the trajectories. To achieve this, an NGMIU has been used. This is an IMU weighting $46[g]$ equipped with an accelerometer with a sample rate of $400[Hz]$. The NGMIU has been attached to the end effector with clamps. To eliminate the impact of the gravity acceleration on the measurements in the X-Y-Z directions, the end-effector was kept stationary (still) before the start of the trajectories and the average of the accelerations measured in the X, Y and Z directions during this period was calculated and then compensated from all measurements made while the robot was in motion. To remove the noise from the measurement, a simple Butterworth lowpass filter has been used. Then, to obtain the velocity of the end effector, the unfiltered accelerations measured have been integrated. The integration acts as a filter but the integration over time of the value of the accelerometer leads to a drift due to the accumulation of the error. To cancel this drift, the hypothesis that the accumulation of error increases linearly was made. A linear regression was then applied to the integrated values and then subtracted from these values. However, as it will be shown, the linearity of the drift is not always true and was not properly cancelled in each graph. As a result, the position was not integrated because the drift was too high after two integrations and so the values no longer made any real sense. More advanced methods for cancelling the error and the noise must be use to obtain the position.

Secondly, the theoretical position, speed and acceleration of the motors were compared to the measured values of the motor. This was made possible by TEKNIC's software, which provided access to all these data.

Finally, two "drawing" experiments were made. The circle and pick and place trajectories were used in combination with a 3D printed mouthpiece (Fig.7.7) to draw the a circle and to test the repeatability in the X-Y plane for the pick and place trajectory. For the circle and the pick and place, a pen with a $5[mm]$ and a $0,3[mm]$ tip width has been use respectively (Fig.7.8). They have been fixed to the mouthpiece via pressure screw. A wooden plate has been used to place the papers. In each corner of the plate screws have been place to level the plate.

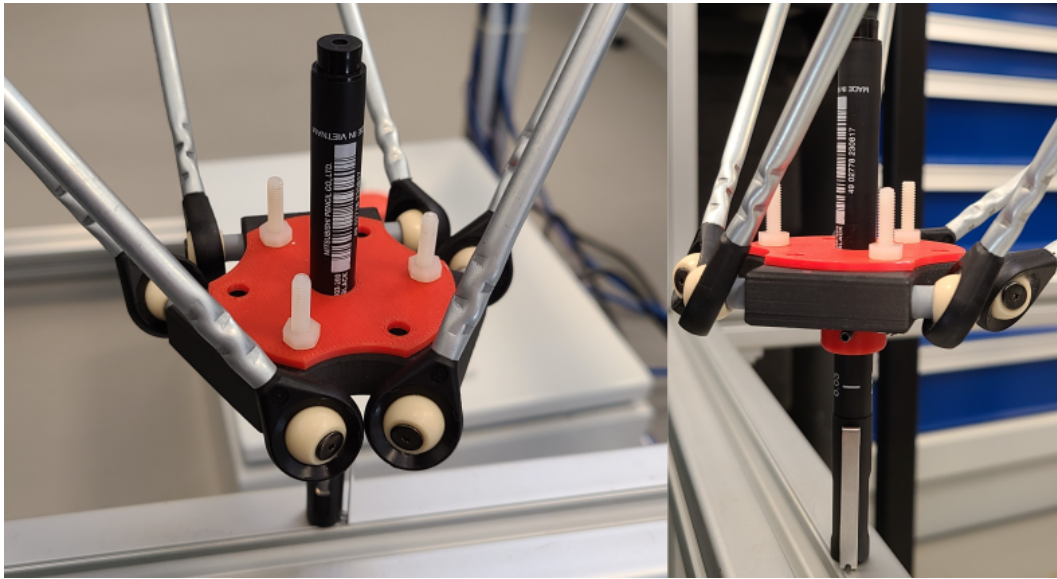


Figure 7.7: 3D printed mouthpiece to fix a pen to the end effector. The piece has been fixed to the end effector via nylon screw and bolt.

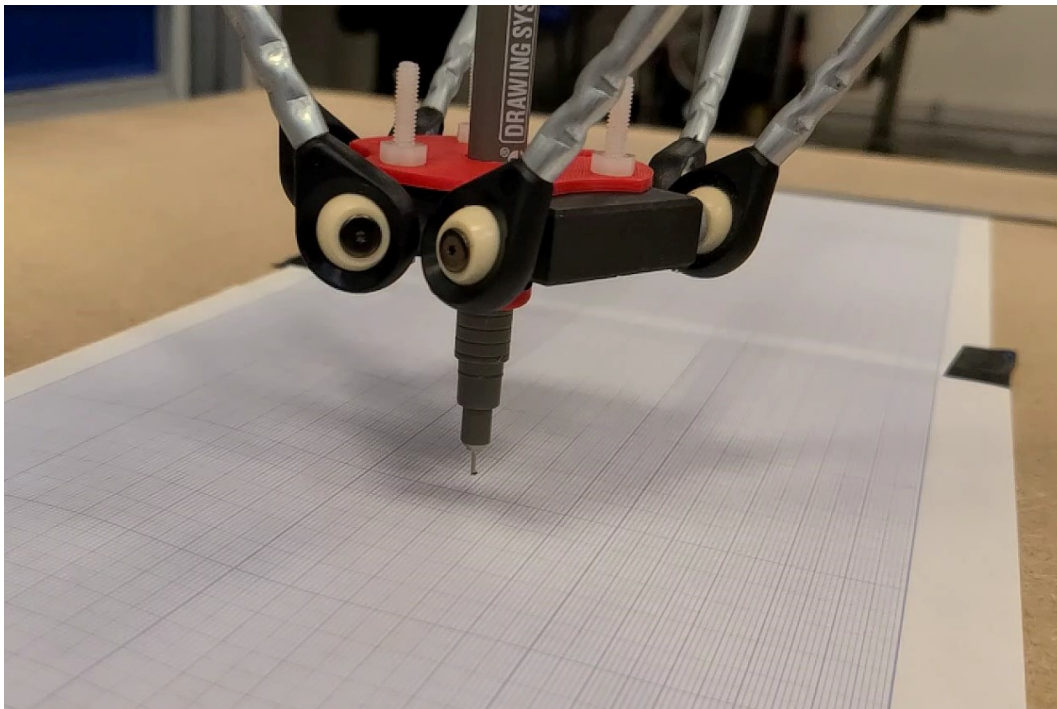


Figure 7.8: View of the pen used in the pick and place to make mark on the graph paper.

7.4.1 Circle trajectory

Accelerometer result

For the circle trajectory (Fig.7.9) the following parameter has been use:

1. The robot make 4 circle in 1 second.
2. The end effector is an uniform circulatory movement thus there will no law of movement use.
3. The circle has a radius of $0,15[m]$.
4. The circle is in the middle of the workspace.

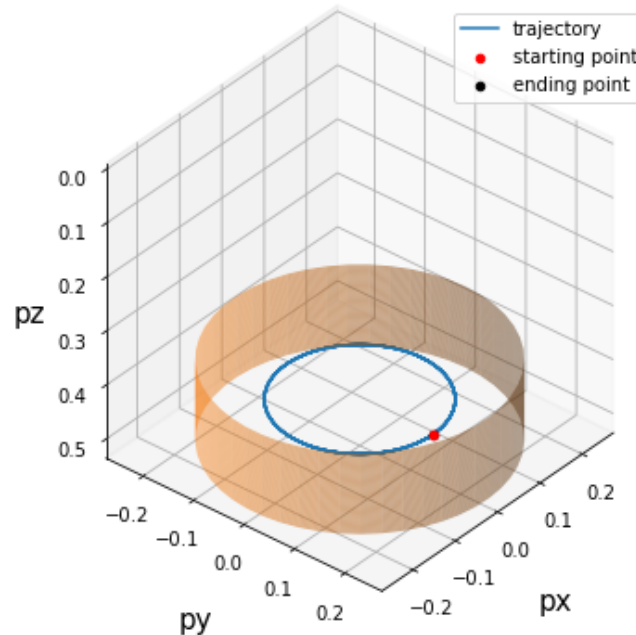


Figure 7.9: Graph of the circle trajectory.

The measured absolute acceleration of the end-effector cannot be properly extract from the noise. Indeed, as shown in the section G.2, the theoretical absolute acceleration of the end-effector is constant. In fact the end effector is an UCM and thus the centripetal acceleration is constant and is the only acceleration applied on the end effector. However, as shown in the Fig.7.10, the unfiltered acceleration is totally altered by noise. The Butterworth filter did not work properly and the mean has been taken instead.

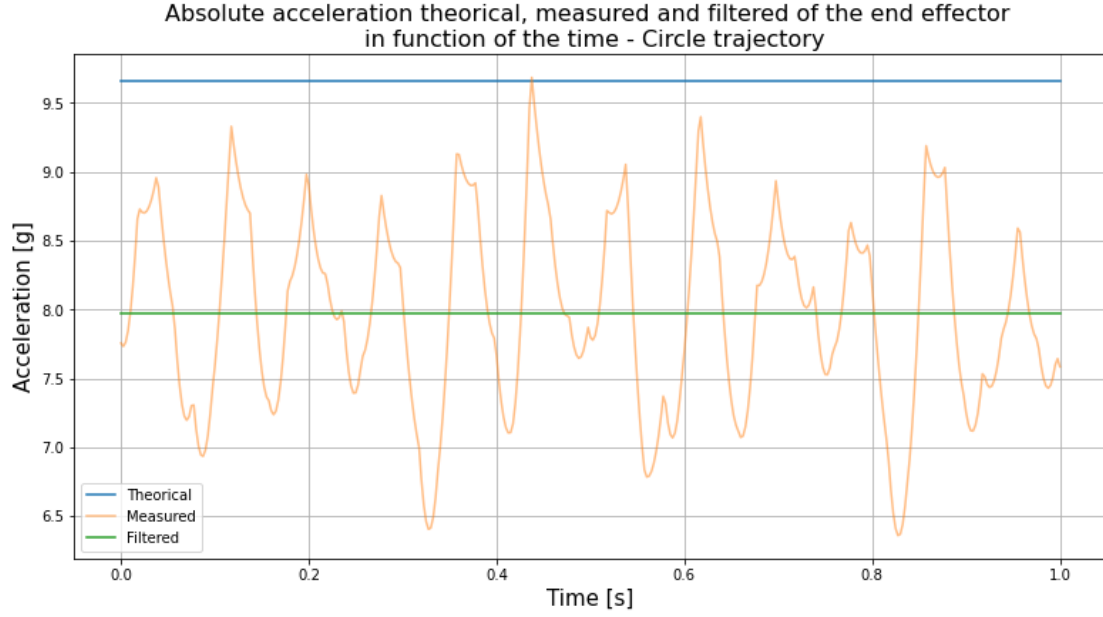


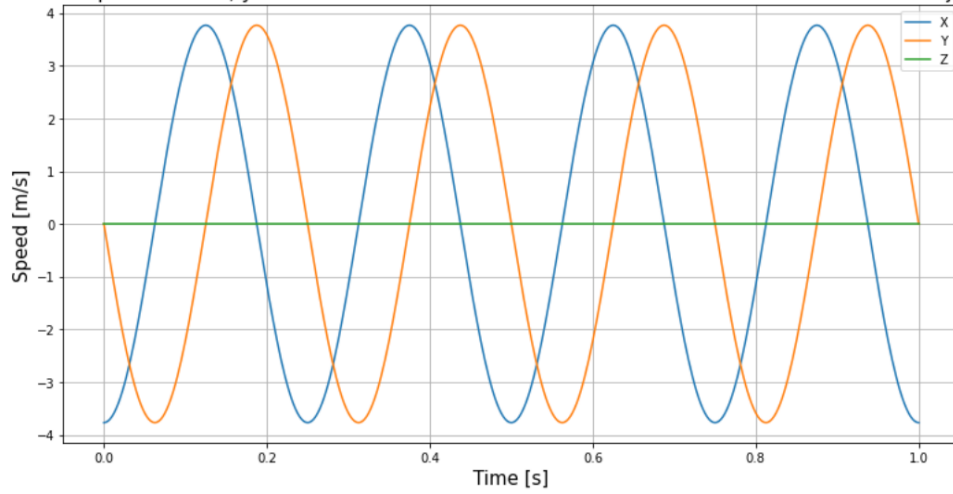
Figure 7.10: Graph of the measured resulting acceleration in [g] of the end effector in function of the time for a circle trajectory.

The measured and the theoretical absolute accelerations and the speed are shown in the Fig.7.10 and Fig.7.11 respectively. The major difference between the measured and theoretical values is due to the noise but the speed and the acceleration can be determined by computation. Indeed, as it will be discussed in the drawing circle experiment, the radius of the circle is 0,145[m] instead of the 0,15[m] due to the PWM limitation discussed earlier. With the radius and the frequency of 4 circle made in 1[s], the speed and the acceleration can be determined as follow:

$$v = \frac{4(2\pi r)}{t} = 3,644[m/s]$$

$$a = \frac{v^2}{9,81r} = 9,33[g]$$

Theoric speed in the x, y and z directions of the end effector in function of the time - Circle trajectory



Integrated speed in the x, y and z directions from the accelerations measured of the end effector corrected with a linear regression in function of the time - Circle trajectory

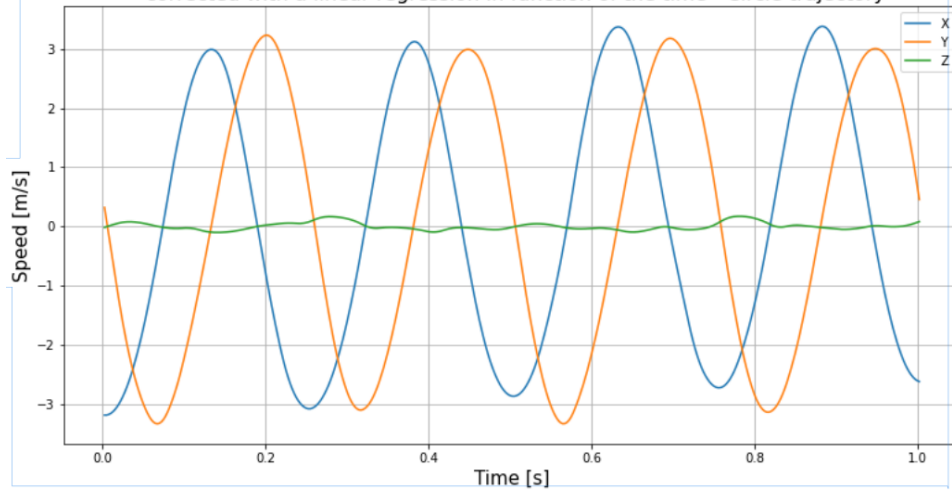


Figure 7.11: Graph of the integrated speed of the end effector in function of the time for a circle trajectory. The drift was not eliminated for this graph. The blue curve is the velocity in the X direction (tangent to the circle) and orange one is in the Y direction (centripetal to the circle)

