ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

BACHELOR IN ELECTROMECHANICAL ENGINEERING

(MECHANICAL SPECIALISATION)

TACTILE ASSEMBLY ROBOT: ELASTIC BEHAVIOR OF A WHITE CANE ROBOT TOOL

Author: Maria Luisa Serrano Irurzun
Director: FH-Prof. Dr.-Ing. Sebastian Repetzki

Madrid
Julio 2018

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TACTILE ASSEMBLY ROBOT:

ELASTIC BEHAVIOR OF A WHITE CANE ROBOT TOOL

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Fdo.: **DR. SEBASTIAN REPETZKI** Fecha: 28/ 6/ **2018**

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

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Director: FH-Prof. Dr.-Ing. Sebastian Repetzki

Madrid
Julio 2018

ROBOT DE ENSAMBLAJE TÁCTIL: COMPORTAMIENTO ELÁSTICO DE UNA VARA PARA CIEGOS COMO HERRAMIENTA DEL ROBOT

Autor: Serrano Irurzun, Maria Luisa.

Director: Repetzki, Sebastian.

Entidad colaboradora: MCI (Management Center Innsbruck)

RESUMEN DEL PROYECTO

Introducción

Este proyecto se desarrolla en torno al robot mostrado a continuación, que fue construido en 2008 y es propiedad de la universidad Management Center Innsbruck (MCI) desde 2010. Con él se ha trabajado desde entonces en numerosos proyectos e investigaciones.

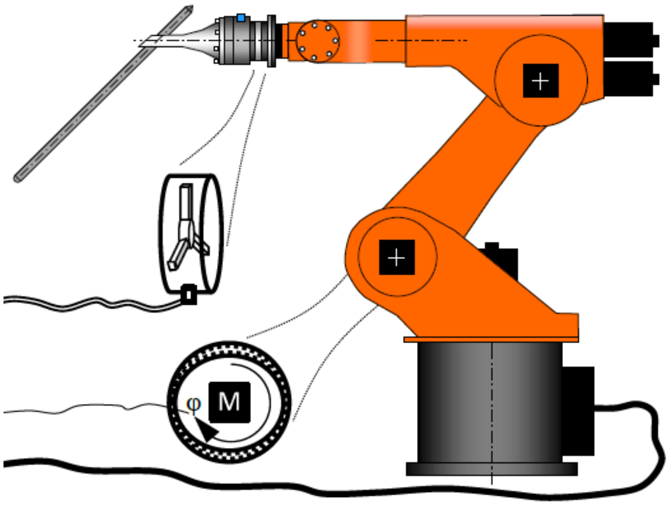

Figura I. Modelo del robot [1]

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En el proyecto de este año el robot se emplea, básicamente, para detectar objetos; como si de un palo para ciegos se tratase. Esto se consigue mediante una vara de aluminio que está montada en su brazo a través de una abrazadera, como se puede apreciar en la figura superior, y que le transmite fuerzas y momentos cuando colisiona con algún elemento. De esta manera, se pueden analizar dichas reacciones y procesarlas electrónicamente, detectando así la presencia de objetos en el entorno.

En dicho proyecto hay, por supuesto, numerosas áreas de trabajo. Esta parte de él se centra en el estudio del comportamiento elástico del conjunto vara abrazadera, así como en la localización del punto de colisión con el determinado objeto, y finalmente en el estudio de ciertas mejoras en el diseño de la fijación entre vara y abrazadera.

Metodología

En primer lugar, se estudió, tanto analítica (con la ayuda de ANSYS®), como experimentalmente (valiéndose de MATLAB®), el comportamiento elástico del conjunto vara abrazadera. El objetivo era encontrar un modelo matemático que expresara su deflexión al aplicar, en algún punto de la vara, una fuerza; o dicho de otra manera, la deflexión de dicha vara al colisionar con un objeto. Esto configura la primera parte de la memoria; objeto del mayor tiempo y desarrollo del proyecto.

La parte analítica, como ha sido mencionado, consiste, básicamente en un simulación del objeto con ANSYS®, para así encontrar los valores máximos de ciertos parámetros como la deflexión, o los esfuerzos axiles y cortantes.

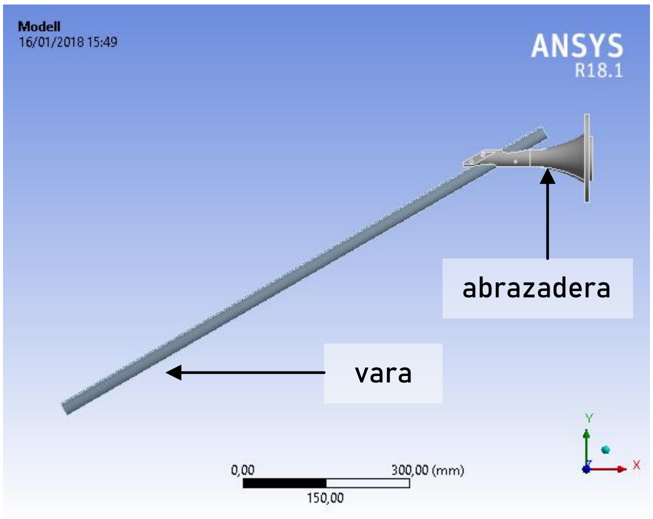

Figura II. Modelo del conjunto vara abrazadera con ANSYS®

El estudio experimental, por otro lado, consiste en una serie de medidas tomadas en el laboratorio, a partir de las cuales se llega al deseado modelo matemático, comparándose con los resultados obtenidos analíticamente. Como se explicará en el informe completo, se aproximó al comportamiento de una vara en voladizo, sumada a un muelle.

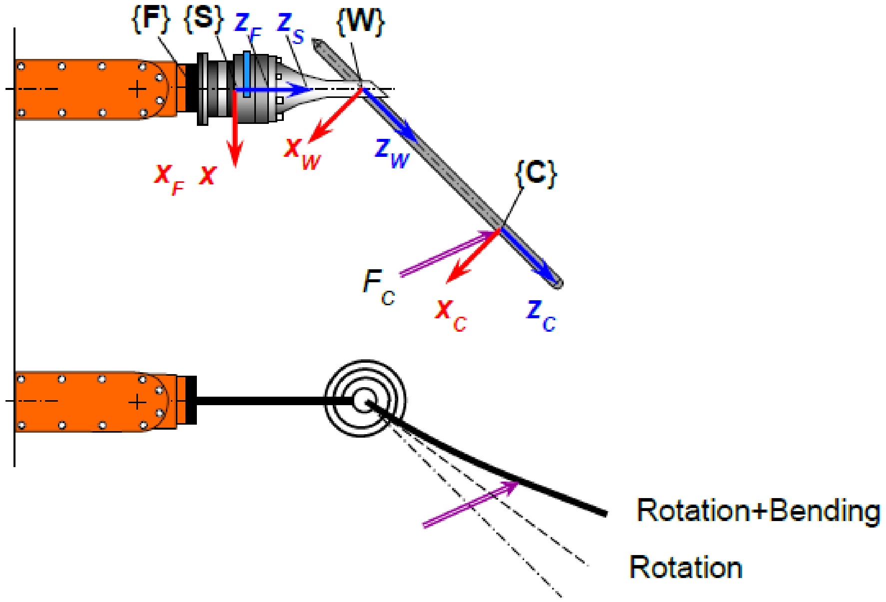

Figura III. Comportamiento del conjunto vara abrazadera bajo el efecto de una fuerza [2]

Con respecto al punto de colisión, aproximando el cuerpo a modelos mecánicos sencillos, se logró encontrar el mismo, a partir del par que provoca la fuerza del impacto con el objeto en el extremo de la barra donde se une con la fijación, y el desplazamiento de la misma. Estos valores son medidos por un sensor electrónico situado en el robot, que no es objeto de estudio en este proyecto. Esto configura la segunda parte de la memoria.

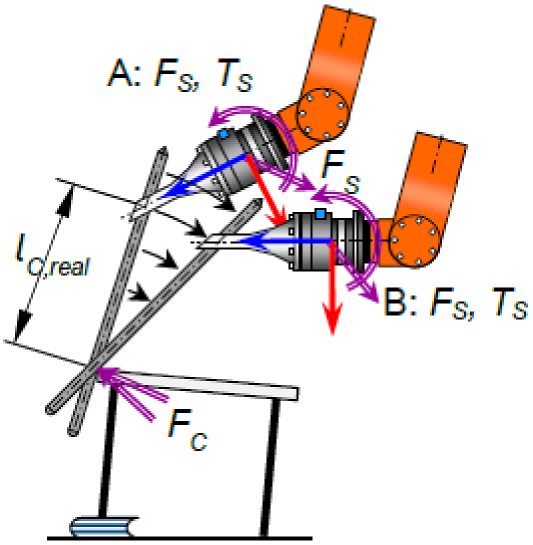

Figura IV. Punto de colisión de la vara con un determinado objeto [3]

Finalmente, aun habiendo resuelto ciertos problemas de linealidad que inicialmente surgieron, y habiendo obtenido resultados considerados coherentes, se procedió al rediseño de la fijación para hacerla simétrica, y más elegante. Se intentó manufacturar, pero el tiempo no fue suficiente, tarea que se deja para proyectos posteriores. En estos rediseños (hubo varios), llevados a cabo con SolidEdge®, consiste la tercera parte de la memoria. El finalmente aceptado es el mostrado en la imagen adjunta a continuación.

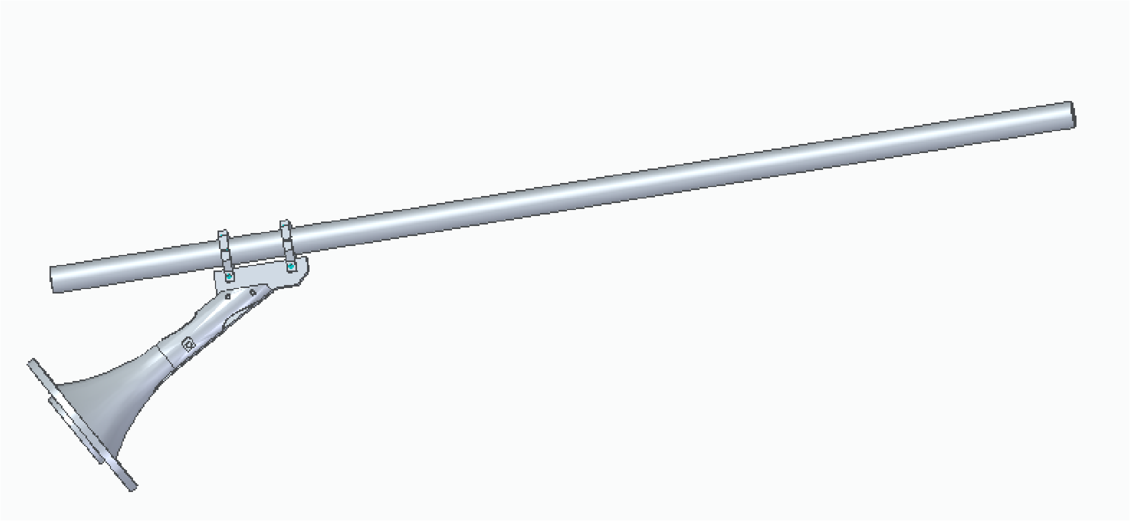

Figura V. Modelo de SolidEdge® del nuevo diseño de la fijación

Conclusiones y Resultados

Tras analizar el conjunto vara abrazadera teóricamente, y tomar medidas experimentalmente de su deflexión bajo el efecto de una fuerza, fue posible desarrollar un modelo matemático de su comportamiento, que puede ser aproximado al de una barra en voladizo unida a un muelle. De esta manera, al tener el modelo matemático deseado, es posible predecir las colisiones del robot, además de, como mencionado anteriormente, el punto en que se produce la colisión.

Es importante recalcar que, en el método experimental, la presencia de errores es reducible, pero nunca eliminable; en el estudio práctico de cualquier proyecto siempre se ha de contar con imprevistos, defectos de linealidad y de precisión, así como con histéresis, y demás factores que alteran el comportamiento del objeto estudiado.

Con respecto al rediseño de la fijación, se aceptó uno desarrollado, aunque no fue posible manufacturarlo en el transcurso del año. Como explicado, se dejará esta tarea para futuros proyectos, esperando mejoras en el comportamiento del cuerpo.

Referencias

[1] Sebastian Repetzki, Management Center Innsbruck. Documentación interna "171002 Project Arquitecture.pdf", 2017

[2] Sebastian Repetzki, Management Center Innsbruck. Documentación interna "Elastic Behavior.pdf", 2017

[3] Sebastian Repetzki, Management Center Innsbruck. Documentación interna "Elastic Behavior.pdf", 2017

TACTILE ASSEMBLY ROBOT: ELASTIC BEHAVIOR OF A WHITE CANE ROBOT TOOL

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Director: Repetzki, Sebastian.

Colaborative Entity: MCI (Management Center Innsbruck)

ABSTRACT OF THE PROJECT

Introduction

This project revolves around a robot, shown in Figure I, that was built in 2008 and is property of the university Management Center Innsbruck (MCI) since 2010. It has been worked with since in multiple projects and investigations.

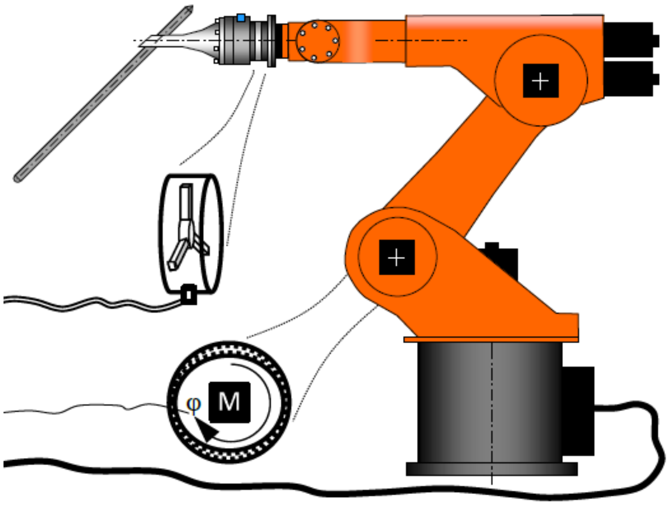

Figure I. Model of the robot [1]

**NOTE: all the figures are self-made, unless they have a reference [X]*

In this year's project, the robot is basically used to detect objects just as if it was a white cane for blind people.

Getting more into detail, the robot is programmed to detect an object in his workspace by touching it. This is achieved by an aluminium cane mounted on a force/torque sensor on the robot. To get the information of whether there is, or not, an object, the sensor sends a certain value to the controller. According to the force, the controller of the robot detects the position where the cane meets such object. To get this distance information, an elastic model of the cane is needed, in order to understand the elastic behavior of the cane. The model is the outcome of a series of measurements performed with several masses and distances to the fixation of the cane to the robot. By the view of these results it is possible to get a factor to compute the distance of the object for a known applied force. The theoretical outcome has to be tested on the real model to check the variation between the analytical and the experimental results.

There are, of course, many different areas of study in the whole project, but, as said, the one on which this part is focused is the elastic behavior of the mentioned cane-clamp body, as well as in the determination of the point where the collision occurs, and the redesign of the clamp to make its behavior more predictable.

Methodology

In the first place, an analytical study (with ANSYS®), as well as an experimental one (with MATLAB®), was held. The aim of it was to study the elastic behavior of the cane clamp body; to find a mathematical model that expressed its deflection when applying a force at any point of the cane, or, in other words, the deflection of the cane when it collided with a certain object. The first part of the Memoir consists in this; it is in which the project is mostly focused.

The analytical part, as mentioned, consists, basically, in a simulation of the object with ANSYS®, with the aim to find the maximum values of certain parameters, such as the deflection, or the stresses and strains that the cane suffers.

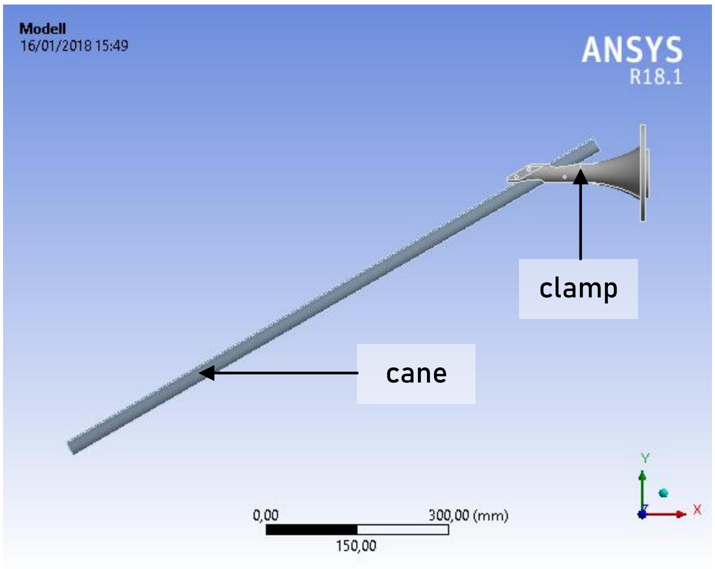

Figure II. Model of the cane clamp body with ANSYS®

The experimental study, on the other hand, consists in a series of measurements taken in the laboratory, with which the desired mathematical model is developed, comparing them to the analytical results. As it will be explained in further detail in the document, the elastic behavior of the cane could be approximated to a cantilever beam with a spring in its end.

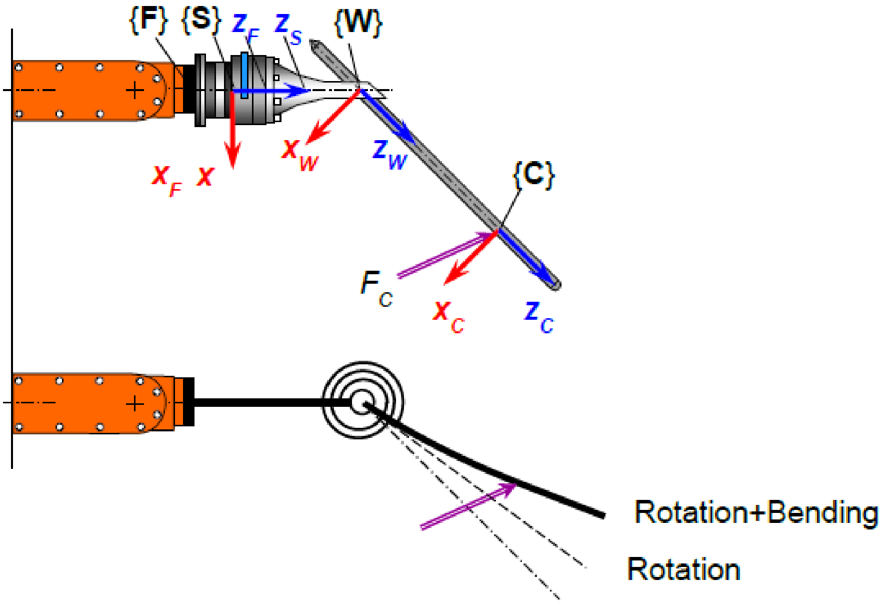

Figure III. Behavior of the cane clamp body under the effect of a force [2]

Furthermore, approximating the body with simple mechanical models, it was achieved to make the robot able to find the point of collision with the object, thanks to the torque that the force of the impact produces in the head of the cane, and the displacement of it. These values are measured by an electronic sensor that is not studied in this project. Part II of the Memoir consists in the determination of the point of collision's coordinate along the cane axis.

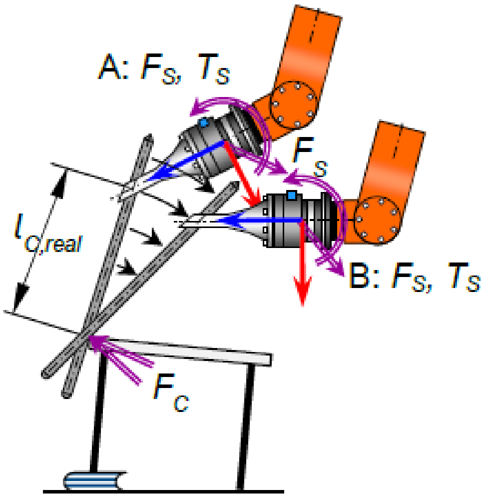

Figure IV. Point of collision of the cane with a certain object [3]

Even if the obtained results were coherent and accepted, and having solved certain problems of friction in the beginning, it was decided to develop a new clamp, symmetrical and more elegant, that made the behavior of the body more linear, and predictable. Several models were thought, but finally one was accepted; it is the one shown in Figure V. The intention was to manufacture it, but it could not be done in time, so this task will be left for future projects. This new design makes up Part III of the Memoir.

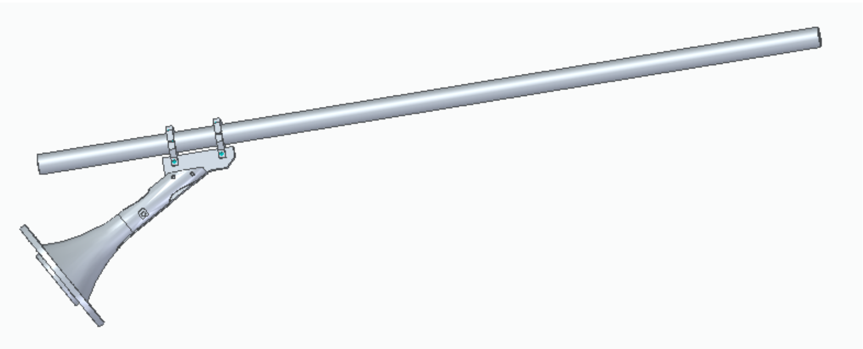

Figure V. SolidEdge® simulation of the new clamp

Results and Conclusions

After analyzing theoretically the cane clamp body, and taking experimental measurements of its deflection under the effect of a certain force, it was possible to develop the mathematical model of its behavior, that can be approximated to a cantilever beam plus a spring. Having found the desired model, it is possible to predict the collisions of the robot as well as, as mentioned previously, the point on which the collision is produced.