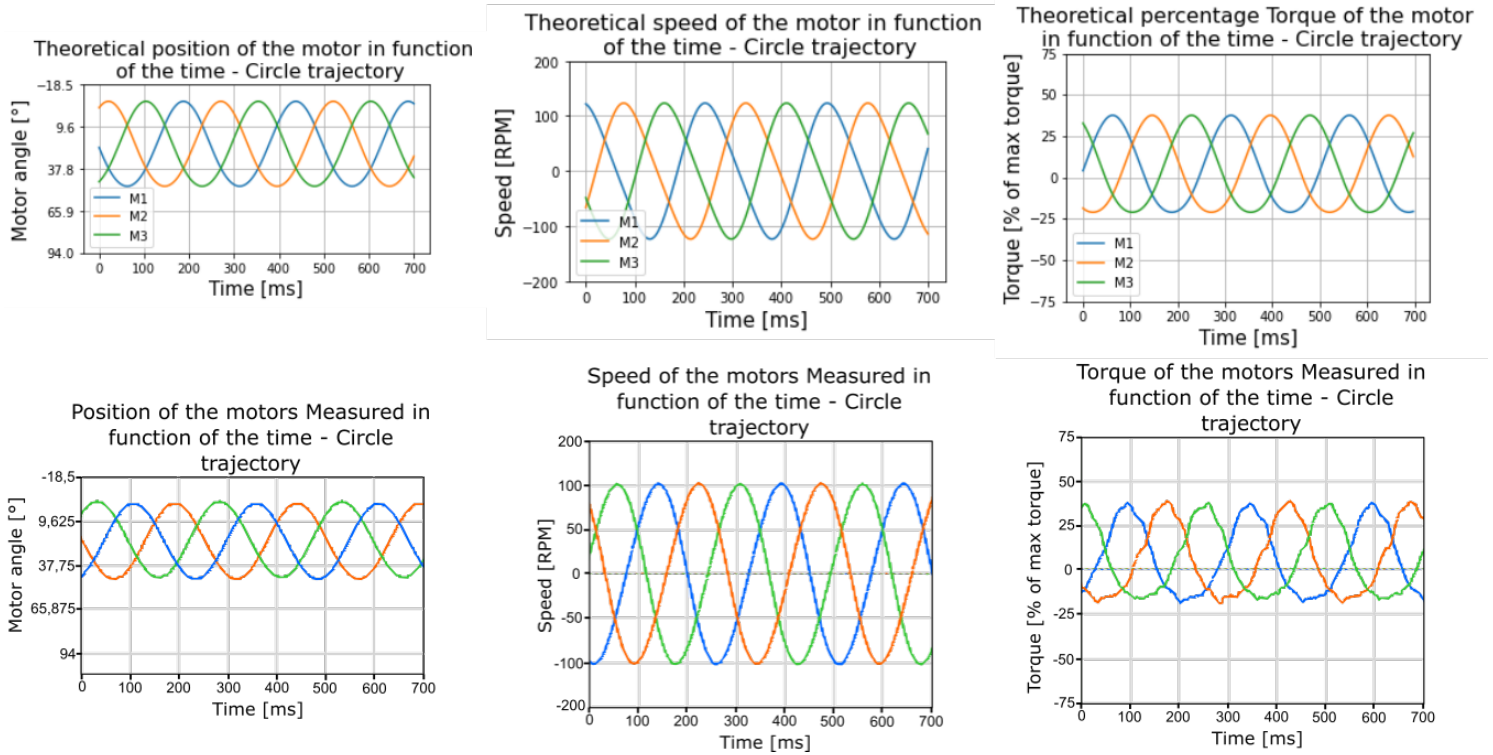


Figure 7.12: Graphs of the measured position in angle, speed in RPM and torque in percentage of the max torque of the motors for a circle trajectory. The motor measure is in blue the motor 2 is in orange and the motor 3 is in green.

Circle result

The goal of this experiment is to study the accuracy of the robot when drawing a circle. The result are shown in the Fig.7.13. For this experiment, the frequency of the circle was reduced to 1 per second but the other parameters stayed the same as in the previous experiment. The diameter of the circle drawn was not $0,3[m]$ but $0,29[m]$. This due to the limitation imposed by the PWM signal. This can be shown through the minimum angles of the motors. Those values can be extracted from the graphs shown in Fig.7.12: $49,02[^\circ]$ theoretically and $48,43[^\circ]$ experimentally. Those two values correspond respectively to $36,81\%$ and 36% of the angle range of the motors (going from $94[^\circ]$ to $-40,5[^\circ]$). The measured value of the motor angle is the rounded value of the commanded angle. By changing the radius in the theoretical model by $0,145[m]$ and thus have the same radius as the circle drawn, the minimum angle is $48,33[^\circ]$ which is the same as the measured angle. Therefore, the $1[cm]$ difference between the theoretical and the experimental diameter is only due to the PWM limitation preventing the use of decimal. Beside

that the overall circle is nearly perfect even if the pen was unable to mark the sheet properly.

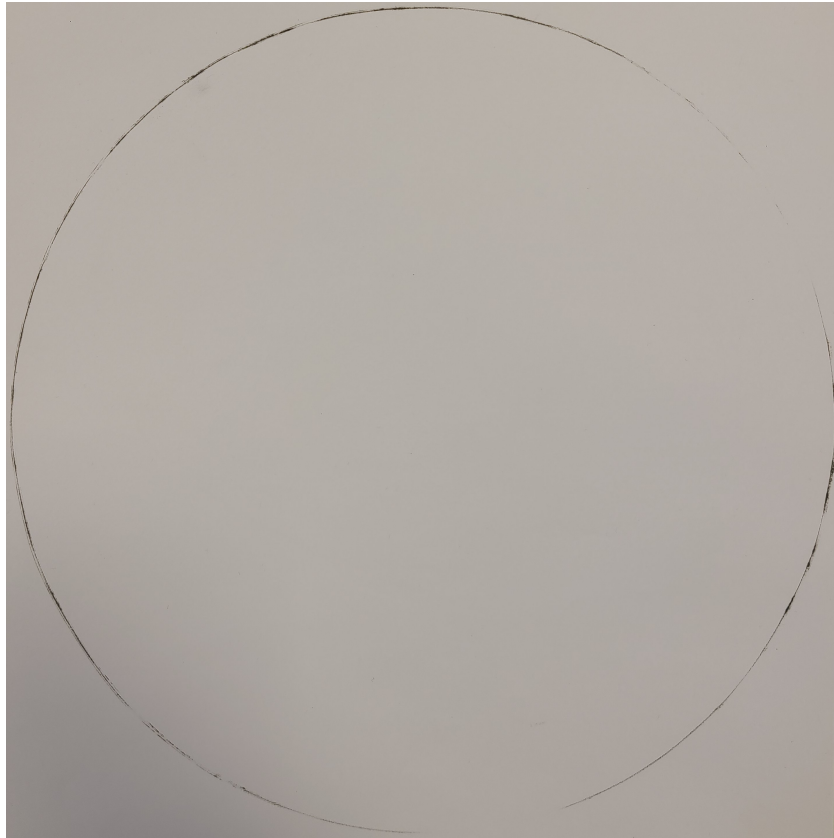


Figure 7.13: Circle drawn by the robot

7.4.2 Pick and place trajectory

Accelerometer results

The parameters used for the pick and place trajectory (Fig.7.14) are the following:

1. The robot makes 4 pick and place in 1 second, this correspond to going 4 times in total from its starting point to its ending point then to its ending point to its starting point.
2. The motion law in this case is the modsin.
3. the distance between the ending and starting point is $0,15[m]$.
4. the end effector will wait $0,3[s]$ in the starting point and in the ending point.

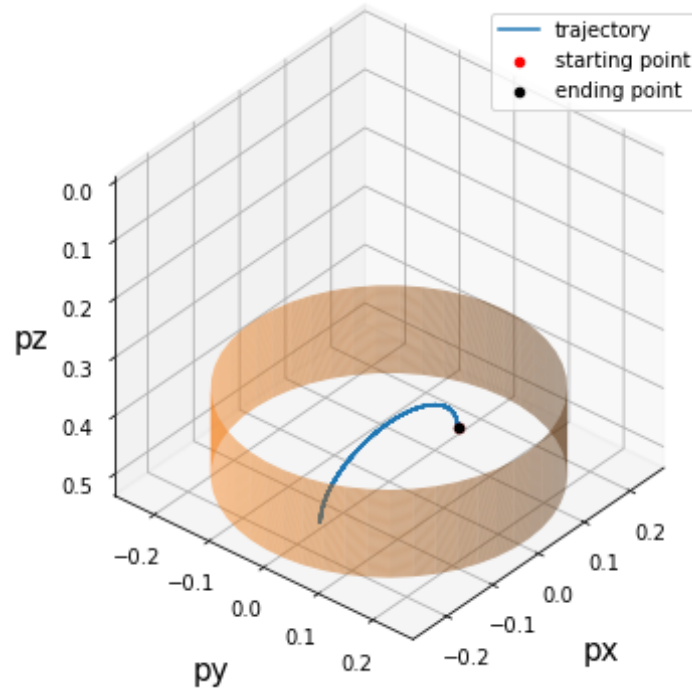


Figure 7.14: Graph of the pick and place trajectory.

For this trajectory the acceleration and the speed seem to be far more smaller than the theoretical one. this is mainly due to the RAS (regressive auto-spline) developed by TEKNIC. This is a vibration and resonance suppression features that will smooth the instantaneous acceleration. In our case, the RAS was set to $99[ms]$ The acceleration pics happening in less than $100[ms]$ are smoothed and

thus the overall acceleration is reduced. Unfortunately, we did not have the time to test further this issue with the RAS and the acceleration of the motors. The absolute acceleration and the speed of the end effector are held over a longer period of time as shown in the Fig.7.15 and in the Fig.G.3 respectively. The maximum acceleration for this trajectory is $10[g]$ and the maximum speed is $4[m/s]$. In the Fig.7.17, the effect of the RAS is quite marked on engines with the speed and the position being less sharp.

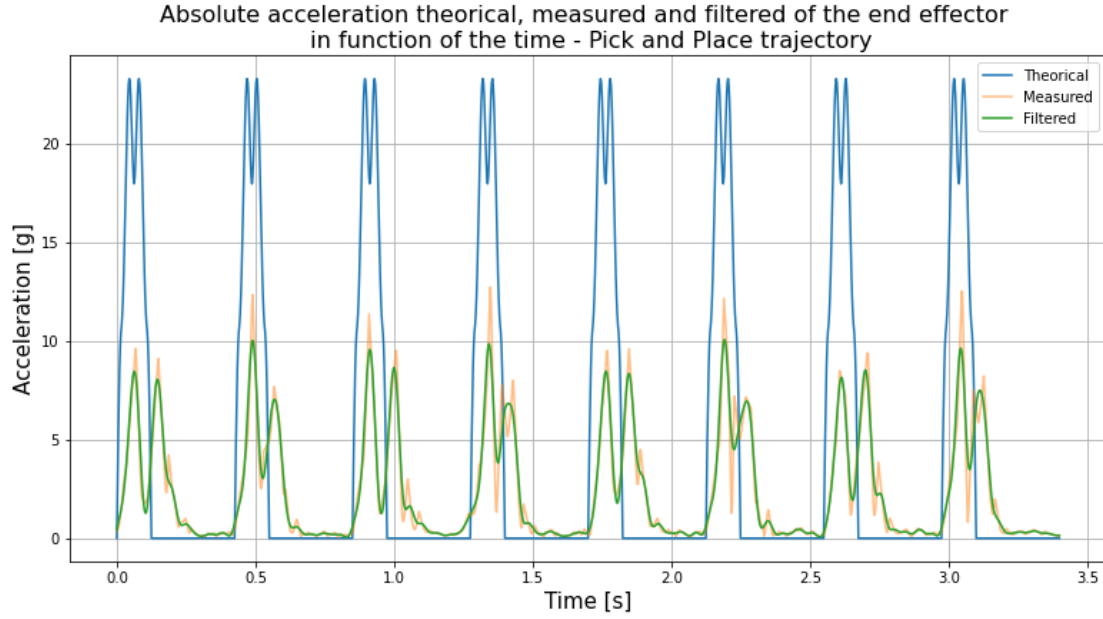
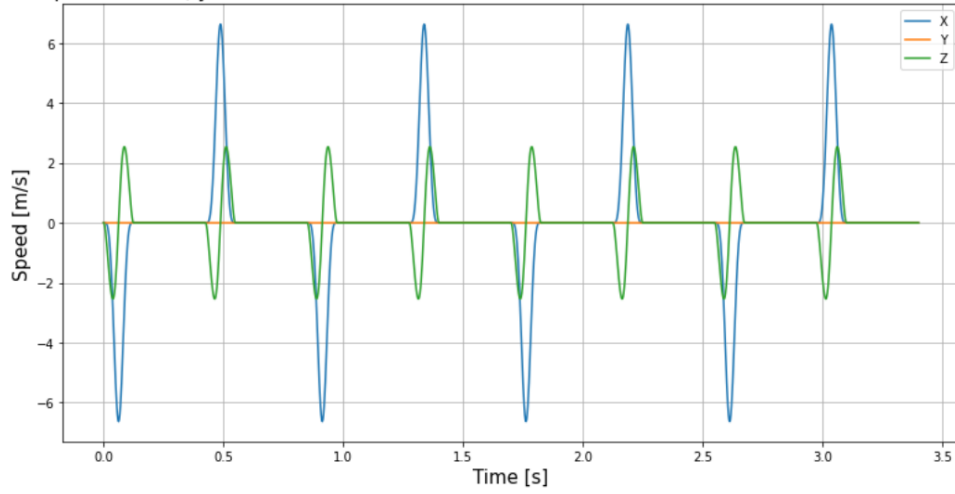


Figure 7.15: Graph of the measured resulting acceleration in $[g]$ of the end effector in function of the time for a pick and place trajectory.

Theoric speed in the x, y and z directions of the end effector in function of the time - Pick and Place trajectory



Integrated speed in the x, y and z directions from the accelerations measured of the end effector corrected with a linear regression in function of the time - Pick and Place trajectory

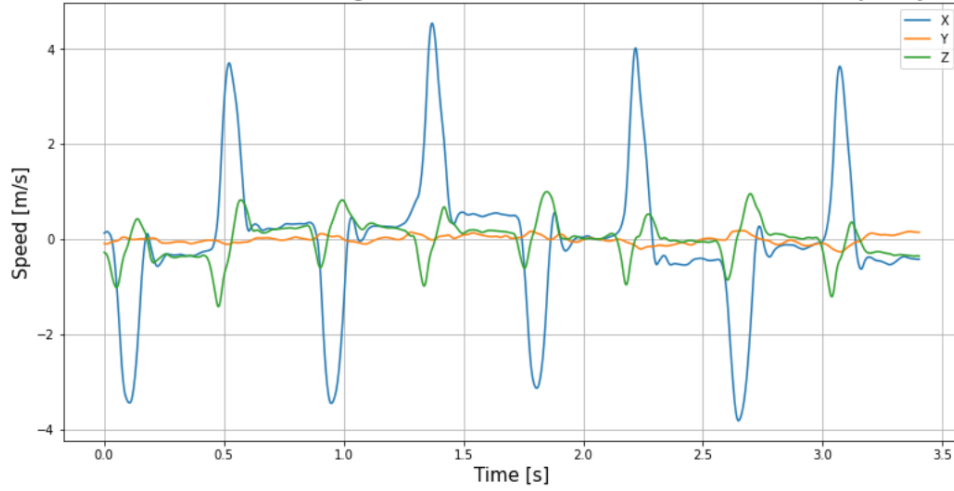


Figure 7.16: Graph of the integrated speed of the end-effector in function of the time for a pick and place trajectory. The graph with the drift can be found in the appendix ???. The blue curve is the velocity in the X direction (in the same plane as the pick and place trajectory), the orange one is in the Y direction (perpendicular to the plane of the pick and place trajectory) and the green one is the Z direction (the direction oriented toward the floor).