It is important to point out that, in the experimental method, the presence of errors is reducible, but never eliminable; in the practical study of any project, there should always be space left for any unforeseen, non-linearity effects, lack of accuracy, or hysteresis, among others.

Finally, about the redesign of the clamp, one of the solutions developed was accepted, although it was not possible to have it manufactured on time. As mentioned before, this task is left for future projects, expecting to have improvements in the elastic behavior of the body.

References

[1] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "171002 Project Arquitecture.pdf", 2017

[2] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "Elastic Behavior.pdf", 2017

[3] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "Elastic Behavior.pdf", 2017

DOCUMENT I

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MEMOIR

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Note: all figures are self-made unless they have a reference[#]. The sources of the ones that do are conveniently noted in the end of the document.

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INTRODUCTION

This project is born in base to the requirements of the modern industry to produce more products in a shorter time period, which is rising with every decade. The industry has to find solutions to be on the line with manufacturing lines supported with conveyor belts and robots. These solutions are very efficient, but for the upcoming future, the robots have to be changed in a way that they get to be self-reliant.

Up to now, robots cannot “feel” anything, which means they execute in their area the given order; a robot needs to be given the exact position of the part it has to move. Nowadays, it is being tried to achieve that the robot can indeed “feel” in which position this part is located to reduce the amount of programming of it.

In this project, the aim is that the robot “feels” whenever it collides with an object. A certain force produces a certain moment on a certain part of the robot, so the software of the system should calculate the position of the part that detected such moment. A long hollow aluminum cane, fixed to the device by an aluminum clamp will act like a white cane for blind people; the robot is driven in a certain direction and if it hits any object, a moment is measured, so the system acknowledges that the cane has collided with something, somewhere. To determine the position of this collision, a theoretical model of the cane was needed in order to compute all information. This process is described in Figure 1.

Therefore, this project is a compilation of the work done for finding out the mathematical model that captures the elastic behavior of the mentioned aluminum cane. As the aim of it is to study the mechanical properties of the cane, it will not focus on the electronics needed to translate the information that the cane receives to the one the robot needs.

The project is based on the work done by previous students of the MCI, Kevin Vannavong and Kevin Osmont. Their report describes the theoretical behavior of the cane made by ABACUS®. Furthermore, they described a method to prove the theoretical outcome to the real system. In this project, the aim is to go deeper on the analytical and experimental study of the cane and its properties.

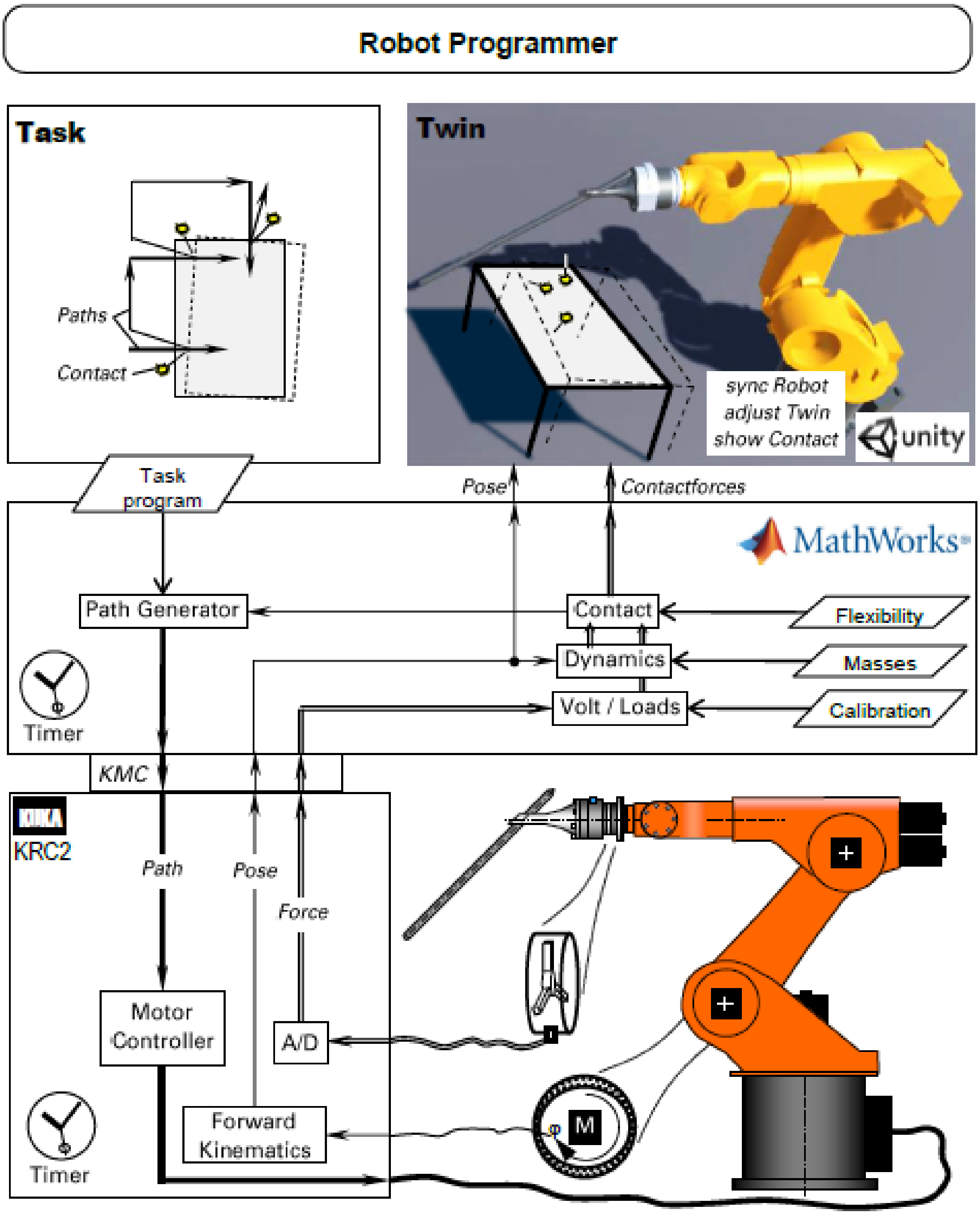


Figure 1. Simulation of the procedure of the robot's detection of an object [1]

The first thing that was needed to do, was to solve some problems that arose, like a tilt of the cane in the clamp which produced friction. It will be explained in further detail in the next points.

After this, theoretical measurements of the displacement of the end of the cane as an effect of an applied force were found with the program ANSYS®. As it will be explained, care was taken in not to exceed certain mechanical parameters of the Aluminum alloy utilized, so that no parts fractured.

Afterwards, experimental lab work was held in order to check if the cane behaved as expected. Having done this, the previously mentioned mathematical model was found, and the elastic behavior of the cane could be defined. All this study is explained in Part I of the Memoir.

Furthermore, it was considered interesting and useful for the complete robot, as mentioned before, to be able to detect the actual point of the cane where it collided with the object. To achieve this, a simple model of the cane-clamp body was considered. As the robot can quantize the torque in its arm, and the displacement of its head while the cane remains where it collided, it was possible to find the point of collision by analyzing the deflection and displacement of the cane, and the forces and torques it experiments. This makes up Part II of the Memoir.

However, as the initial clamp was not symmetrical, the behavior of the cane strongly depended on the direction of the force. Therefore, it was decided to redesign the fixation of the cane to the arm of the robot into a more elegant, and symmetrical part. The first intention was to manufacture it, but finally there was no time for it and for repeating the experiment. It will, therefore, be used in the next projects of the following years. Part III of the Memoir consists in this new designs.

PART 1

STUDY OF THE ELASTIC BEHAVIOR OF THE CANE

First of all, and for a further understanding of the cane-clamp body, an ANSYS® model was obtained, as it can be seen in Figure 2. The body consists of an aluminum hollow cane, sustained by a clamp that is fixed to the arm of the robot. The cane has a total length of 1000mm and the clamp is fixed at 20mm from its end; its outer diameter is of 25mm and the inner one of 23. The clamp is a round pole with a central slit and a crossing hole non-perpendicular to the pole axis. Two screws press the pole's jaws at their ends onto the cane. As it will be commented further on the document, the pressure distribution is uneven and unsymmetrical.

This can be seen in further detail in the structural plans attached at the end of the document.

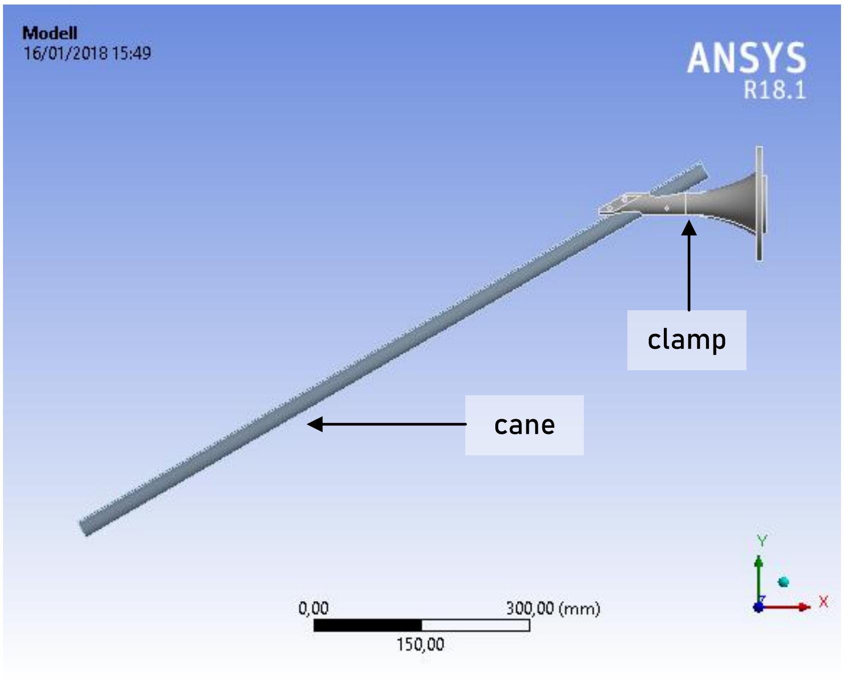


Figure 2. ANSYS® simulation of the cane-clamp body

To develop the elastic behavior study of the cane tool, it was necessary to analyze certain parameters analytically to be able to finally get experimental results. However, before being able to start with the such study, it was necessary to solve certain problems encountered, as friction and non-linearity.

1.1 PROBLEM SOLVING

The major problems were two: the cane tilted from its fixation on the clamp, and there was a lot of dry friction between fixation and cane which led to hysteresis after load application.

Firstly, comparing Figure 3 and Figure 4, the mentioned tilt can be appreciated: in the first one, being the cane pushed to its right's extreme position, four complete black sticks can be seen at its left. However, in the second one, being pushed to its left's extreme position, only two are uncovered. In red, the direction of the applied force before the cane was released.