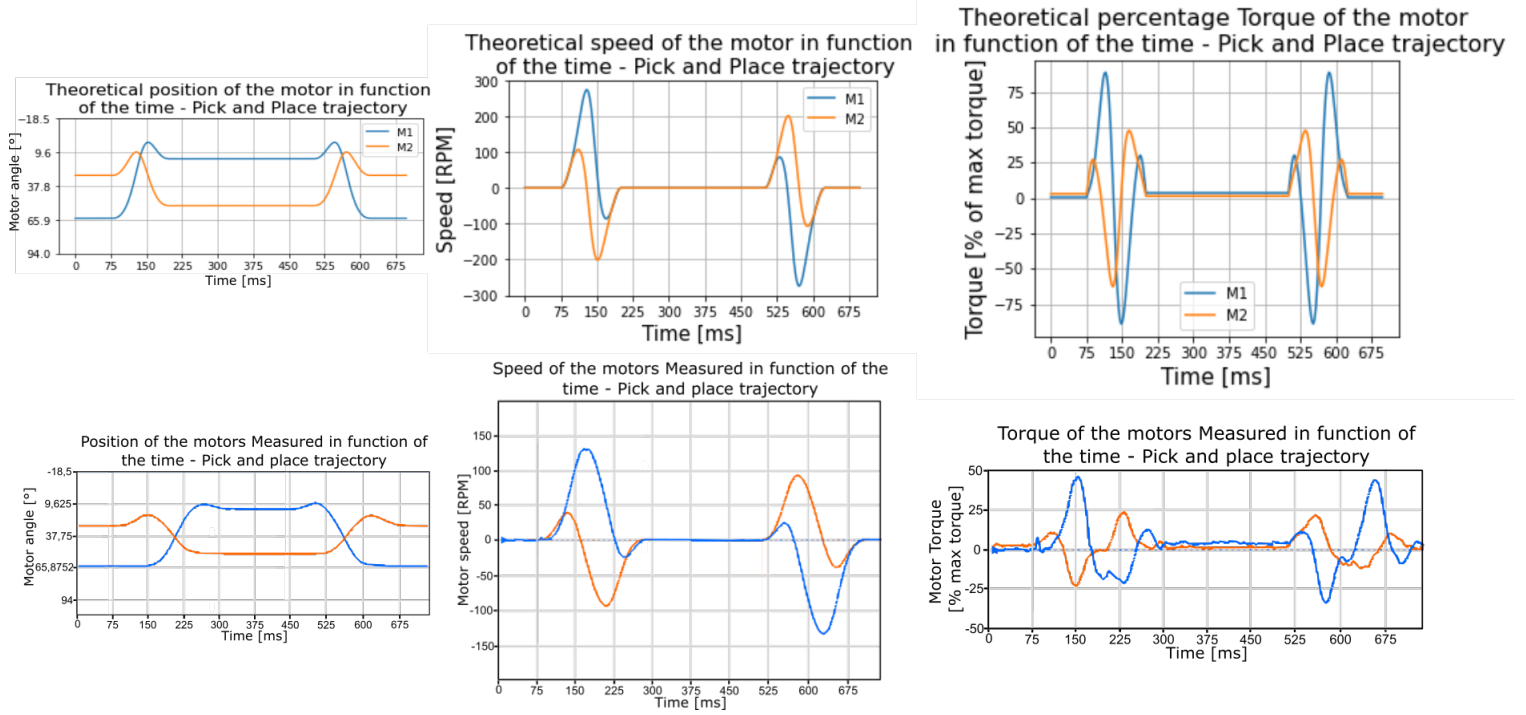


Figure 7.17: Graphs of the measured positions in angle, speed in RPM and torque in percentage of the max torque of the motors for a Pick and place trajectory. The motor 1 measure is in blue the motor 2 is in orange, the measure of the motor 3 are exactly the same has the one of the motor 2.

Pick and place result

The result of the pick and place experiment on the millimetre paper is shown in the Fig.7.18. The distance between the center of the two marks is 298[mm]. Again the 2[mm] difference is due to the PWM issue. The mark have been obtain after 10 minute in contact with the pick and place. The repeatability in the x direction, the direction of the movement, is 2[mm] and the 1[mm] in the y direction, the direction perpendicular to the movement. This was mainly due to the aluminium profile box which was moving a lot during the acceleration and deceleration phases. However, this result is promising to reach the repeatability of 0,5[mm] (section 2).

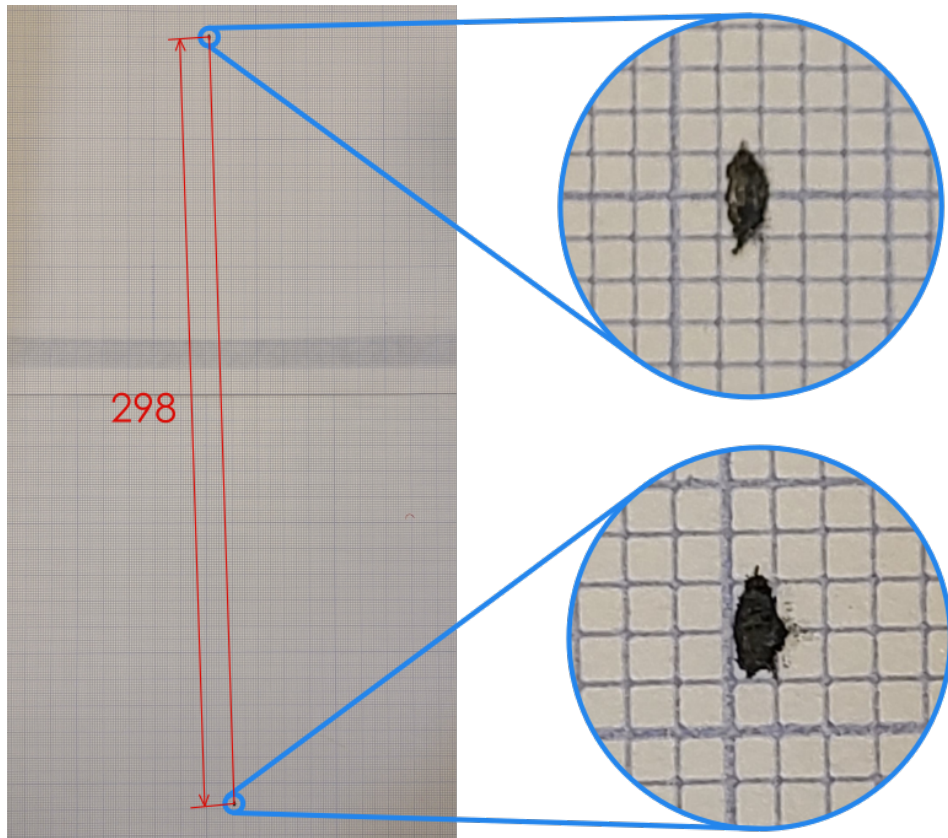


Figure 7.18: Mark of the pen left during the experiment to test the repeatability of the end effector as part of the pick and place process.

7.4.3 Helix trajectory

The helix trajectory (Fig.7.19) parameters are the following:

1. A frequency of two circle per second.
2. The trajectory is performed in 6[s].
3. The radius is 0.25 and therefore runs along all the edges of the workspace.
4. The motion law used is the modsin

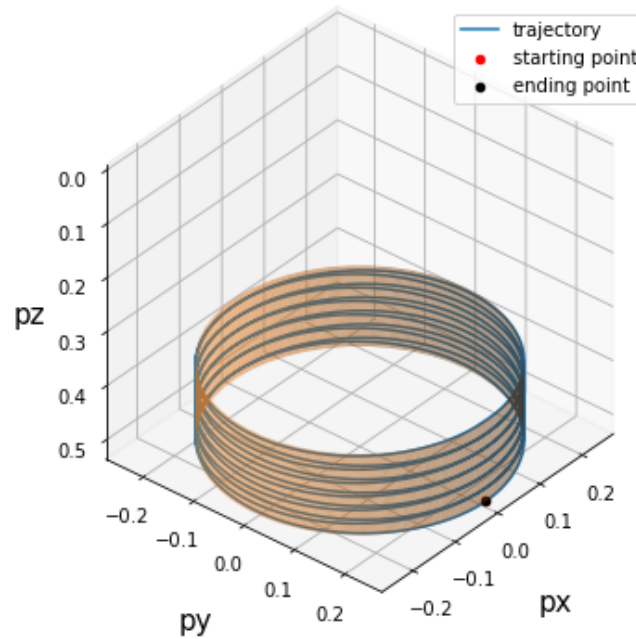


Figure 7.19: Graph of the Helix trajectory.

The helix trajectory is our current flagship movement. It reached the acceleration of 11,245[g] (Fig.G.4) and show that the robot can go to the boundaries of its workspace. This is shown through the motor angles in the Fig.7.21 in which the whole motor range is travelled by the motor. As this trajectory is spread over 6[s] it does not suffer from the other problems encounter in the circle and in the Pick and place. All graphs show the behaviour of the robot and the motors properly. The speed of the end effector goes up to 5[m/s].

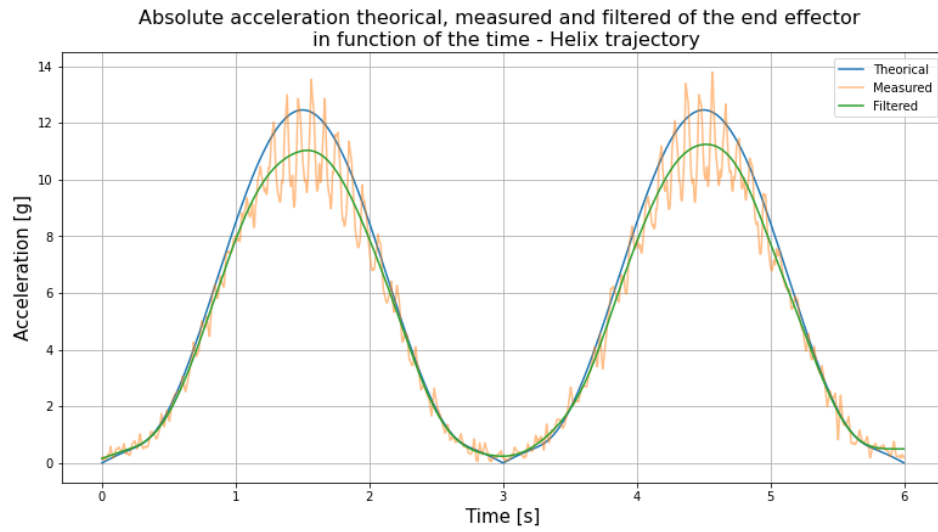


Figure 7.20: Graph of the measured resulting acceleration in [g] of the end-effector in function of the time for a helix trajectory.

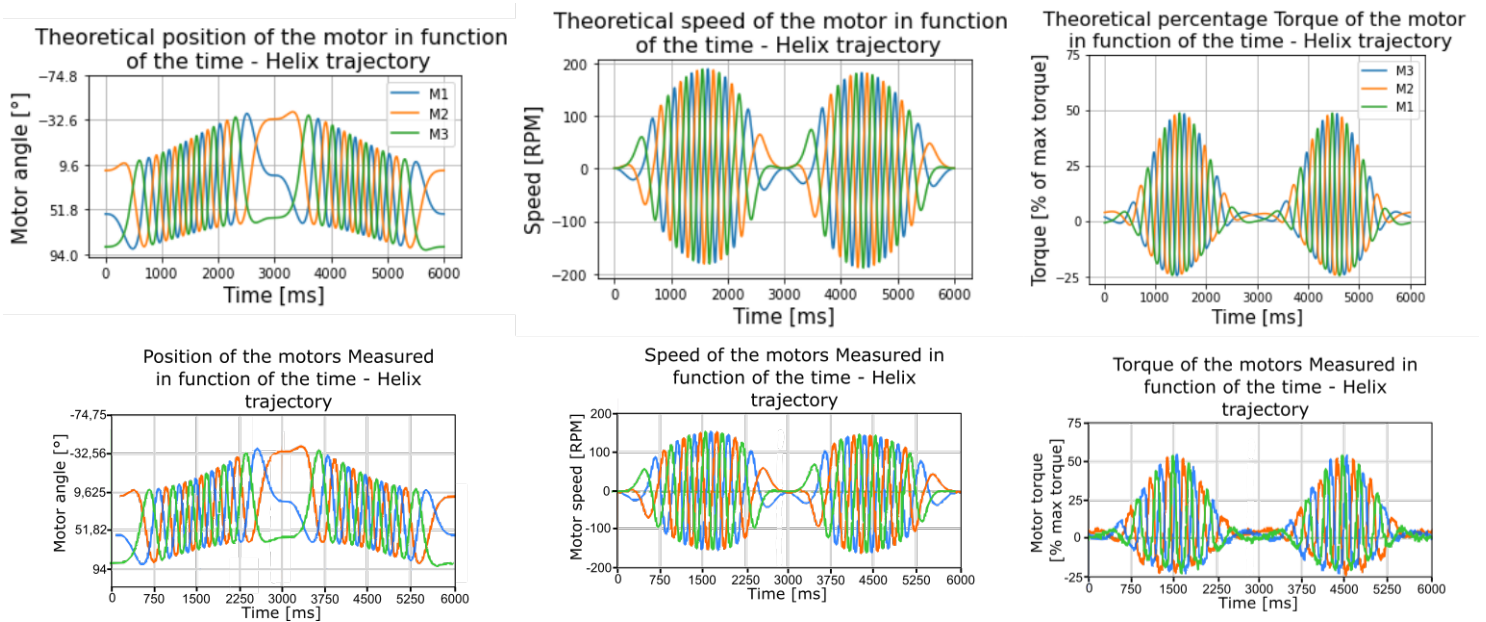
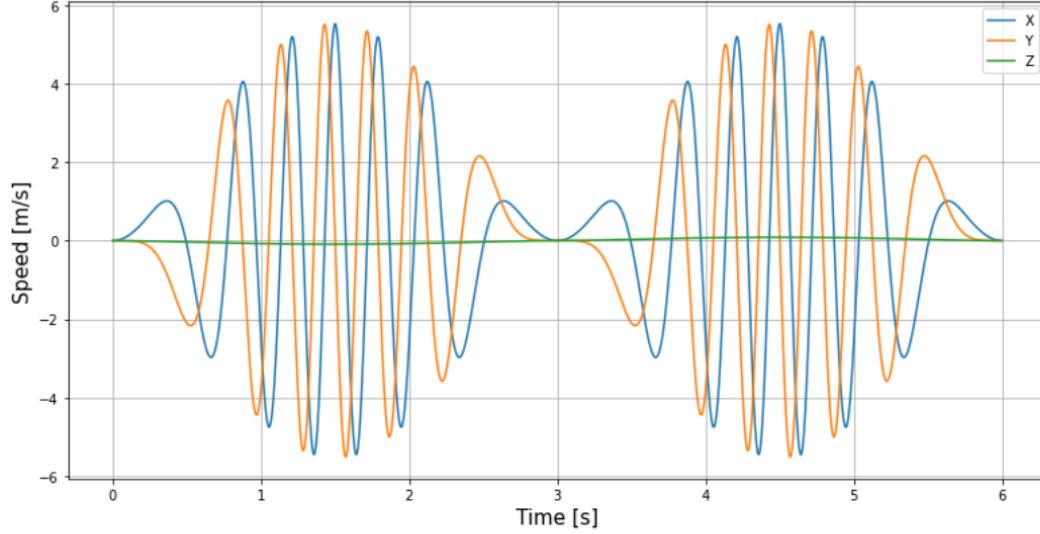


Figure 7.21: Graphs of the measured position in angle, speed in RPM and torque in percentage of the max torque of the motors for a Helix trajectory. The motor measurement is in blue for motor 1, in orange for motor 2 and in green for motor 3.

Theoric speed in the x, y and z directions of the end effector in function of the time - Helix trajectory



Integrated speed in the x, y and z directions from the accelerations measured of the end effector corrected with a linear regression in function of the time - Helix trajectory

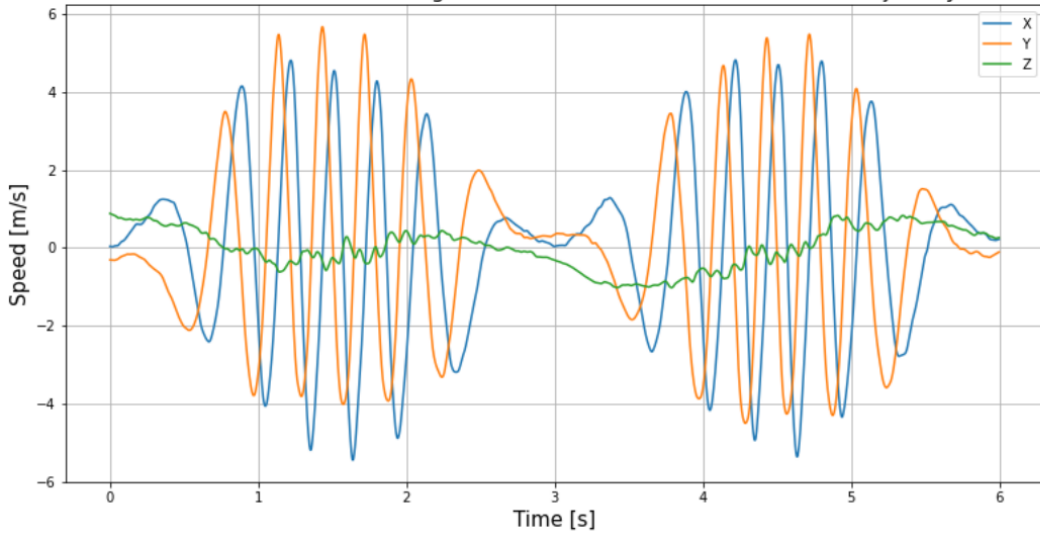


Figure 7.22: Graph of the integrated speed of the end-effector in function of the time for a helix trajectory. The graph with the drift can be found in the appendix ???. The blue curve is the velocity in the X direction (tangent to the helix trajectory), the orange one is in the Y direction (Centripetal to the helix trajectory) and the green one is the Z direction (the direction oriented toward the floor).

Chapter 8

Amelioration and future work

The Delta Robot resulting from this year's work is already a solid basis for future work. However, throughout the text, certain problems have been highlighted and the solution to these problems must therefore be addressed. The future works must also be cover to give an idea on what is the next steps into that master thesis.

8.1 Controller

In this master thesis, the motor controller have been tuned through the auto-tuning sequence made by TEKNIC. However has shown in the Fig.8.1 the error between the commanded position of the motor and the measured position of the motor increase the quicker it goes. It reach $0.9[^\circ]$ of error for the Helix trajectory and more than $2[RPM]$ of error for the Pick and place trajectory. There is two possibilities to improve the encoder: modify the parameter of the auto-tuned controller of implement a whole new controller.

Auto-tuned controller improvement

It has been found that the value of the controller can be modifier trough files generated by the MSP software. Indeed, after a calibration process the motor profile can be save on the user computer in a format .mtr. This file can then be open with the notepad application of Windows and the constant of the motor controller are available here. They can be modified in this file to improve the controller. However, there is no indication to which constant correspond to which controller and thus the future student will have to contact TEKNIC to have more information.

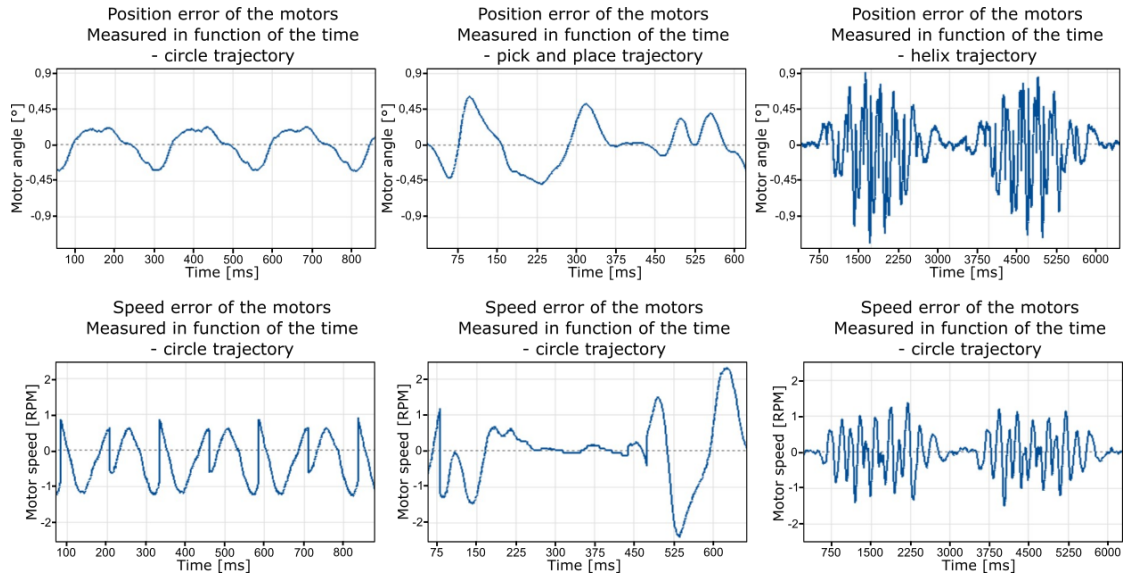


Figure 8.1

Advanced control strategy

If in the future, a more advanced controller could be implemented through the Clearcore library. Indeed, the value of the encoder is available with the class `ClearCore::EncoderInput`. The controller can be done from scratch in C++. However, this will require to "hack" somehow the motor to not use the .mtr profile as controller.

8.2 Electronic improvements

Currently the Clearcore board's full potential is not exploited. For example, the board allows to use a SD slot which can save all the trajectory programmed and even the computed motor angles from the inverse kinematic. The card can be connected via Ethernet to a PC to run in real time a simulation in ROBOTRAN while the robot is moving and. When the pick and place mouthpiece is done, the vacuum pump can be connected to the Clearcore and then controlled by it. But before all of that, two important points must be addressed: the communication with the motor and the collision.

Communication method

As discussed in the previous chapter 7, the PWM communication method limits the resolution of the motor. Indeed, the PWM signal can only send values from 1 to

100% without the possibility of using decimals. One solution would be to use the motor frequency control mode. This would send a signal at a certain frequency corresponding to a motor position. However, the library doesn't provide a function for using this communication mode. We tried to implement the function ourselves, but were unable to do so. In fact, the signal must be sent continuously to the motors, but each time the motor positions are updated (i.e. when the 0.25ms delay has elapsed and the next angles are taken from the array), the signal is no longer sent. The frequency of the signal is thus erroneous. In the future master thesis, the first problem to solve is this one to use the motors at their full capacity.

Prevent collision

Proximity sensors must be placed on the structure to prevent the end-effector to collide the box and to prevent the proximal arm to reach position in which the distal arm and the motor mounting bracket enter in contact. The proximity sensors will measure the position of the proximal arm externally and prevent them to reach the position that could lead to the collisions.

Currently, the state of the micro switches are checked every 0.25[ms]. This is not robust as if the code has a problem, for example an infinite loop, it would not detect if the the proximal arm are entering in contact motor mounting bracket. However, Clearcore library give the possibility to define only one port as an Emergency stop. If this port does not conduct all the motor are stopped. As only one port can act as emergency stop a little PCB with Logical doors can be made to bring together all the micro switches and to have only one input that is connected to the Clearcore board. And thus when on micro switches is activated the state of the PCB change and all the motors will stop.

8.3 End effector sleeves and mouthpiece

The sleeves need to be redesigned to prevent the play that occur between the ball joint and the end effector piece. A washer could be added between the end effector and the sleeves, for example.

The mouthpiece of the end effector must still be designed. The 3D printed part used in the drawing experiment need to be rethink with a spring which maintains contact between the sheet and the pen. The mouthpiece of the vacuum pump need to be totally design. The current fixation method is not optimal and must be improved to be much quicker.

8.4 Distal arm in carbon

As mentioned in the section 5.0.3, initially the distal arm should have been made in carbon fiber. The design of the piece have been done (Fig.8.2) and was made of an threaded aluminium tip in which the rod-end from igus can be screw. This tip is fixed to the carbon fiber tube with resin. This design can replace the IGUS distal arms in the future. However, the estimate cost for the six distal links has been estimated at less than 600€ in total. If in the future the performance of the delta robot need to be improve in term of acceleration and speed. This should one of the first parameter to be taken into account.

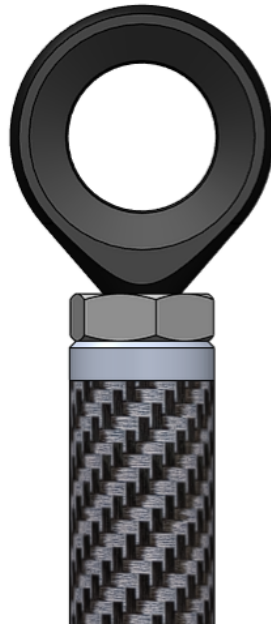


Figure 8.2: Carbon design arm

8.5 Profile box

The structure in aluminium profile is currently moving a lot during the movement of the delta robot. It must be reinforced by adding more aluminium profile to rigidified the whole frame. This may require diagonal profiles to be placed right in the view of the Delta robot and therefore conflict with visibility constraints. Another solution could be to replace the current structure by a structure composed of square-section steel sections welded together.

The structure should be fix to a wall or a table to prevent it from oscillating.

Another point, is how to fix the electrical box. There is two possibility: fix the box to profile aluminium structure or fix is to the table with the button oriented toward the ceiling.

8.6 User interface

The next big step for the demonstrator is to make an user interface which will make the delta robot easier to use. This can be done on labview for example. Currently, The way to launch the robot and test trajectories is not straightforward and requires a number of steps. A little guide has been made and is available in the appendix H to use the motor.

8.7 Security

Last but not least, the delta robot must be secured. The Box containing the Delta robot is currently fully open and thus the next big step is to make the whole robot pass the risk analysis of UCLouvain. The whole robot must be enclose into polycarbonate plate.

Conclusion

The design of this Delta robot has been challenging but exciting task. We're proud of the result and can't wait to see what the future students can do with the base we've provided.

Through the state of the art, we were able to provide a glimpse of all the studies that have been carried out on parallel structures. Thanks to the history of the Delta robot, we were able to contextualise our work and learn about its development since its creation in 1985.

Chapter 2 is dedicated to the specifications of the Delta robot. The Main functions and main constraints were presented. The pick and place, circle and Helix trajectories were also tested and discussed.

Chapter 3 presented the different models of the Delta robot that are used in the rest of the thesis. Geometry, kinematics, elasticity and dynamics have been modelled and discussed. Chapter 4 presented the singularities of the Delta robot. It was shown that the Jacobian did not detect all singularities of the Delta robot. The performance indices were introduced and used in the dimensioning of the kinematic parameters.

Chapter 5 took care of the dimensions of the links and other elements that were not synthesised in chapter 4. The motors, spherical joints, connecting links, distal links and proximal links were dimensioned using the models previously defined.

In chapter 6, the whole detail design is covered. The motors from TEKNIC are selected as they fulfill the dimensioning outputs. After this motor choice, the whole electrical scheme can be determined. The Clearcore has been selected to control the motor due to its versatility and the possibility that its card offer for the future works. The mechanical parts design is then addressed. The moving parts are described first, starting with the end-effector and its fixation method to the distal arm. This piece has been 3D printed in ONYX and reinforced with Kevlar layer to make it lightweight and as rigid as the aluminium. The proximal arm is then

discussed and validated through FEM simulations. A global simulation of the whole kinematic chain is then performed to validate the whole design of the moving parts. The fixed parts are then studied and also validated through FEM simulation. The motor mounting bracket functions and shapes are explained in first place and validated. Then the mounting plate is briefly described and validated. Finally, the Aluminium profile box dimension are discussed.

In chapter 7, the fabrication of the Delta robot and the problem encountered are discussed. The machined pieces fit well with all the elements and the 3D printed end effector were perfectly working within the whole design. However, some mechanical problems have been encountered: the clearance due to the sleeves, the collision between the end effector and the aluminium profile box, the collision between the distal arm and the motor mounting bracket, and the oscillation of the box. The total budget of the robot is 3660,68€. Then the code of the robot is discussed, an inverse kinematic model has been implemented in C++ and is perfectly working, however the PWM signal used limits the resolution of the motors. Finally the circle, the pick and place and the helix trajectories were tested. With the circle the acceleration and the speed reached are respectively $3.64[m/s]$ and $9.33[g]$. A circle has also been draw and the impact of the limitation of the PWM signal has shown. Indeed, the circle was clean but its diameter was $0.29[m]$ and the angle min and max value of the motors were rounded off to unity. The pick and place trajectory has reached acceleration up to $10[g]$ and speed around $4[m/s]$. From the drawing experiment made with the pick and place, the resulting repeatability of the pick and place is $2[mm]$ in the direction of the movement and the $1[mm]$ perpendicular to it. The movement of the box perturbed the measure but this result is promising to reach the $0.5[mm]$ of repeatability. The helix trajectory has enabled us to achieve the greatest acceleration and the highest speed with $11.245[g]$ and $5[m/s]$ respectively.

The possible amelioration and future work have been showed in the last chapter. The controller has been discussed through the modification of the auto-tuned value or the implementation of a new controller from scratch. Then, the electronic improvements have been presented: using the full potential of the Clearcore board, the use of the frequency instead of the PWM to solve the issue and the improvement of the security by preventing the collision. The mouthpieces such as the vacuum pump are mentioned. The design of the carbon fiber tube made is presented after. Ways of resolving box movements are presented such as reinforcing the box, fixing the box,... And finally, the user and the security are addressed.

To conclude this master thesis, we may not have been able to test the robot in all its seams but we are sure that we have succeeded in providing a really solid basis for future students who will work on it. We hope that in the near future the robot will be able to carry out numerous tasks, each more impressive than the last that will showcase the pedagogical aspect of this robot.