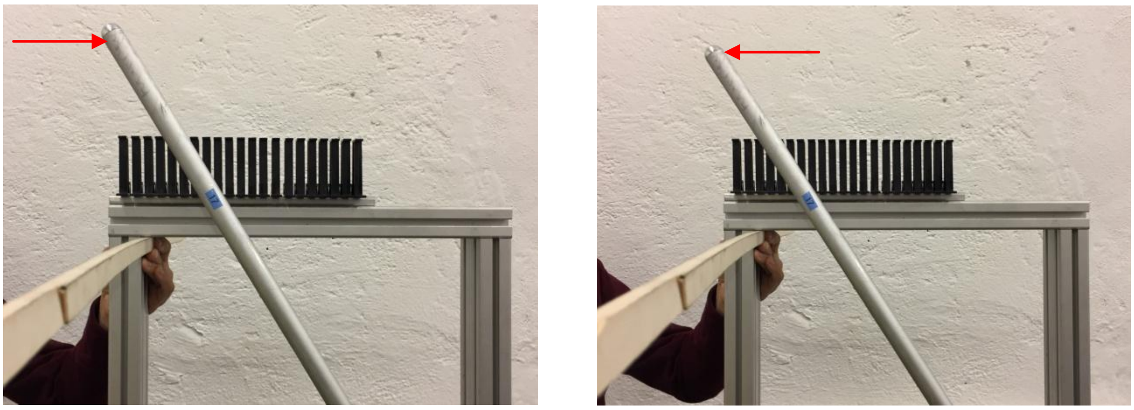


Figure 3 and Figure 4. Comparison of the positions of the cane at each extreme

Secondly, the friction between fixation and cane can be appreciated in Figure 5, where the marks of attrition are perfectly visible: several marks were painted on the cane where it is fixed to the clamp before applying any force to it, and after applying certain forces, these marks were blurred, meaning the cane tilts and produces dry friction with the clamp.

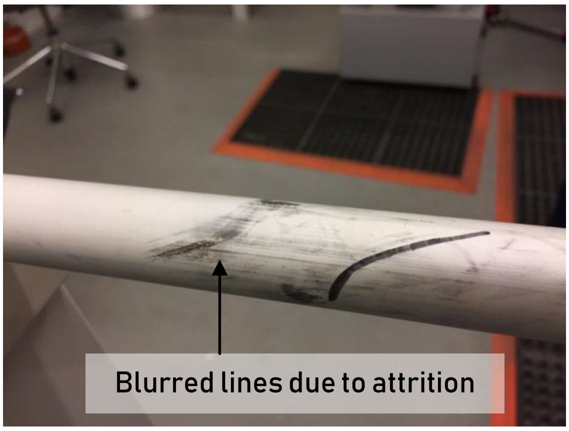


Figure 5. Marks of attrition on the cane

After coming up with some ideas to have the cane fixed better, it was decided to put a screw on the bottom of the clamp. By doing this the aim was to achieve the non-tilt of the cane, and non-friction between it and the clamp, so that it behaved in a linear-elastic way, and no hysteresis was observed when applying a force. Care was taken in where to put the screw, so that any parts crashed.

This process can be appreciated in the following images. In Figure 6, the initial clamp with no screw; in Figure 7 and Figure 8, several perspectives of the clamp with the mentioned screw already fixed.

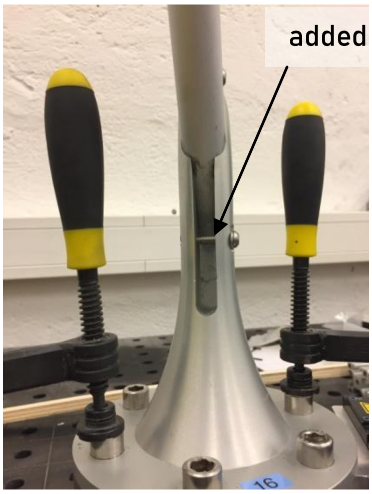


Figure 6. Initial clamp with no screw

Figure 7. Clamp with fixed screw (I)

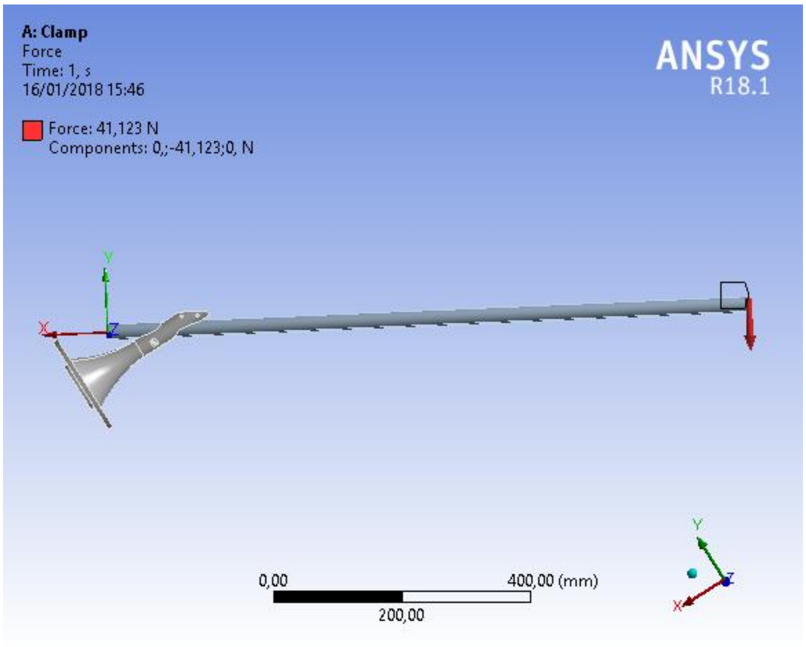
Figure 8. Clamp with fixed screw (II)

Although the described problems could not be solved totally, they were significantly reduced.

1.2 THEORETICAL STUDY

Having reduced the friction problems, the study of the elastic behavior of the cane tool could be developed. First of all, the theoretical study was held. The aim of it was to find the maximum loads that can be applied without destroying the cane, as well as to find the displacement of the cane when applying bending forces. For such purpose, the aluminum cane tool's finite element model was obtained with ANSYS®, and the displacement of the end of the cane was observed when applying such forces at its end . As one of the weights worked with in the laboratory was of 4,213kg, this was the force chosen to apply; the other one was of 1.513kg, but it was considered to be more significant the bigger one, and therefore the analytical study focuses on it.

By choosing this "particular" forces analytically, it would be possible to compare the exact analytical and experimental results.



A: Clamp
Force
Time: 1, s
16/01/2018 15:46

🟥 Force: 41,123 N
Components: 0,;-41,123;0, N

Figure 9. Applied transversal force at the end of the cane

However. it was necessary to assure that with the available weights, no important mechanical limits of the aluminum were over passed, this is, the cane maintained its initial mechanical properties while and after the force was applied. For this to be achieved, the cane could not be subject to a force big enough to make it behave in a plastic way, or in other words, to make it over pass the Yield Strength of the Aluminum alloy it is made of. If the cane behaved in such way, it would not recover its original properties after the force was eliminated.

Therefore, the cane was desired to behave in a purely (ideal) elastic way. As it will be explained further on the document, the first thing done was to study the behavior of the cane when subjected to axial forces, finding out that the limits that could not be over passed were so high that they were not worth any more study. Therefore, bending moments were the subject of the deeper study.

$$\sigma = E \cdot \varepsilon \ [Pa]$$

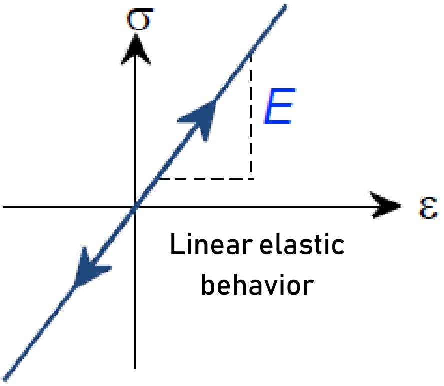


Figure 10. Hooke's law - Linear elastic behavior of a material [2]

In the previous equation (Hooke's law), σ is the applied tension (stress) to the object, ε its deformation (strain), and , E the Young's Modulus of the material.

$$\sigma = \frac{F}{S_o}\left[\frac{N}{m^2} = Pa\right] \qquad \varepsilon = \frac{\Delta L}{L_o} = \frac{L - L_o}{L_o}$$

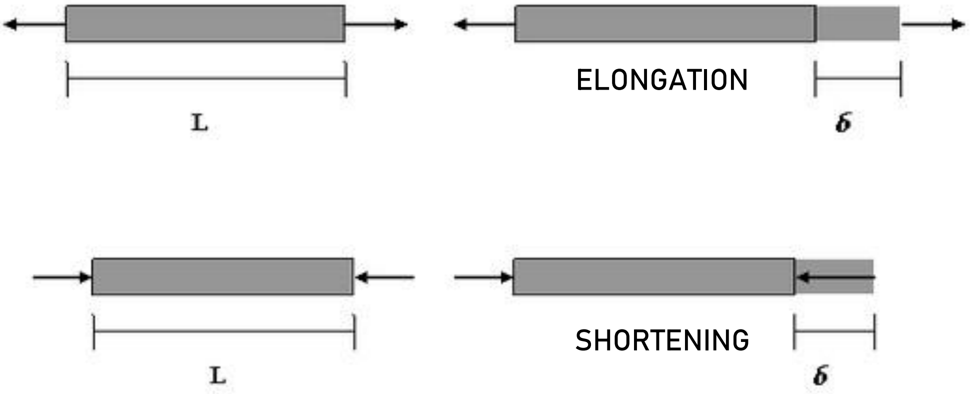


Figure 11. Deformation of a cane when applying an axial force at its end [3]

As it can be appreciated in Figure 12, after reaching the Yield Strength's point of stress, the material would not behave according to Hooke's law, but in a plastic way, and if the force were bigger, it could reach the Ultimate Strength point, or even fracture, which cannot be permitted to happen.

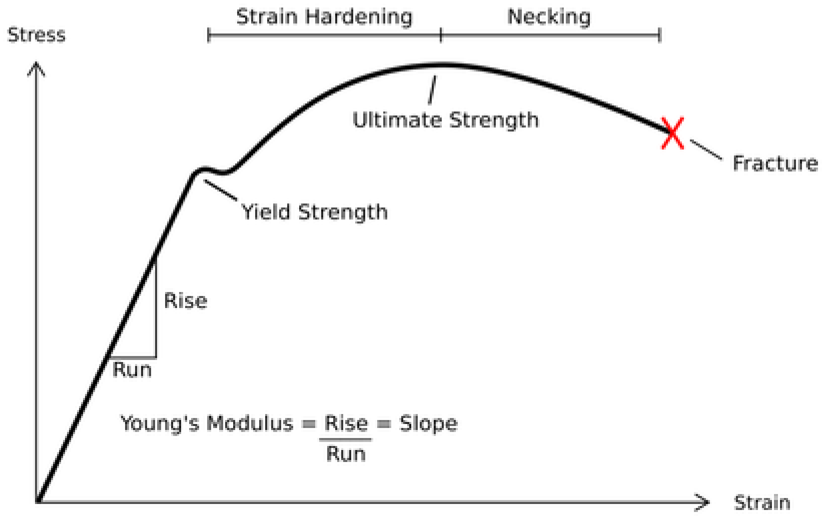


Figure 12. Stress-strain curve [4]

The diameters of the cane are Dout=25mm (R=12,5mm), and din=23mm (r=11,5mm). The Tensile and Compressive Yield Strength of the used Aluminum alloy, 280MPa, and its Young's Modulus 71GPa.