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Appendix A

Specifications

	Delta Robot Specifications	Date : 07/04/2023 Version : 6
Context: For the TFE23-249 we need to develop a 3 d.o.f Delta robot. The robot will be used for pedagogical purpose by the teaching staff.		
Date	Main Functions	
7/10/2022	MF1 : Accuracy, Repeatability and Resolution of the robot	
7/10/2022	MF2 : Max payload	
7/10/2022	MF3 : Speed and Acceleration	
7/10/2022	MF4 : Perform a range of tasks	
10/10/2022	MF5 : Replaceability	
10/10 20/10	Optional MF6 : Integrate computer vision MF7 : 4 th degree of freedom	
	Functional Requirement (FR) criteria and levels	
7/10/2022	FR 1.1 : Accuracy: the robot should be able to reach a target within an error margin of 1 mm	
7/10/2022	FR 1.2 : Repeatability: the distance in the 0xyz space between different consecutive measurements of a reached target should be in the interval of $\pm 0.5\text{mm}$	
2/3/2023	FR 1.3 : Resolution: the minimal distance the robot should be able to travel is 0.6mm	
7/10/2022	FR 2.1 : The robot should be able to carry a static payload of 1 kg	
2/3/2023	FR 2.2 : The robot should be able to carry a dynamic payload of 250 g	
7/10/2022	FR 3.1 : The platform should be able to reach a maximum speed of 3 m/s	
7/10/2022	FR 3.2 : The platform should be able to reach a maximum acceleration of 10 g's	
7/10/2022	FR 4.1 : Pick and place task to show the acceleration, speed, accuracy and repeatability of the robot	
11/10/2022	FR 4.2 : Path following task to show the acceleration and speed of the robot	
7/10/2022	FR 4.3 : Drawing task to show the accuracy and precision of the robot	
7/10/2022	FR 4.4 : Target reaching task in order to show the accuracy and repeatability of the robot	
20/10/2022	FR 4.5 : Race between the user and the robot to show the speed and acceleration of the robot	
10/10/2022	FR 5.1 : If any mechanical or electrical failure occurs, the exchange of pieces should be easy to do	
10/10/2022	FR 6.1 : The robot should be able to recognize objects and act accordingly	
20/10/2022	FR 7.1 : Accuracy: the robot should be able to rotate an object within an error margin of 4°	
20/10/2022	FR 7.2 : Repeatability: different measurements of the same rotation of the end effector along the z-axis should be in the interval of $\pm 2^\circ$	
20/10/2022	FR 7.3 : Resolution: the minimal angle the end effector should be able to rotate is 2°	
	Main constraints	
7/10/2022	MC1 : Price of conception	
7/10/2022	MC2 : Workspace dimensions	
7/10/2022	MC3 : Power consumption	
7/10/2022	MC4 : Working temperature range	
7/10/2022	MC5 : Noise	
7/10/2022	MC6 : Safety	
18/10/2022	MC7 : Usability	
20/20/2022	MC8 : Transportability	

7/10/2022	MC9: Future master theses
	Constraint Requirement (CR) criteria and levels
7/4/2023	CR 1.1 : The robot's conception price should be less than 4000 €
7/10/2022	CR 2.1 : The robot's workspace dimensions for the Oxy axis should be 300 to 300 mm
2/3/2023	CR 2.2 : The robot's workspace dimension for the Oz axis should be 150 mm
10/10/2022	CR 2.3 : There should be no singularities in the workspace
7/10/2022	CR 3.1 : The maximum electrical power consumption of the robot should be 2000 W
7/10/2022	CR 4.1 : The robot should be able to work in a range of temperatures of 0 to 45 °C
7/10/2022	CR 5.1 : The robot's noise should be less than 60 dB
7/10/2022	CR 6.1 : The robot should pass the risk analysis of UCLouvain
20/10/2022	CR 7.1 : Usable without any risk of overheating for normal usage
11/10/2022	CR 7.2 : Usable without any terminating mechanical failure for 10 years
7/10/2022	CR 7.3 : Easy to use, the activation of the robot should not require complex actions
7/10/2022	CR 7.4 : Allow clean view of the robot for filming and viewing during sessions
20/10/2022	CR 7.5 : Have a clear documentation for the usage of the robot
20/10/2022	CR 8.1 : The robot should be able to be transported in a utility vehicle
20/10/2022	CR 8.2 : The robot and its frame should be able to pass through doorways 75cm wide
7/10/2022	CR 9.1 : Allow further work for future master theses by considering the potential upgrades on the robot
7/10/2022	CR 9.2 : Have a clear documentation for future work on the robot

Appendices :

Specifications	Value	Unit
FR1.1 : Accuracy	1	mm
FR1.2 : Repeatability	± 0.5	mm
FR1.4 : Resolution	0.6	mm
FR2.1 : Max static load	1	Kg
FR2.1 : Max dynamic load	250	g
FR3.1 : Max speed	3	m/s
FR3.2 : Max acceleration	10	g's
FR7.1 : Accuracy	$\pi/45$	rad
FR7.2 : Repeatability	$\pm \pi/90$	rad
FR7.3 : Resolution	$\pi/90$	rad
CR1.1 : max Price	4000	€
CR2.1 : Workspace Oxy plane	300 x 300	mm
CR2.2 : Workspace Oz axis	150	mm
CR3.1 : Max power consumption	2000	W
CR4.1 : Temperature range	0 – 45	°C
CR5.1 : Noise	60	dB
CR7.2 : Warranty	10	years
CR8.2 : Max width	750	mm

Appendix B

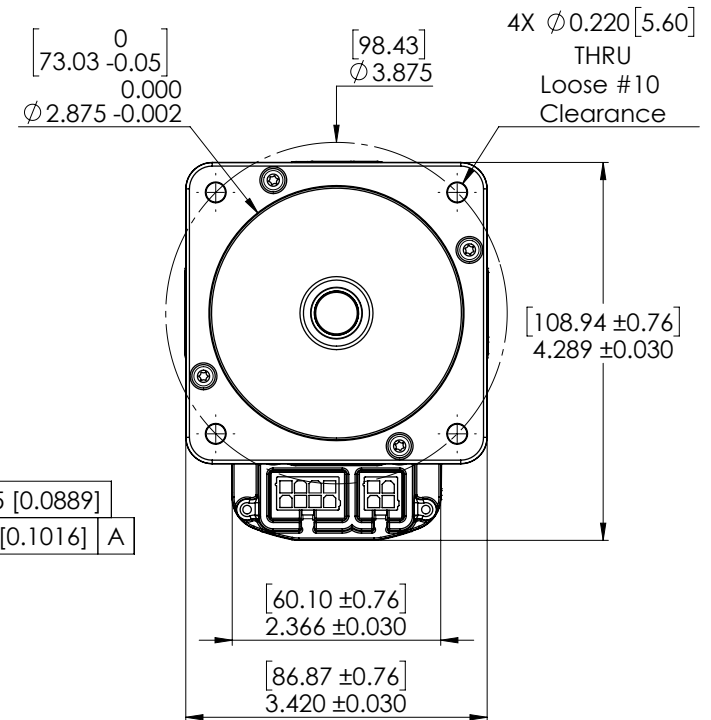
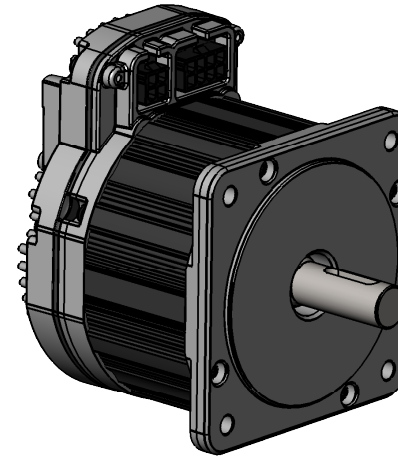
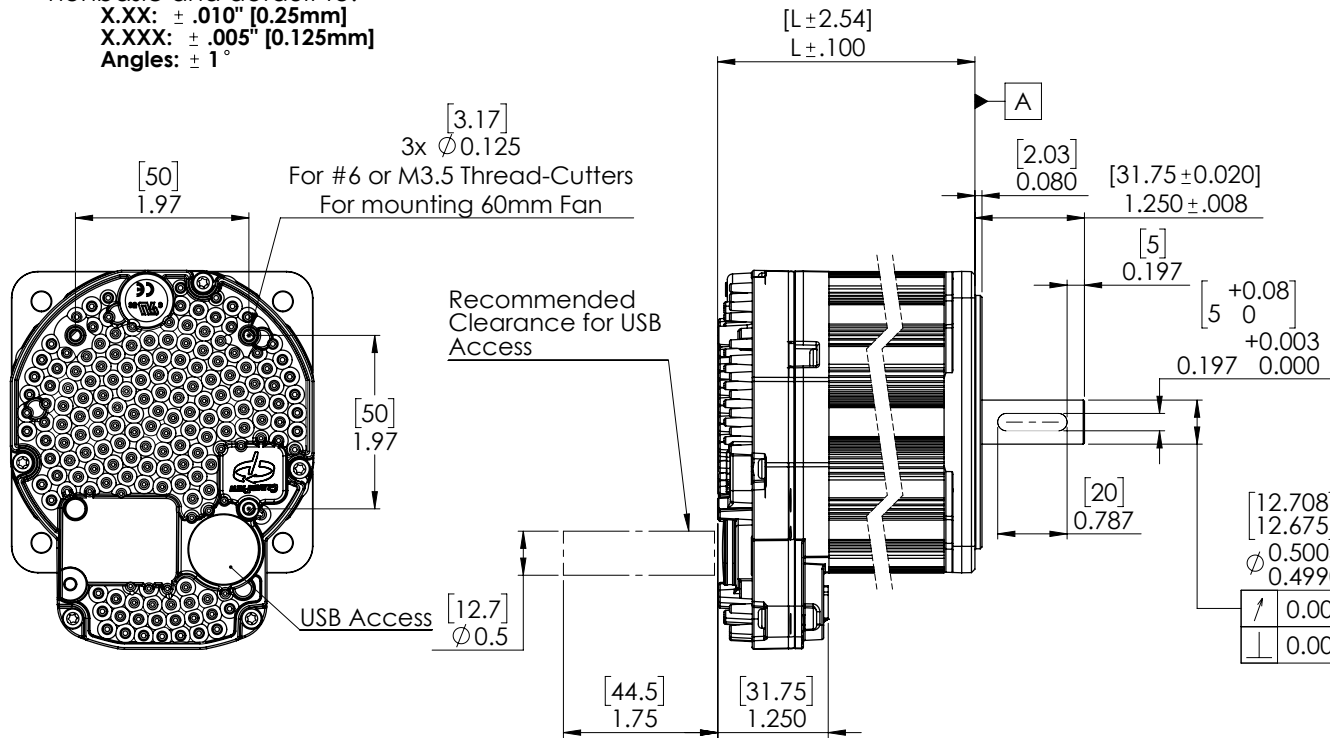
Motor

Teknic ClearPath®

Fractional HP, DC Input
NEMA 34

- All dimensions are in inch [mm] unless otherwise noted.
- Sheet Scale 1:1.5
- Undimensioned features are per 3D file for model of interest for reference use.
- Unless otherwise specified untoleranced dimensions are nonbasic and default to:

X.XX: $\pm .010"$ [0.25mm]
X.XXX: $\pm .005"$ [0.125mm]
Angles: $\pm 1^\circ$

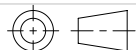


Model Number	L
CPM-____-341__-____	3.138 [79.70]
CPM-____-342__-____	3.879 [98.52]
CPM-____-343__-____	4.627 [117.52]
CPM-____-344__-____	5.382 [136.70]

Teknic, Incorporated

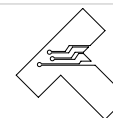
Victor, NY 14564 USA

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Third-Angle Projection

Interpret Geometric Tolerances per ANSI/ASME Y14.5 (2009)



Additional documentation including product specifications, up-to-date compliance information, and manuals can be downloaded from Teknic's website.

Visit <https://www.teknic.com/> to access that documentation.

D1170/H

DWG.
NO./REV

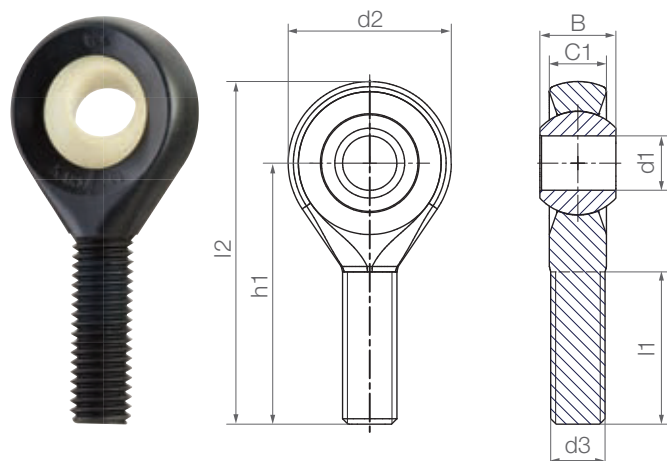
TITLE: 34xx ClearPath Motor Family

1
of 1
Pages

Appendix C

Igus Catalogue

Embouts à rotule filetés, 2ème génération : KARM CL



Constitution de la référence

Type	Taille [mm]	Options
K A R M - 06 CL MH		
Gamme dimensionnelle K	Boîtier avec filetage	Type de filet L = filet à gauche R = filet à droite
Filet à droite	Filet à droite	Ajout : MH = avec douille en inox
Métrique	Ø intérieur	
	2ème génération	

- Nouveau design ne laissant aucune chance à la saleté
 - Compensation des défauts d'alignement
 - Très faible poids
 - Insensibilité absolue à la corrosion
 - Version à douille en inox dans la calotte disponible pour un couple de serrage plus élevé
 - Gamme dimensionnelle K selon DIN ISO 12240
 - Vis calibrée avec serre-clip disponible
- Accessoires, **page 802**



Matériau :

Boîtier : **igumid G** ► **page 1560**

Calotte : **iglidur® W300** ► **page 171**

Autres matériaux pour la calotte sur demande
► **page 783**

Données techniques

Référence	Force de traction statique maxi		Force transversale statique maxi		Insertion mini de la tige	Couple de serrage maxi	Couple de serrage maxi sur calotte		Poids		
	à courte durée	en continu	à courte durée	en continu			sans douille	avec douille			
										MH	MH
	[N]	[N]	[N]	[N]	Filet [mm]	Filetage [Nm]	[Nm]	[Nm]	[g]		
KA□M-06 CL	1 000	500	100	50	15	0,5	10	15	3,5		
KA□M-08 CL	1 700	850	200	100	18	2,0	12	40	6,2		
KA□M-10 CL	2 500	1 250	300	150	20	5,0	20	50	11,2		
KA□M-12 CL	2 700	1 350	400	200	22	6,0	30	70	15,6		

Cotes [mm]

Référence	d1 E10	d2	d3	C1	B		h1	l1	l2	Angle de pivotement maxi
					sans douille MH	avec douille MH +0,2				
KA□M-06 CL	6	20	M6	7,0	9	9,2	36	21	46	40°
KA□M-08 CL	8	24	M8	9,0	12	12,2	42	25	55	35°
KA□M-10 CL	10	30	M10	10,5	14	14,2	48	28	63	35°
KA□M-12 CL	12	34	M12	12,0	16	16,2	54	32	71	35°

Les embouts à rotule peuvent être commandés en cotes métriques avec une douille en inox. Il suffit d'ajouter la mention **MH** après les numéros d'articles listés ici. Exemple : KARM-10 CL **MH** (Ø intérieur : 10 mm).