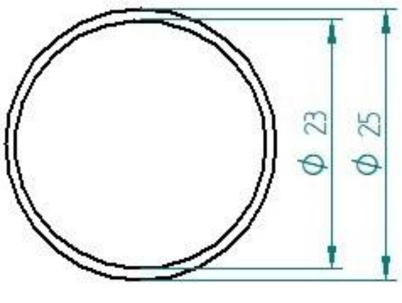


Figure 13. Inner and outer diameters of the cane, in mm

Therefore it can be calculated that a maximum force of approximately 880N can be applied longitudinally to the end of the cane before over passing the Yield Strength limit; this is, before the aluminum starts getting deformed in a plastic way. With this force, it gets deformed ε.

$$S_o = \pi * (R - r)^2 = \pi \, \mathrm{mm}^2$$

$$F = \sigma * S_o = 879{,}65 \, N$$

$$\varepsilon = \frac{\sigma}{E} = \frac{280}{71000} = 0{,}0039$$

As it can be seen, the cane can support an extremely big force before deforming in a plastic way, so this limit (axial forces) will not be considered further on, as they will never be over passed and therefore do not pose a risk.

All the data of the Aluminum alloy utilized can be seen in Table 1.

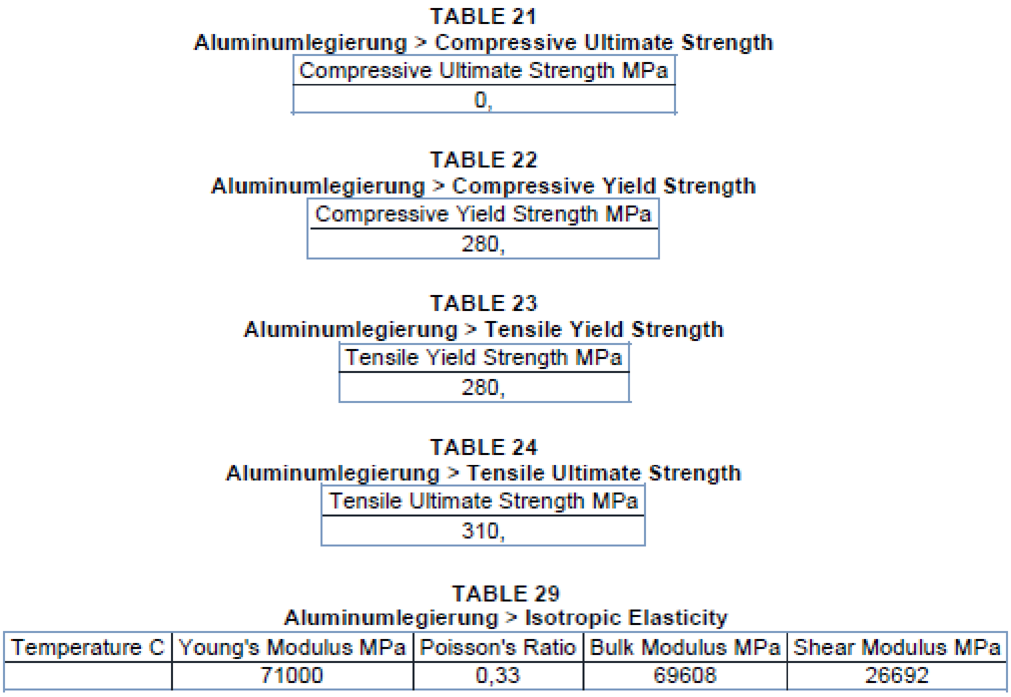


TABLE 21
Aluminumlegierung > Compressive Ultimate Strength

Compressive Ultimate Strength MPa
0,

TABLE 22
Aluminumlegierung > Compressive Yield Strength

Compressive Yield Strength MPa
280,

TABLE 23
Aluminumlegierung > Tensile Yield Strength

Tensile Yield Strength MPa
280,

TABLE 24
Aluminumlegierung > Tensile Ultimate Strength

Tensile Ultimate Strength MPa
310,

TABLE 29
Aluminumlegierung > Isotropic Elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	71000	0,33	69608	26692

Table 1. Mechanical properties of the used Aluminum alloy

As the previous calculated limits do not pose a risk, and as the cane will probably not touch objects longitudinally, but more likely, transversally, the most dangerous forces applied to the cane will not be axial efforts, but more likely, bending moments. Even if the cane did collide with an object longitudinally, it would not be subject to a tensile force, but to a compressive one, and the chances of breaking would be very low compared to the other mentioned scenario; considering the length of the cane it would probably experiment buckling first.

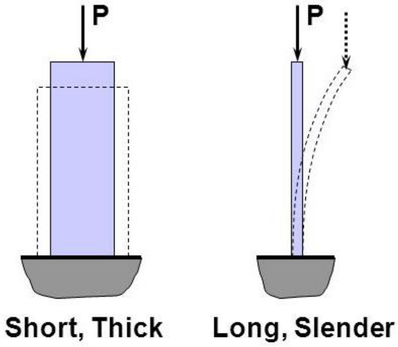


Figure 14. Compression vs. Buckling of a bar [5]

In other words, the bending of the cane is much more significant than its compression or elongation. Therefore, from this point on, the project will be focused on bending forces and reactions of the cane.

Therefore, and having calculated the significant parameters for a longitudinal collision (cane subject to axial forces), it can now be analyzed the scenario of a transversal collision (cane subject to bending moments). This is shown in Figure 15.

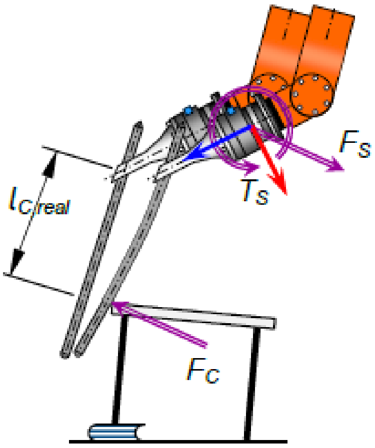


Figure 15. Transversal collision of the cane with an object + bending [6]

Looking at the geometry of the cane and the clamp, it seems that the biggest tension will be produced in the case of a force applied perpendicular, and downwards at the end of the cane, and that the most critical point will be in the part of the cane where it is attached to the clamp. It will be subject to a tension-compression force. Such behavior was simulated with ANSYS® to get accurate results, and it was observed that this is exactly what happened. It can be appreciated in Figure 16.

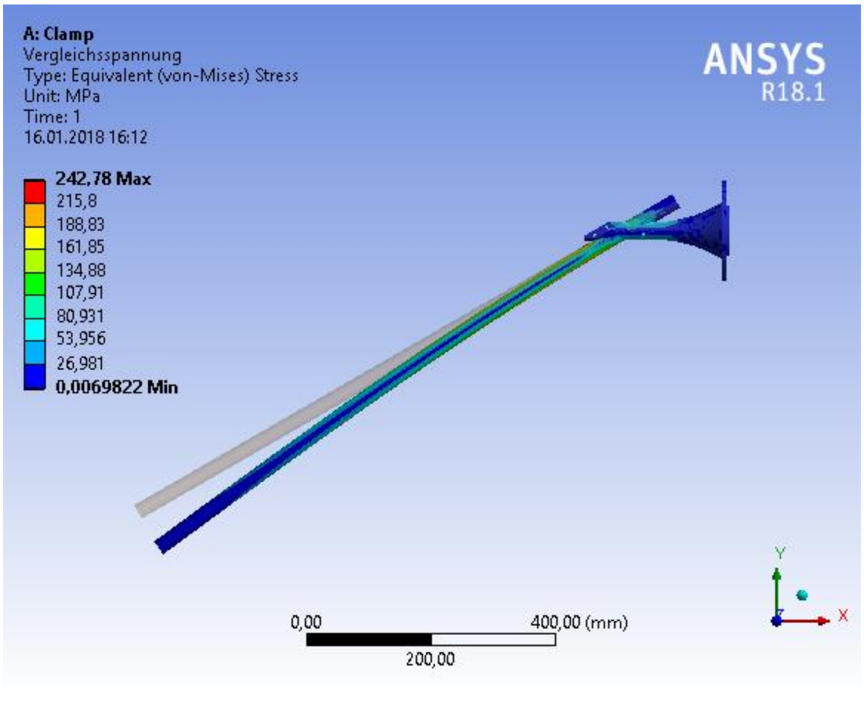


Figure 16. Maximum transversal force applicable to the cane

The results were, as it can be seen above, that a force of 120N would create an equivalent (Von-Misses) stress at the most critical point of 242,78MPa < 280MPa. This means that with a safe factor of 1.15, a maximum force of 120N can be applied at the end of the cane without producing catastrophic consequences.

Having done this, the behavior of the cane with the available masses was studied. As the maximum torque and force in the fixation, the displacement of the end of the cane, and the deformation and stresses of it would be produced with the highest chosen weight (4,213kg) applied downwards, and with the cane in horizontal position, this scenario was the one subject to study.

As it can be appreciated with the following simulations, the maximum equivalent Von-Misses stress (applying the mentioned force of 41,33N) is of 108,45MPa; the maximum equivalent elastic strain, of 0,0016886mm/mm; and the maximum displacement of the end of the cane, of 26,579mm.

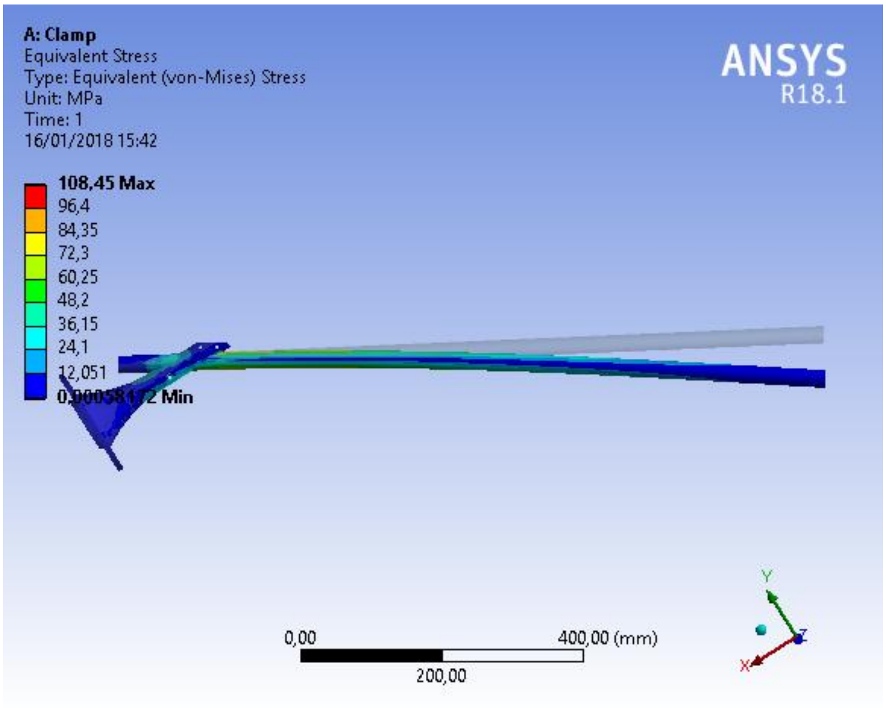


Figure 17. Maximum equivalent Von-Misses stress in the scenario of study

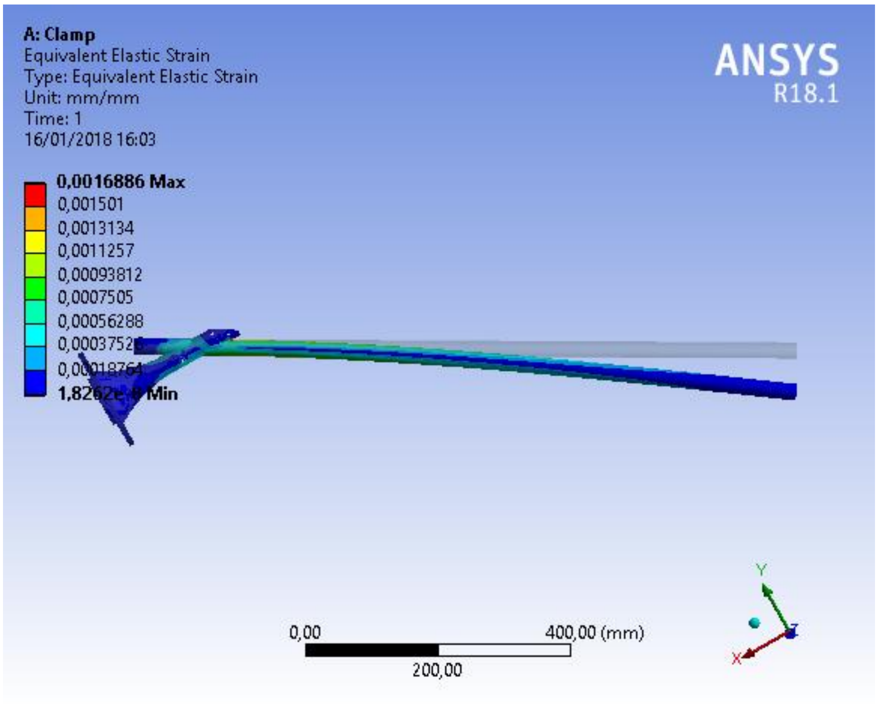


Figure 18. Maximum equivalent elastic strain in the scenario of study

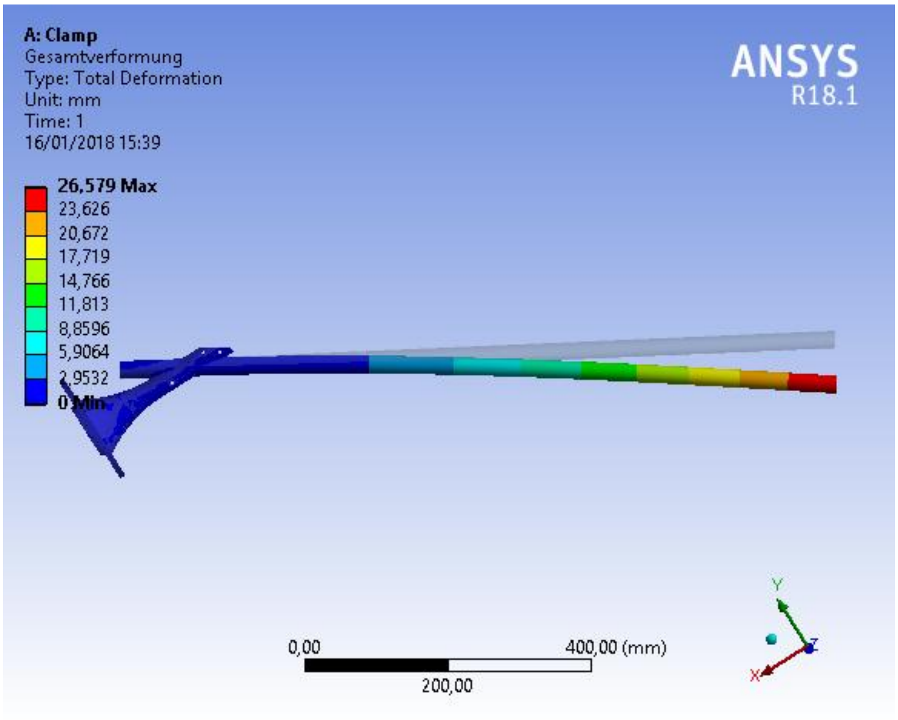


Figure 19. Maximum displacement of the end of the cane in the scenario of study

Having completed the analytical study, and having made sure that with the available forces in the laboratory, the cane would not exceed the mentioned limits, the experimental study could be developed.

1.3 EXPERIMENTAL STUDY

Knowing theoretical results from numerical calculations, measurement data was obtained from experiments in the laboratory.

In order to develop the mathematical model that expresses the deformation of the cane, measures were taken in the laboratory. The study was held with the cane in three positions, fixed in with a laboratory desk and a few objects specifically designed for this purpose, as it can be appreciated in the following figures (20 – 24)

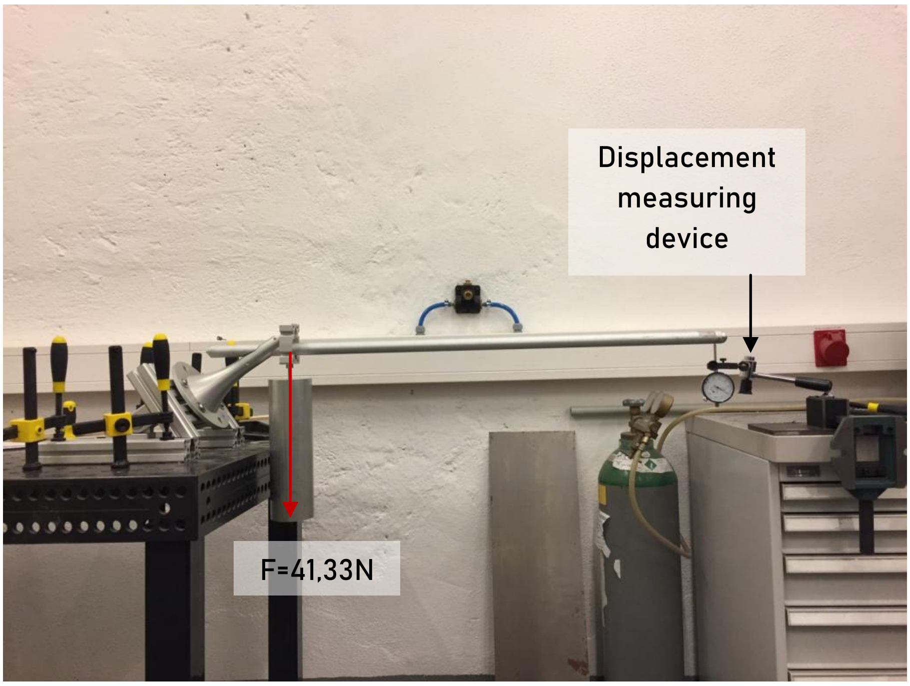
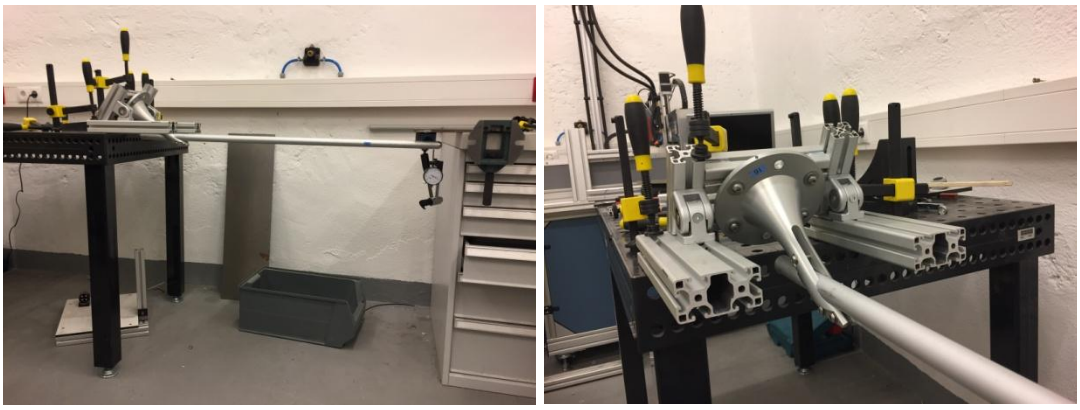
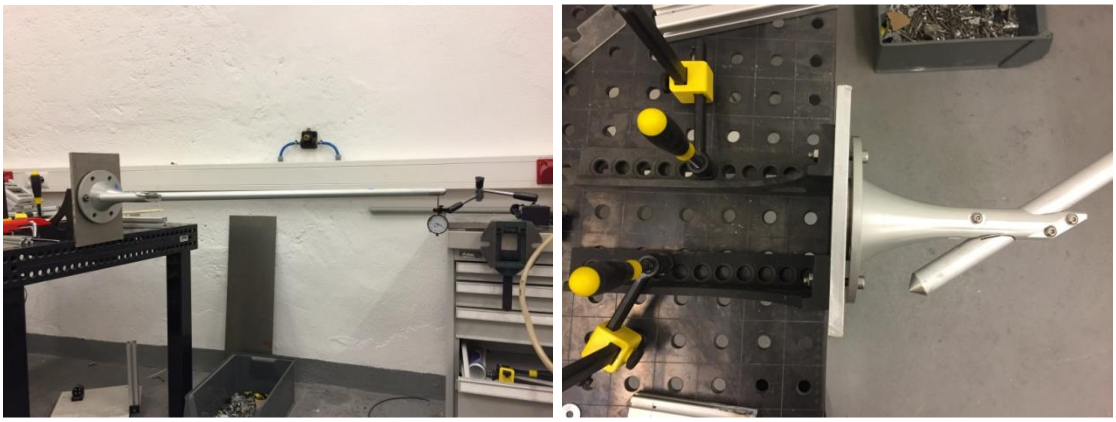


Figure 20. Experimental study in position 1 - front



Figures 21 and Figure 22. Experimental study in position 2 - back



Figures 23 and Figure 24. Experimental study in position 3 - left

Certain measurements, as mentioned, were taken in this three positions, and with each of the two forces applied in 17 points of the cane at different distances from the fixation (one at a time). This can be better understood with the following simulations (Figures 25 to 27).