Pour une calotte en matériau autre que le matériau standard iglidur® W300, veuillez ajouter le suffixe « **J** » après la référence. Exemple : KARM-10 CL **J**.

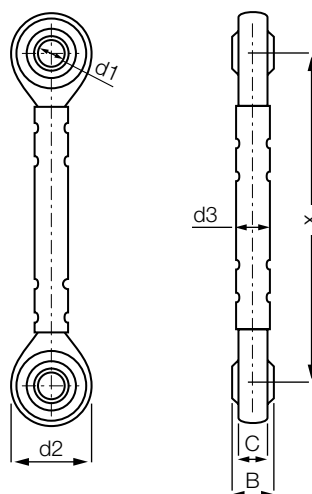
igubal® spherical bearings | Product Range

KDGM - Variable Double joint



Version A

Version B



Order key

Type	Size [mm]	Options
K DG M - 06 - A - SR - J		
Dimensional K series	Double joint	Options:
	Metric	Tube material
	Inner-Ø [mm]	SR = Galvanized steel
	Pitch X	ER = Stainless steel (AISI 303)
	Tube material option	Spherical ball material
	Spherical ball material options	Blank = iglide® W300
		J = iglide® J
		J4 = iglide® J4
		R = iglide® R
		EK = Stainless steel (AISI 303)

i Material:
Housing: igumid G ► Page 1782
Standard spherical ball: iglide® W300 ► Page 211

- Ball diameters 6, 8, 10 and 12 mm
- Individual center dimensions and lengths
- Individual alignment of the bearing position

Dimensions [mm]

Part No.	d1	d2	d3	X	B	C	Max. pivot angle
	E 10			min.			
KDGM-06-A-SR-J ☐ ³²⁾	6	20.0	6.0	72.0	9.0	7.0	40°
KDGM-08-A-SR-J ☐ ³²⁾	8	24.0	8.0	84.0	12.0	9.0	35°
KDGM-10-A-SR-J ¹⁴⁵⁾ ☐ ³²⁾	10	30.0	10.0	96.0	14.0	10.5	35°
KDGM-12-A-SR-J ☐ ³²⁾	12	34.0	12.0	108.0	16.0	12.0	35°

³²⁾ Please add the required center distance in mm

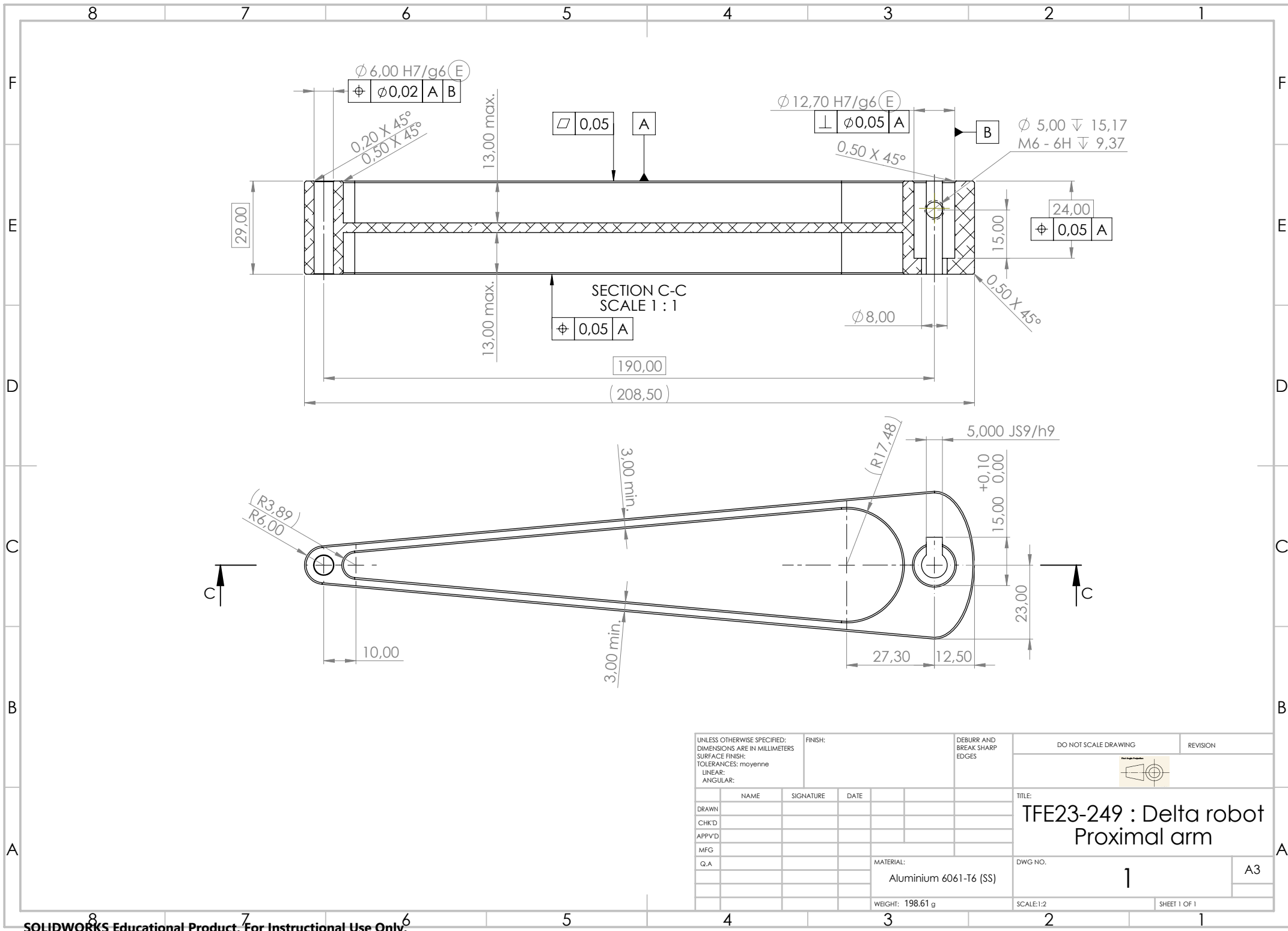
¹⁴⁵⁾ Size only available with stainless steel tube



Order example, KDGM-05-A-SR, 100 : Double joint with 5mm inner diameter, version A, tube material made of steel, spherical ball made of iglide® W300, center distance 100mm

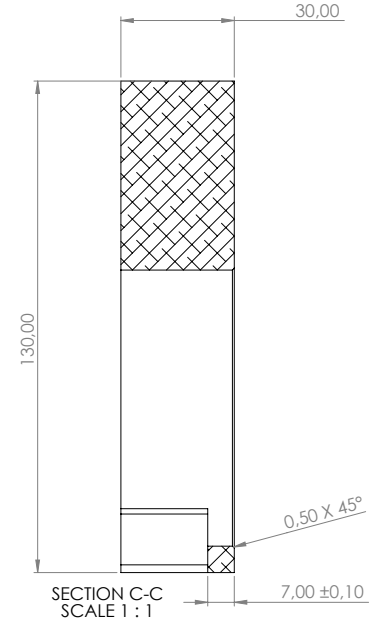
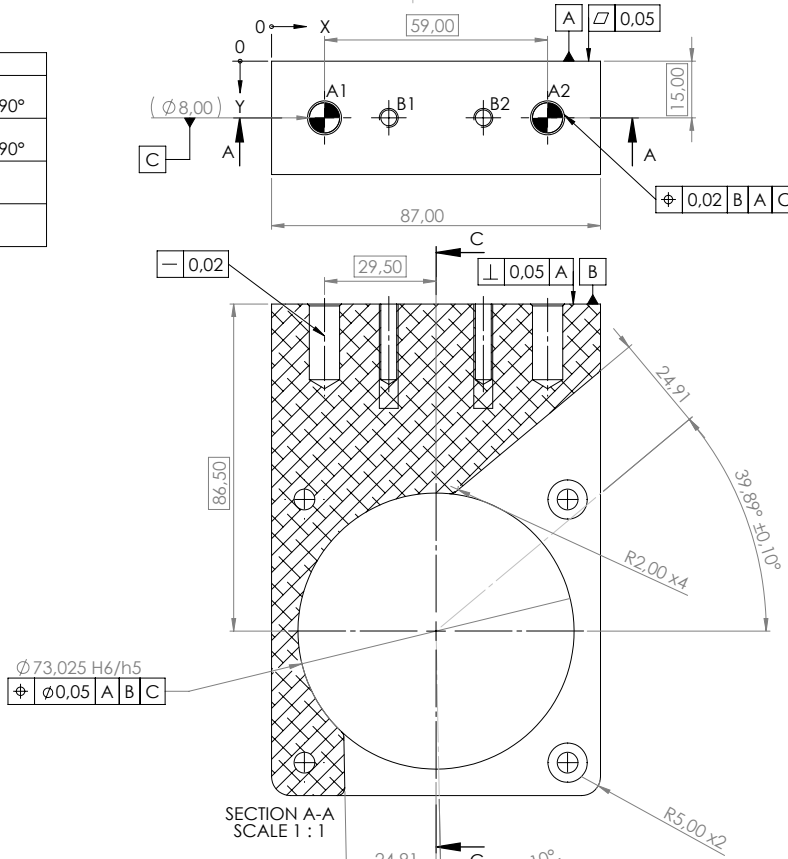
Appendix D

Technical drawing of the mechanical parts

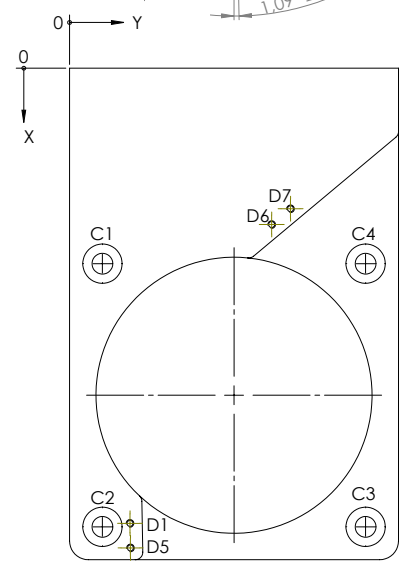


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: moyenne LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
											
								TITLE:			
								TFE23-249 : Delta robot Proximal arm			
								DWG NO.		A3	
								1			
								SCALE:1:2		SHEET 1 OF 1	

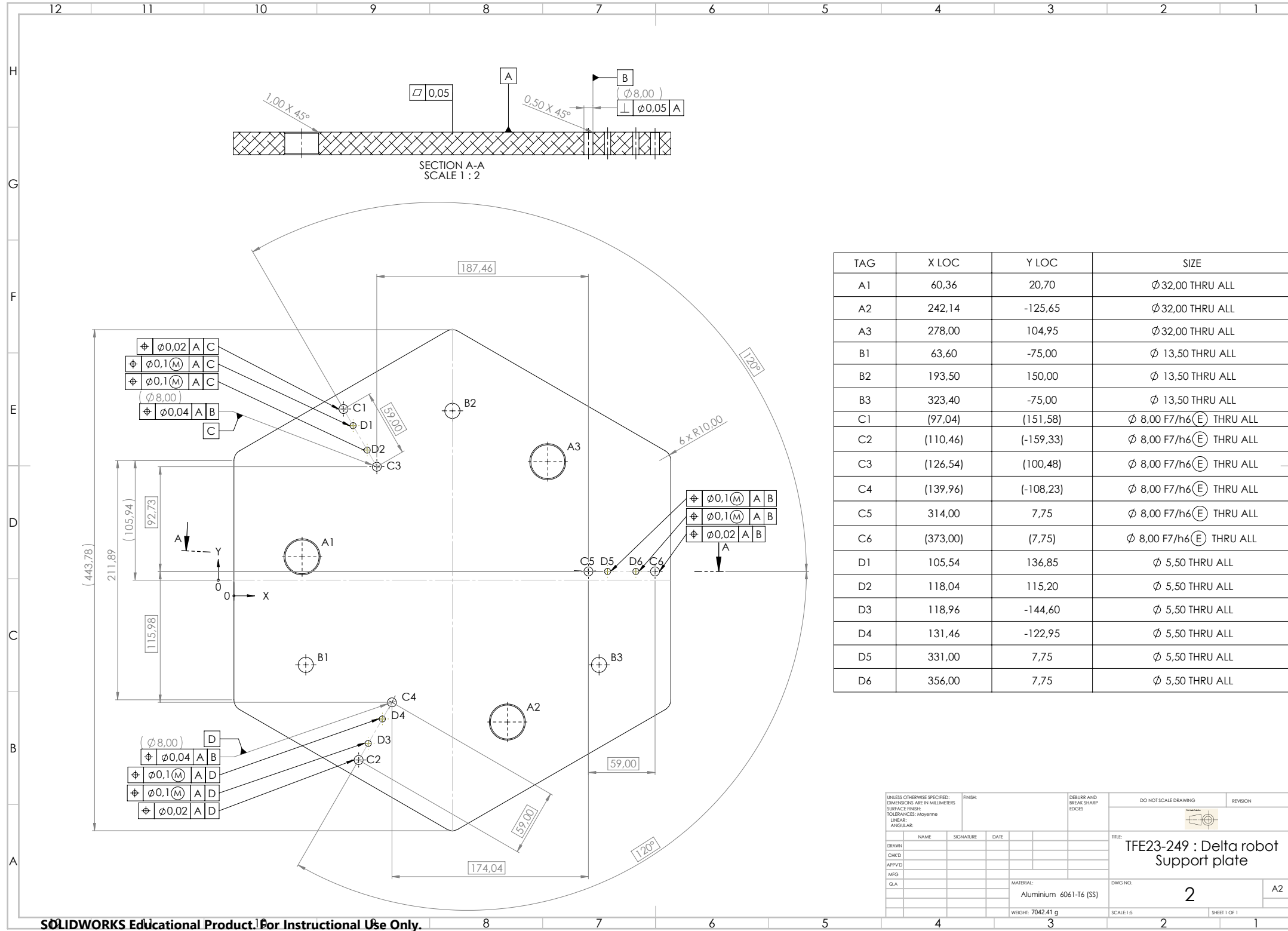
TAG	X LOC	Y LOC	SIZE
A1	14	15	$\checkmark$ $\varnothing 8,00 \nabla 20,00$ $\varnothing 9,00$ H7/m6 X 90°
A2	73	15	$\checkmark$ $\varnothing 8,00 \nabla 20,00$ $\varnothing 9,00$ H7/m6 X 90°
B1	31	15	$\varnothing 4,20 \nabla 20,00$ M5 - 6H $\nabla 27,59$
B2	56	15	$\varnothing 4,20 \nabla 20,00$ M5 - 6H $\nabla 27,59$