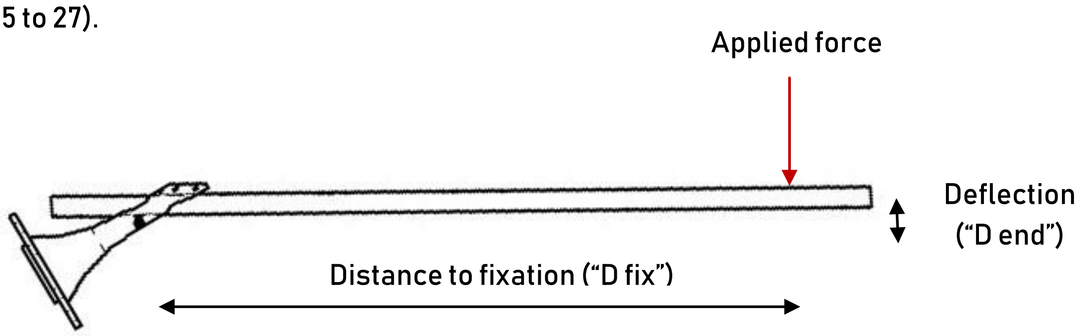


Figure 25. Forces applied to the cane in position 1 – front

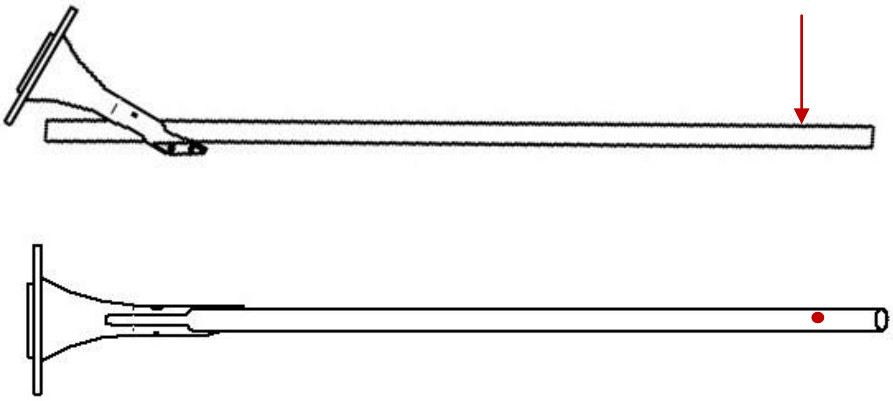


Figure 26. Forces applied to the cane in position 2 – back

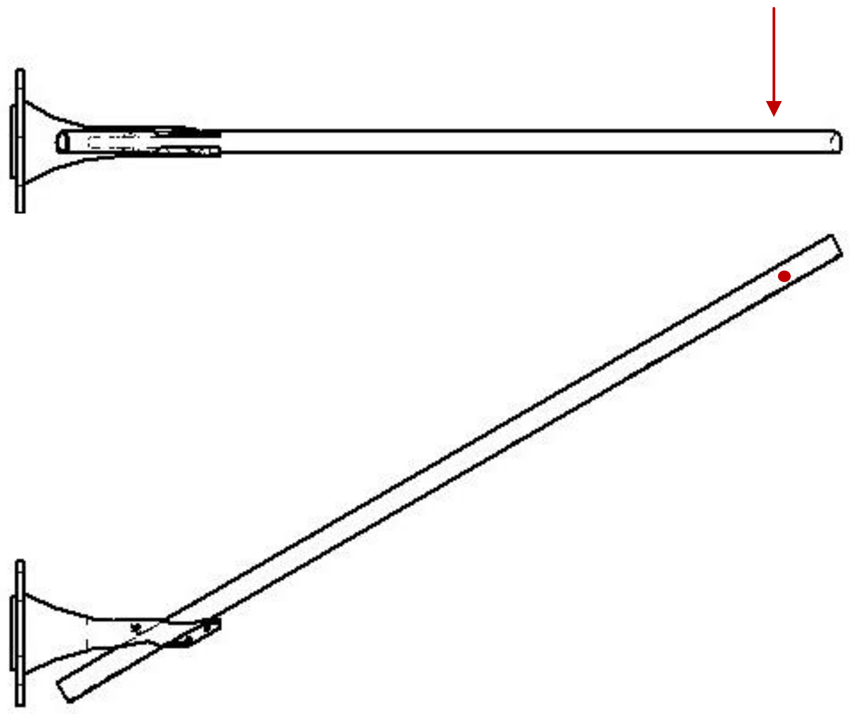


Figure 27. Forces applied to the cane in position 3 – left

The obtained results are shown in Tables 2 – 4.

POSITION OF THE CANE: 1 - FRONT				
Mass of 4.213 kg			**Mass of 1.565 kg**	
D fix (mm)	D end (mm)		D fix (mm)	D end (mm)
0	0.53		0	0.03
50	0.76		50	0.05
100	1.40		100	0.31
150	2.24		150	0.65
200	3.51		200	1.50
250	4.44		250	1.61
300	5.89		300	2.19
350	7.62		350	2.76
400	9.45		400	3.34
450	11.00		450	4.00
500	12.52		500	4.71
550	14.78		550	5.49
600	16.55		600	6.14
650	18.35		650	6.85
700	20.25		700	7.60
750	22.15		750	8.50
800	24.10		800	9.24

Table 2. Displacement of the end of the cane in position 1 for several weights

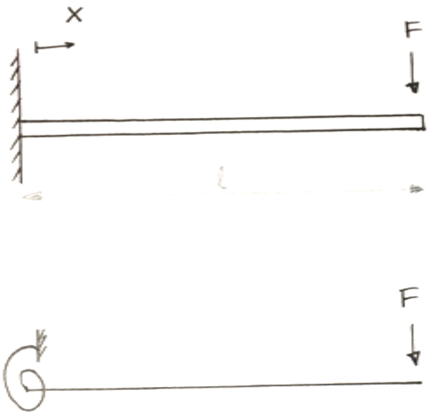
POSITION OF THE CANE: 2 - BACK				
Mass of 4.213 kg			**Mass of 1.565 kg**	
D fix (mm)	D end (mm)		D fix (mm)	D end (mm)
0	0.96		0	0.34
50	1.00		50	0.50
100	1.60		100	0.60
150	2.38		150	0.92
200	3.40		200	1.35
250	4.60		250	1.80
300	5.70		300	2.30
350	7.15		350	2.80
400	9.04		400	3.50
450	11.30		450	4.05
500	13.45		500	4.75
550	15.85		550	5.50
600	18.26		600	6.00
650	21.00		650	6.80
700	24.00		700	7.60
750	OOR		750	8.50
800	OOR		800	9.20

Table 3. Displacement of the end of the cane in position 2 for several weights

POSITION OF THE CANE: 3 - LEFT				
Mass of 4.213 kg			**Mass of 1.565 kg**	
D fix (mm)	D end (mm)		D fix (mm)	D end (mm)
0	0.08		0	0.00
50	0.13		50	0.00
100	0.46		100	0.01
150	1.07		150	0.25
200	1.89		200	0.64
250	2.98		250	1.00
300	4.05		300	1.47
350	5.38		350	1.88
400	6.61		400	2.40
450	8.31		450	3.06
500	9.85		500	3.70
550	11.41		550	4.30
600	13.32		600	5.07
650	15.60		650	5.70
700	17.31		700	6.40
750	19.27		750	7.15
800	21.44		800	7.86

Table 4 Displacement of the end of the cane in position 3 for several weights

With these measurements, the desired mathematical model was found with the help of Matlab®. A polynomial of 3rd degree was chosen for such model, as the deflection of the cane-clamp object can be approached to a cantilever beam plus a beam connected to a spring, as it can be appreciated in Figures 28 and 29. The possibility of approaching the cane's behavior to such model will be proved further on the document when the mathematical model is found.



$$f \sim x^3 \quad (f = \frac{1}{3 * E * I} * F * l^3)$$

$$f \sim x^2 \quad (f = F * x * Cs * x)$$

Figure 28. Model of the deflection of the beam

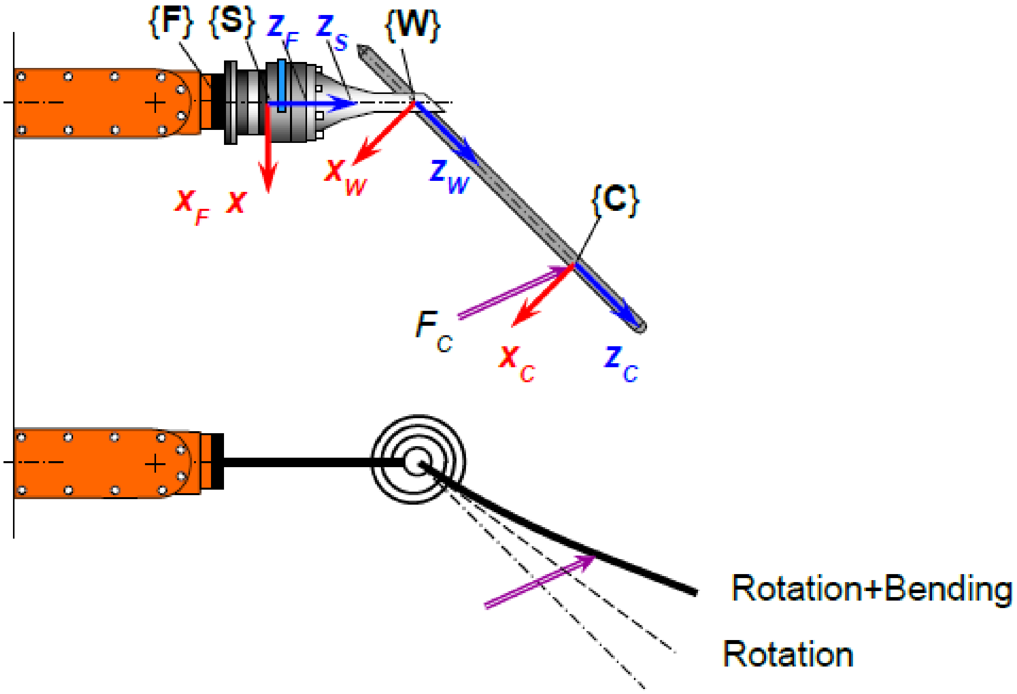


Figure 29. Simulation model of the deflection of the beam [7]

A program code in Matlab® was developed as follows. First of all, a program to read all the measurements was done. For each file of the measurements, the values are stored in vectors (A,B,C…) that will be used further on to plot the graphs of displacement vs. distance of the applied force to the fixation. This is Program Code 1.

```
%1=Distance in mm
%2= displacement in mm 4kg
%5= displacement in mm 2 kg
A=dlmread('Measurements_front.txt');%Measurements Front

A1=A(:,1);
A2=A(:,2);
A3=A(:,5);

% Column 4 -> Displacement for 2 kg
B=dlmread('Measurements_back.txt');%Measurements back 180°
B1=B(:,1);
B2=B(:,2);
B3=B(:,4);

C=dlmread('Measurements_side.txt');%Measurements side 90°
C1=C(:,1);
C2=C(:,2);
C3=C(:,4);

%With new clamp 4kg
D=dlmread('Measurements_clamp.txt');%Measurements new clamp

D1=D(:,1);
D2=D(:,2);


%%THIS PART OF THE CODE WILL NOT BE USED YET

%With new clamp each 50mm (from 0 to 500mm) 4kg
F=dlmread('Measurements_clamp25.txt');%Measurements with
new clamp
F1=F(:,1);
F2=F(:,2);

%With new clamp each 50mm random (0 to 800) 4kg
F=dlmread('Measurements_clamprandom.txt');%Measurements
with new clamp
R1=F(:,1);%Distance
R2=F(:,2);
R3=F(:,3);
R4=F(:,4);

%With new clamp each 50mm left side of weight 4kg
F=dlmread('Measurements_clamprandomleft.txt');%Measurements
with new clamp
CR1=F(:,1);%Distance
CR2=F(:,2);
CR3=F(:,3);
```

Program Code 1. "get_Data"

Further on, another code was written to find the polynomial mentioned before, for each of the positions and weights, and to plot the solutions. This configures Program Code 2.