TAG	X LOC	Y LOC	SIZE
C1	51,70	8,70	$\checkmark$ $\varnothing 5,50$ THRU $\varnothing 10,40$ X 90°
C2	121,30	8,70	$\checkmark$ $\varnothing 5,50$ THRU $\varnothing 10,40$ X 90°
C3	121,30	78,30	$\checkmark$ $\varnothing 5,50$ THRU $\varnothing 10,40$ X 90°
C4	51,70	78,30	$\checkmark$ $\varnothing 5,50$ THRU $\varnothing 10,40$ X 90°
D1	120,39	15,98	$\varnothing 1,60 \nabla 6,00$ M2 - 6H $\nabla 11,20$
D5	126,88	16,11	$\varnothing 1,60 \nabla 6,00$ M2 - 6H $\nabla 11,20$
D6	41,35	53,45	$\varnothing 1,60 \nabla 6,00$ M2 - 6H $\nabla 11,20$
D7	37,18	58,44	$\varnothing 1,60 \nabla 6,00$ M2 - 6H $\nabla 11,20$



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: FRACTIONAL LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN		NAME		SIGNATURE		DATE		TITLE: TFE23 -249: Delta robot Motor mounting	
CHKD		NAME		SIGNATURE		DATE		DWG NO. 3	
APPVD		NAME		SIGNATURE		DATE		SHEET 1 OF 1	
MFG		NAME		SIGNATURE		DATE		A2	
QA		NAME		SIGNATURE		DATE		SCALE: 2:1	
		MATERIAL:		Aluminium 6061 T6 (SS)		WGHT: 421,77 g			



TAG	X LOC	Y LOC	SIZE
A1	60,36	20,70	Ø 32,00 THRU ALL
A2	242,14	-125,65	Ø 32,00 THRU ALL
A3	278,00	104,95	Ø 32,00 THRU ALL
B1	63,60	-75,00	Ø 13,50 THRU ALL
B2	193,50	150,00	Ø 13,50 THRU ALL
B3	323,40	-75,00	Ø 13,50 THRU ALL
C1	(97,04)	(151,58)	Ø 8,00 F7/h6(E) THRU ALL
C2	(110,46)	(-159,33)	Ø 8,00 F7/h6(E) THRU ALL
C3	(126,54)	(100,48)	Ø 8,00 F7/h6(E) THRU ALL
C4	(139,96)	(-108,23)	Ø 8,00 F7/h6(E) THRU ALL
C5	314,00	7,75	Ø 8,00 F7/h6(E) THRU ALL
C6	(373,00)	(7,75)	Ø 8,00 F7/h6(E) THRU ALL
D1	105,54	136,85	Ø 5,50 THRU ALL
D2	118,04	115,20	Ø 5,50 THRU ALL
D3	118,96	-144,60	Ø 5,50 THRU ALL
D4	131,46	-122,95	Ø 5,50 THRU ALL
D5	331,00	7,75	Ø 5,50 THRU ALL
D6	356,00	7,75	Ø 5,50 THRU ALL

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: moyenne LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
DRAWN:				NAME:		SIGNATURE:		DATE:		TITLE: TFE23-249 : Delta robot Support plate	
CHECKED:										DWG NO.: 2	
APPROVED:										A2	
MFG:										SCALE: 1:5	
Q.A:										SHEET 1 OF 1	
						MATERIAL: Aluminium 6061-T6 (SS)					
						WEIGHT: 7042,41 g					

Appendix E

FEM validation

E.1 Proximal arm

	Simu 1	Simu 2		Simu 3	Simu 4		Simu 5	
Forces [N]	left/right	left	right	left/right	left	right	left	right
X-axis	33, 45	42, 93	-17,05	21, 05	23, 9	-16,16	-32,11	6, 24
Y-axis	0, 0	9, 47	-2,30	0, 0	4, 61	-1,46	6, 82	-1,68
Z-axis	3, 79	11, 70	-10,37	26, 04	-32,14	-11,44	-17,13	3, 04

Table E.1: Table of the force in the X-Y-Z direction applied on the extremities left and right of the connecting rode for each FEM simulation

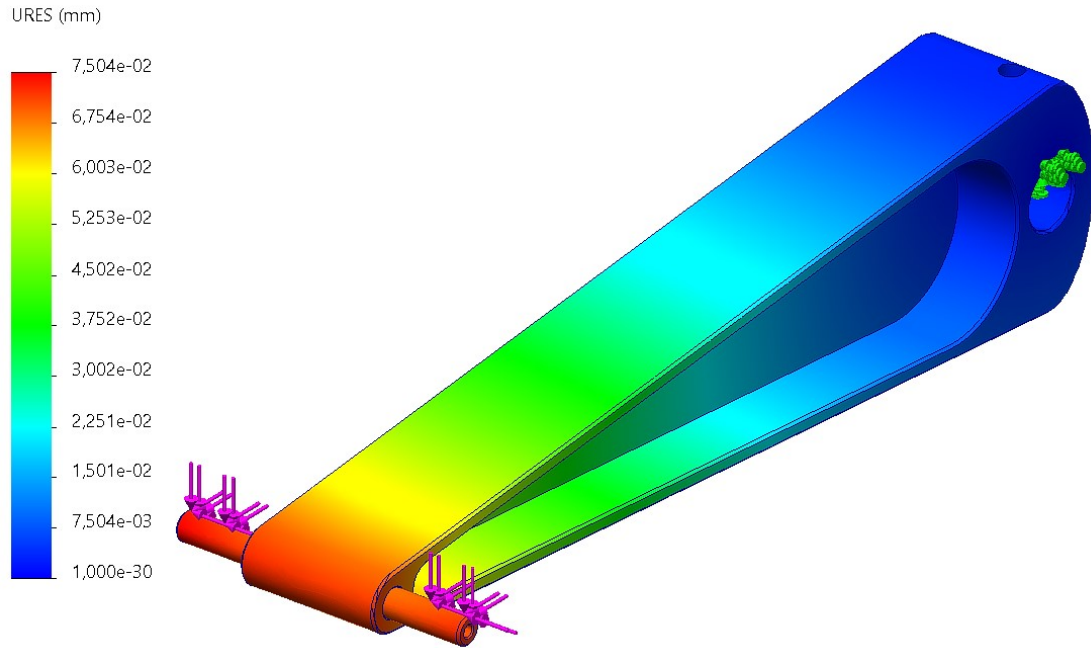


Figure E.1: FEM simulation 3 result of the deformation of the proximal arm for the maximum force obtained in the z-axis for the arm aligned with the trajectory.

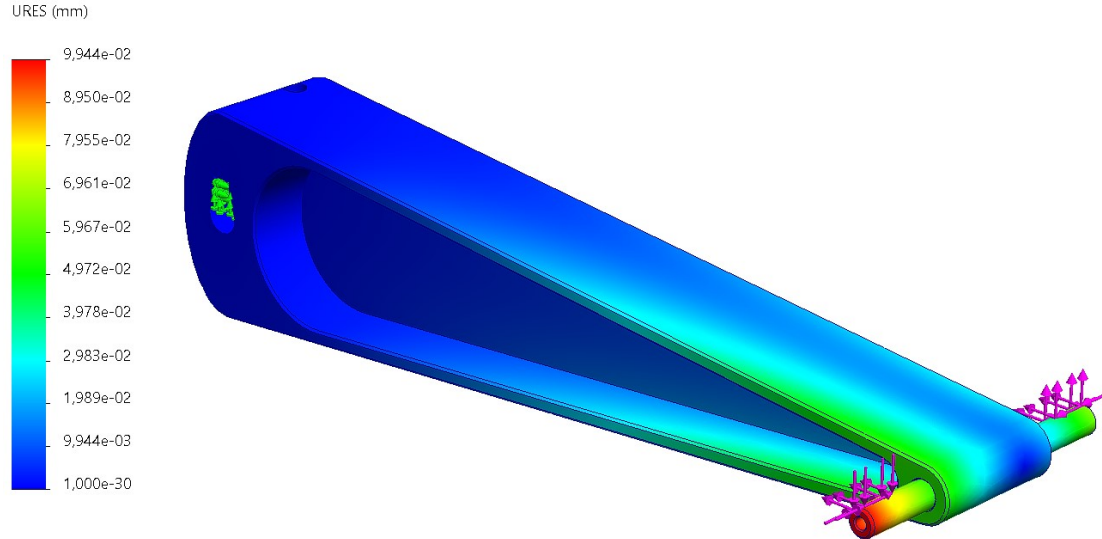


Figure E.2: FEM simulation 4 result of the deformation of the proximal arm for the maximum force obtained in the z-axis for the arm at 120° from the trajectory.

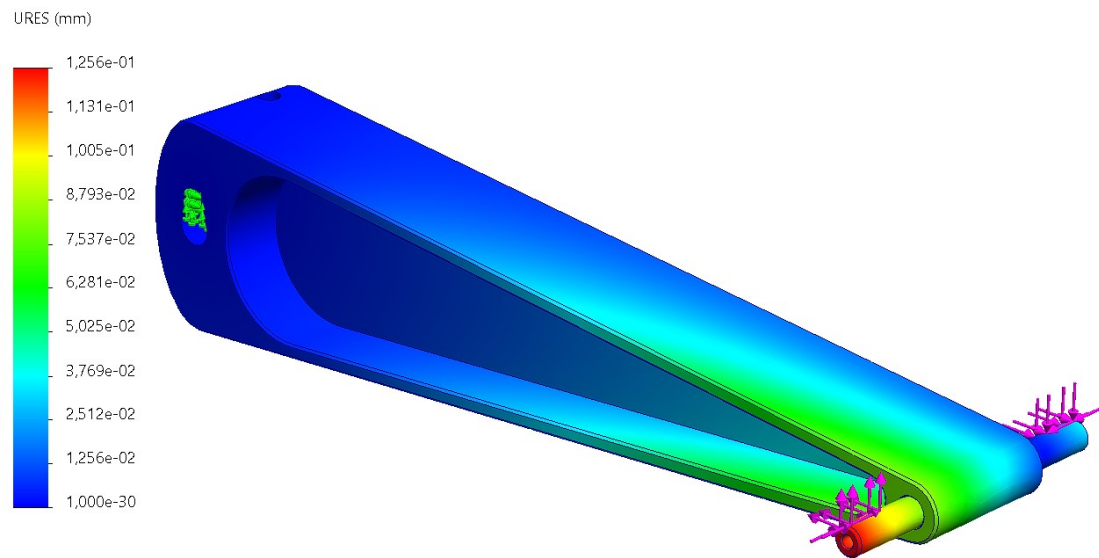


Figure E.3: FEM simulation 5 result of the deformation of the proximal arm for the maximum force obtained in the z-axis for the arm at 120° from the trajectory.

E.2 Mobile parts

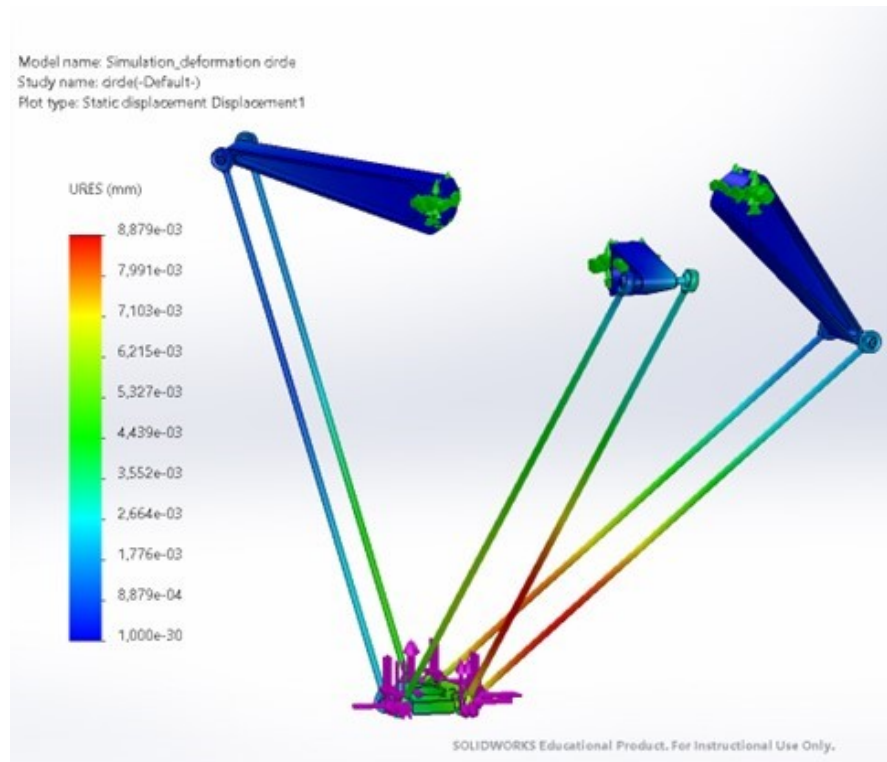


Figure E.4: Complete FEM simulation of the whole kinematic chain for a circle trajectory. The maximum deformation are located in the distal arm.

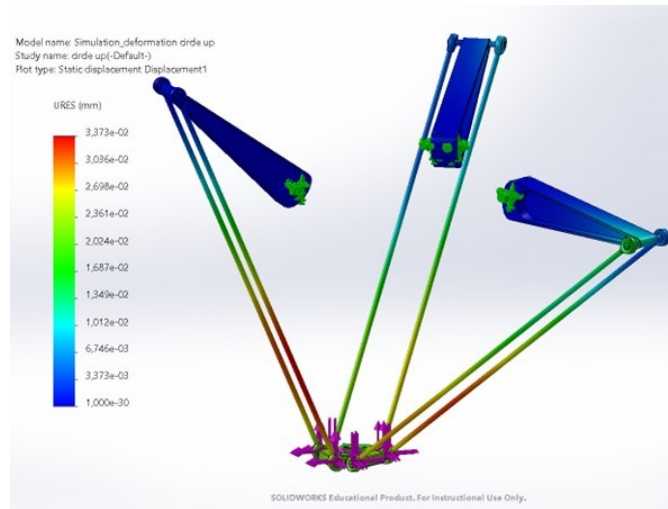


Figure E.5: Complete FEM simulation of the whole kinematic chain for a Helix trajectory. The maximum deformation are located in the distal arm.

E.3 Full platform

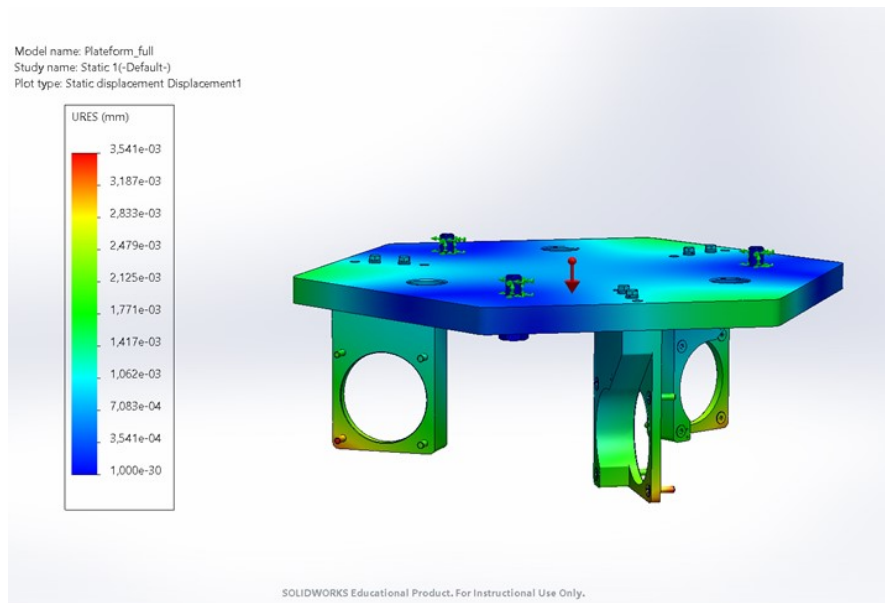


Figure E.6: FEM simulation of the mounting plate and the motor mounting bracket showing that the deformation in this piece are negligible.

Appendix F

Detailed budget

Pièce	Référence	Provenance	Prix	Nombre	Coût total
TEKNIC					
Moteur	CPM-MCPV-3441S-ELS	Teknic	550,6	3	1651,8
AC Power cable	IPC35-CABLE110	Teknic	13,16	1	13,16
Carte Puissance	IPC-5	Teknic	233,23	1	233,23
Industrial I/O and motion controller	CLCR-4-13	Teknic	90,69	1	90,69
DC Power cable	CPM-CABLE-PWR-MS120	Teknic	17,86	3	53,58
Control Cable	CPM-CABLE-CTRL-MU120	Teknic	21,62	3	64,86
USB Cable	CPM-CABLE-USB-120	Teknic	8,46	1	8,46
Total Teknic :					2275,08

Alimentation et sécurité					
Borniers enfichables 3 voies	MC000097	Farnell	1,41	7	9,87
Alimentation AC/DC 24VDC	MP002001	Farnell	25,59	1	25,59
Microrupteurs	DM1-01P-30-3	Farnell	0,46	6	2,76
Câble USB, Type A mâle vers Type B mâle	11.99.8831	Farnell	2,49	1	2,49
Boîtier Rittal AX en Tôle d'acier	202-3903	RS-comp	253,68	1	253,68
Connecteur IEC Mâle C14		RS-comp	4,22	1	4,22
Adaptateur de rail DIN universel	804-7397	RS-comp	33,37	1	33,37
Bouton-poussoir vert	330-8638	RS-comp	19,19	1	19,19
Bouton-poussoir rouge		RS-comp	19,2	1	19,2
Contacteur	3RH2131-1BB40	RS-comp	63,48	1	63,48
Bouton d'arrêt d'urgence	XB4BS8442	RS-comp	44,47	1	44,47
Alimentation pour rail DIN 24V c.c.out	DRC30US24	RS-comp	21,53	1	21,53
Total alimentation et sécurité:					499,85

BRAS PROXIMAUX					
Bras en Alu usiné	/	UCL	50	3	150
Manchon imprimer en 3D	/	UCL	0,13	3	0,39
Axes d'articulation	CBLM6-64	Misumi	4,9	3	14,7
Vis à tête plate	CBSKE3-6	Misumi	0,19	6	1,14
Clavette	KESS5-20	Misumi	3,06	3	9,18
Vis de serrage	MSSTS6-15	Misumi	1,81	3	5,43
Total bras proximaux:					180,84

BRAS DISTAUX					
Bras distaux en acier	KDGM-06-A-SR-J	IGUS	12,78	6	76,68
Total bras distaux:					76,68

SUPPORT					
Plaque de fixation structurel	/	UCL	120	1	120
Equerre de fixation moteurs	/	UCL	52,5	3	157,5
Profilé Bosh Fixation des deux plaques	HFS8-4040-85-RTP	Misumi	9,57	3	28,71
Goupilles cylindriques	MS8-40	Misumi	0,52	6	3,12
Boulons M12	933A21255	Misumi	0,29	3	0,87
Rondelle M12	SPWF12	Misumi	0,67	3	2,01
Rondelle élastique M12	SLW12	Misumi	0,66	3	1,98
Boulons M5	933A2540	Misumi	0,28	6	1,68
Rondelle M5	SPWF5	Misumi	0,19	18	3,42
Rondelle elastique M5	SLW5	Misumi	0,87	6	5,22
Vis d'assemblage à tête plate M5 15mm	SFB5-15	Misumi	0,67	6	4,02
Vis d'assemblage à tête plate M5 40mm	CSHCS-SUS-M5-40	Misumi	0,15	6	0,9
écrou hexagonaux M5	SLBNR5	Misumi	0,53	12	6,36
Total support:					335,79

STRUCTURE EN PROFILE					
Support profilé Bosch taraudé	HBKTSB8-SEU	Misumi	4,86	20	97,2
Support profilé Bosh	HBKTS8-SEU	Misumi	4,12	18	74,16
Total structure:					171,36

END-EFFECTOR					
Impression 3D de la base	/	UCL	5,99	1	5,99
Bielette	CBLM6-64	Misumi	4,54	3	13,62
Vis à tête plate	CBSKE3-6	Misumi	0,18	6	1,08
Manchon imprimer en 3D	/	UCL	0,13	3	0,39
Total end-effector:					21,08

Coût total : 3560,68

Appendix G

Validation Graph

G.1 Circle trajectory theoretical absolute acceleration

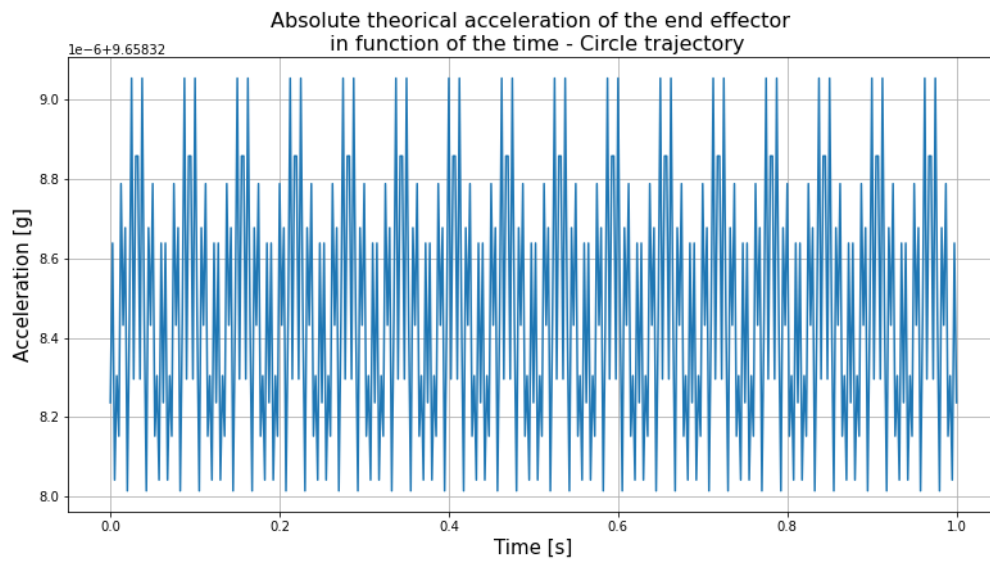


Figure G.1: Graph of the theoretical resulting acceleration in [g] of the end-effector in function of the time for a circle trajectory.

G.2 Graph with uncorrected drift

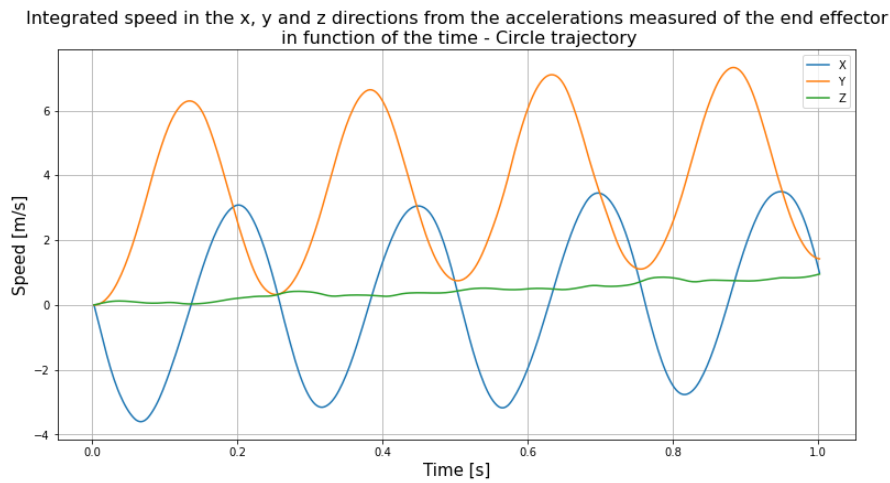


Figure G.2: Graph of the integrated speed of the end-effector in function of the time for a pick and place trajectory. The blue curve is the velocity in the X direction (in the same plane as the pick and place trajectory), the orange one is in the Y direction (perpendicular to the plane of the pick and place trajectory) and the green one is the Z direction (the direction oriented toward the floor).

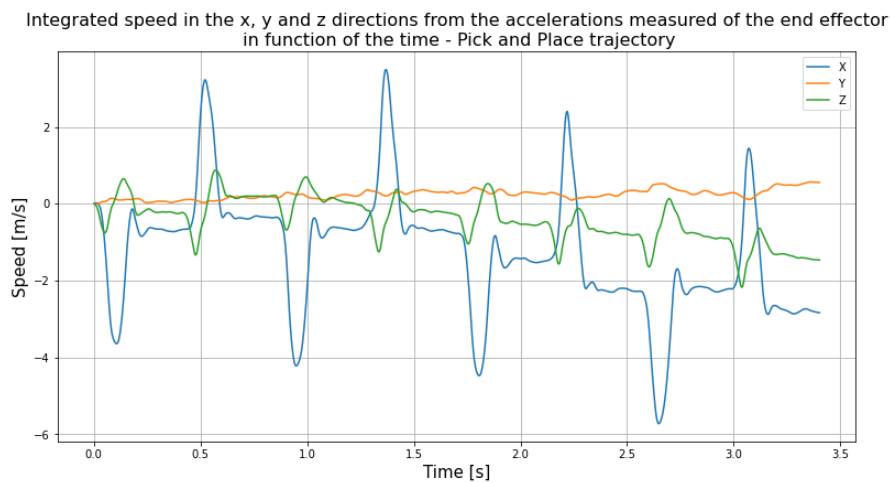


Figure G.3: Graph of the integrated speed of the end-effector in function of the time for a pick and place trajectory. The blue curve is the velocity in the X direction (in the same plane as the pick and place trajectory), the orange one is in the Y direction (perpendicular to the plane of the pick and place trajectory) and the green one is the Z direction (the direction oriented toward the floor).

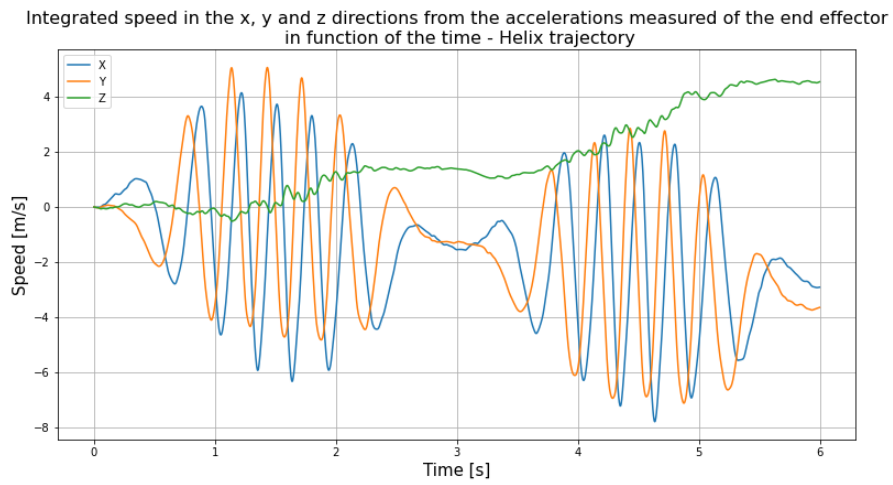


Figure G.4: Graph of the integrated speed of the end-effector in function of the time for a helix trajectory. The blue curve is the velocity in the X direction (tangent to the helix trajectory), the orange one is in the Y direction (Centripetal to the helix trajectory) and the green one is the Z direction (the direction oriented toward the floor).

Appendix H

How to use the Delta robot

This appendix is not a user manual but rather a guide for future students who will be working on the Delta robot.

H.1 Setup the Motors on the MSP software

The motors need to be setup via the micro USB port on the back of the motor at least once before using the robot. Each time the user want to change the control mode of the motor is need to be done via the MSP software. This software can be download following this link: <https://teknik.com/downloads/>. This link lead to a lot of useful information such as the datasheet of the motor and the Clearcore, the driver need to operate the motor etc... When the MSP software is downloaded and the driver downloaded, simply power the motor and connect it to your PC. Next the following step can be done to setup the motor:

1. When the motor is connected and the software is running the software will automatically recognize the motor
2. A page will open asking you to select the motor profile to use. If no profile is already loaded into the motor you must choose a profile already existing and saved on your computer or make the auto tune. The auto-tune step is clearly explained by the software simply follow the steps one by one, leaving everything at the optimum values. The only step in which you must be careful is when the software ask you the boundaries of the operating angle of the motor. Do not stick the arm to the mechanical stop, the movement of the proximal arm can be rough during the auto tune and the arm could collide with the motor mounting bracket. Leaving a margin of a few degrees will prevent this from happening. The auto tune can be saved and applied to

all the 3 motors. As the motor is fully symmetric the same controller can be applied on all the three motor.

3. After that the motor has load is profile, you can choose the motor communication mode. Currently, the Follow Digital Position with PWM signal mode is used. If the profile is already loaded into the motor the page will immediately open on this mode.
4. The mode page can be use to setup all the values needed to use the motor.
5. Beginning by the angle range corresponding to the percentage of the PWM signal.
6. Torque range can be set to prevent the proximal arm to collide with the motor mounting bracket.
7. The homing sequence can also be define in the software. Attention : during the test on the MSP software the homing sequence seems not to work when it is launched via the software and the proximal arm will push at max toque on the motor mounting bracket. The homing sequence must be only launch via the Clearcore board.
8. Please read the Cleatpath user manual carefully, as it explains in detail which value corresponds to what. In particular, the RAS and the g-Stop that can have a big impact on the motor behavior.

H.2 Programming the Clearcore board using AT-MEL studio

Now that all the motors are setup the programming of the Clearcore board can be done using ATMEL studio (ATMEL sutio = Microship studio). Useful links:

- TEKNIC give a manual to install studio in <https://teknik.com/downloads/>
- The whole library of the Clearcore board can be found following this link: <https://teknik-inc.github.io/ClearCore-library/index.html>
- The Github of the of the Clearcore board can be found here: <https://github.com/Teknic-Inc/ClearCore-library>

TEKNIC provide a lot of example to help the user to make their own code. This could be useful to understand how to use a mode as their code is well commented. The following steps must be done to make and run a project:

1. On the home page of ATMEL studio, click on file, then open and click on project of solution.
2. Double click on the .atsln file of the project you want to run.
3. 3 window will open asking you to regenerate the pack information, always click on No. If you click on yes the .xml file will be replace and you will not be able to run your code.
4. Right click and the .cpprog you want to run and click on select as startup project.
5. Select the .ccp you want to modify.
6. once the modification click on start without debugging or ctrl+altf5 to run your code.
7. if your pc is connected to the Clearcore board via a USB-B cable, the code will be uploaded on the board and the motor will start moving.

If the code you have upload on the board is erroneous the card might freeze. To solve this issue double click quickly on the reset button of the Clearcore board. This will make the card goes in Bootloader mode and then you can upload a healthy code on it.

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