The following Matlab codes are used:

- *polyfit*: p = polyfit(x,y,n) returns the coefficients for a polynomial p(x) of degree n that is a best fit (in a least-squares sense) for the data in y. The coefficients in p are in descending powers, and the length of p is n+1. [8]
- *polyval*: y = polyval(p,x) returns the value of a polynomial of degree n evaluated at x. The input argument p is a vector of length n+1 whose elements are the coefficients in descending powers of the polynomial to be evaluated. [9]
- The results are plotted in a graph with the function *plot*. These graphs are shown further on the document (Figures 30 to 35).

```
clear
run('get_Data');

p1 = polyfit(A1,A2,3)

x1 = 1:10:800;
y1 = polyval(p1,x1);
figure
plot(A1,A2,'o',x1,y1)
title('Front (0 degrees) 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
% y=p(1)*x.^3+p(2)*x.^2+p(3)*x.^1+p(4)*x.^0;

p2 = polyfit(A1,A3,3)

x2 = 1:10:800;
y2 = polyval(p2,x2);
figure
plot(A1,A3,'o',x2,y2)
title('Front (0 degrees) 1,565 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
%%
p3 = polyfit(B1,B2,3)

x3 = 1:10:800;
y3 = polyval(p3,x3);
figure
plot(B1,B2,'o',x3,y3)
title('back (180 degrees) 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
```

```
grid on

p4 = polyfit(B1,B3,3)

x4 = 1:10:800;
y4 = polyval(p4,x4);
figure
plot(B1,B3,'o',x4,y4)
title('back (180 degrees) 1,565 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
%%
p5 = polyfit(C1,C2,3)

x5 = 1:10:800;
y5 = polyval(p5,x5);
figure
plot(C1,C2,'o',x5,y5)
title('side (90 degrees) 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on

p6 = polyfit(C1,C3,3)

x6 = 1:10:800;
y6 = polyval(p6,x6);
figure
plot(C1,C3,'o',x6,y6)
title('side (90 degrees) 1,565 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
%%
A=[p1; p2; p3; p4; p5; p6;];
%dlmwrite('Parameters.txt',A);
dlmwrite('Parameters.txt',A,'delimiter','\t','precision',4)
```

Program Code 2. "Regression"

As it can be derived from the code, "p1" corresponds to the coefficients of the polynomial of the cane in the original position, and under the force applied by the mass of 4.213kg. "p2" corresponds to the coefficients of the polynomial of the cane in the original position, and under the force applied by the mass of 1.565kg, and so on.

The results of the coefficient of the polynomials are stored, as it can be seen in the end of the code, in a document called Parameters.

The results of these parameters, and therefore the searched polynomials are:

$$-2.899\text{e}-08*x^3+\ 5.368\text{e}-05*x^2+\ 0.005051*x+0.4372$$

$$-6.164\text{e}-09*x^3+\ 1.492\text{e}-05*x^2+\ 0.003652*x+-0.08222$$

$$-6.578\text{e}-09*x^3+\ 4.818\text{e}-05*x^2+\ 0.00248*x+0.8986$$

$$-1.041\text{e}-08*x^3+\ 1.991\text{e}-05*x^2+\ 0.001463*x+0.3307$$

$$-1.679\text{e}-08*x^3+\ 4.526\text{e}-05*x^2+\ 0.001312*x+-0.01216$$

$$-1.013\text{e}-08*x^3+\ 2.125\text{e}-05*x^2+\ -0.0006653*x+-0.03706$$

And the graphics of these deflections, and the polynomials of each case are shown in Figures 30 – 35.

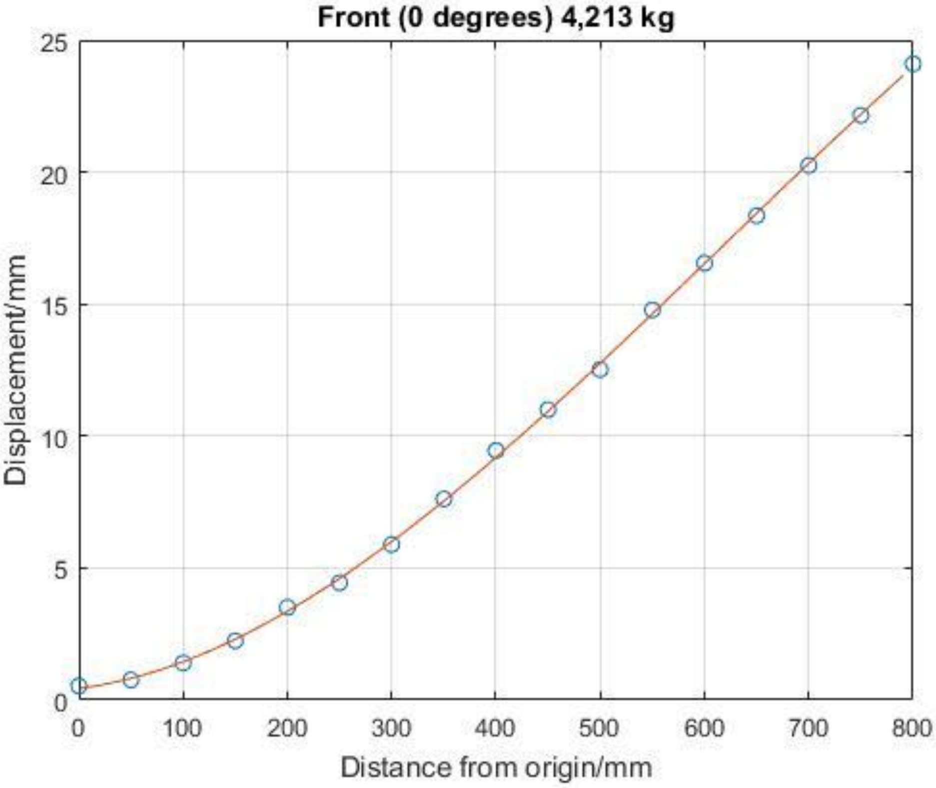


Figure 30

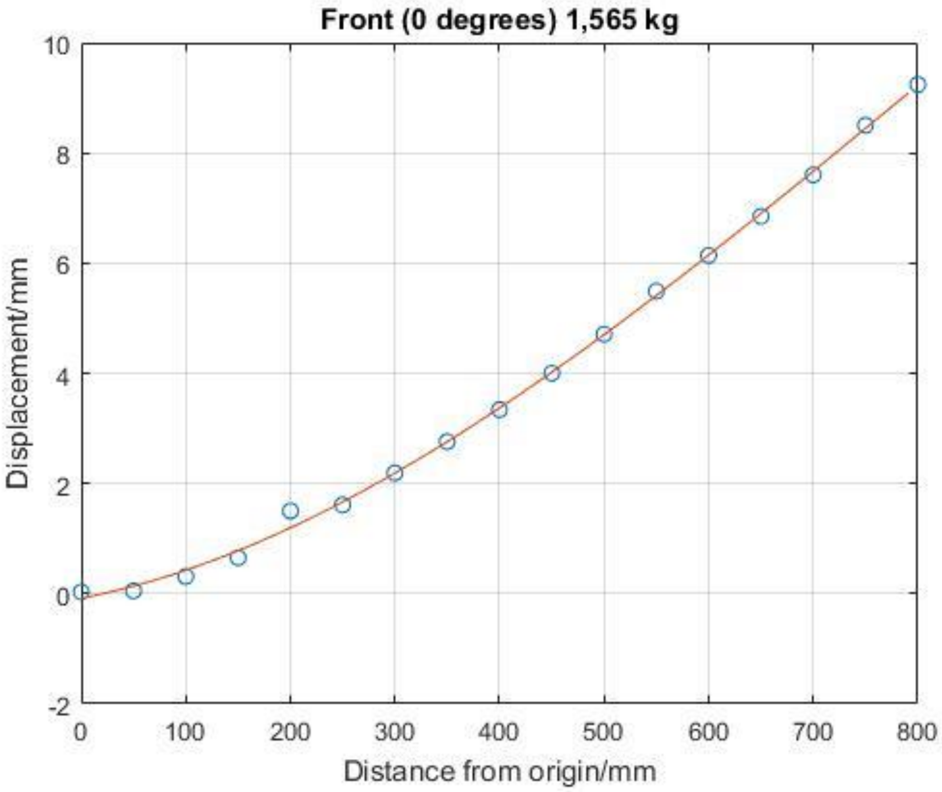


Figure 31

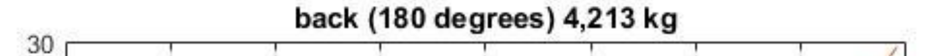


Figure 32

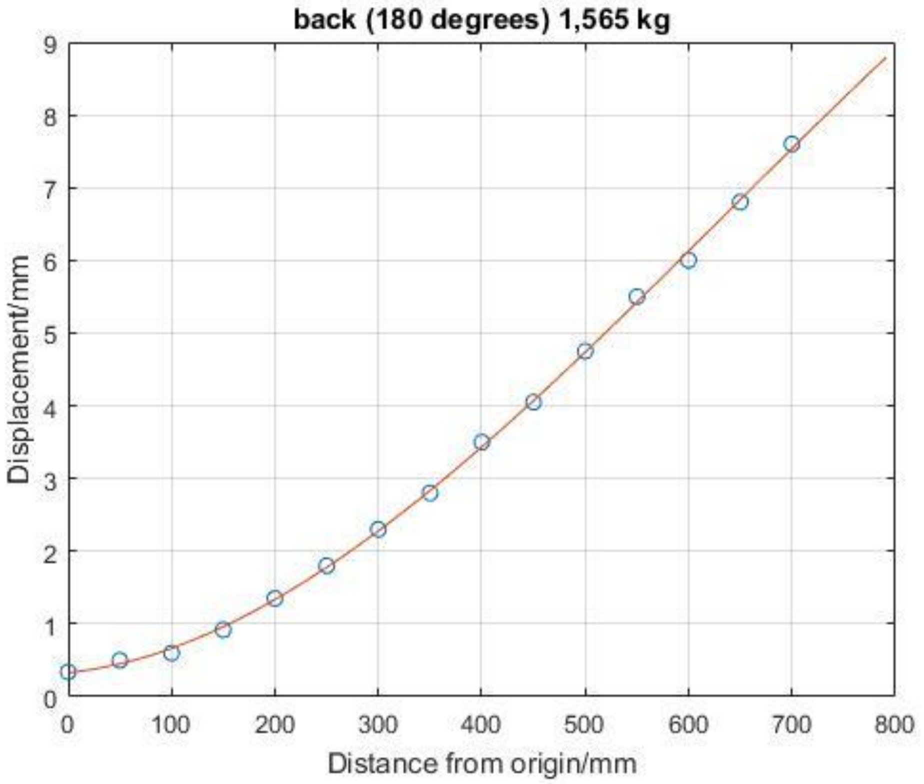


Figure 33

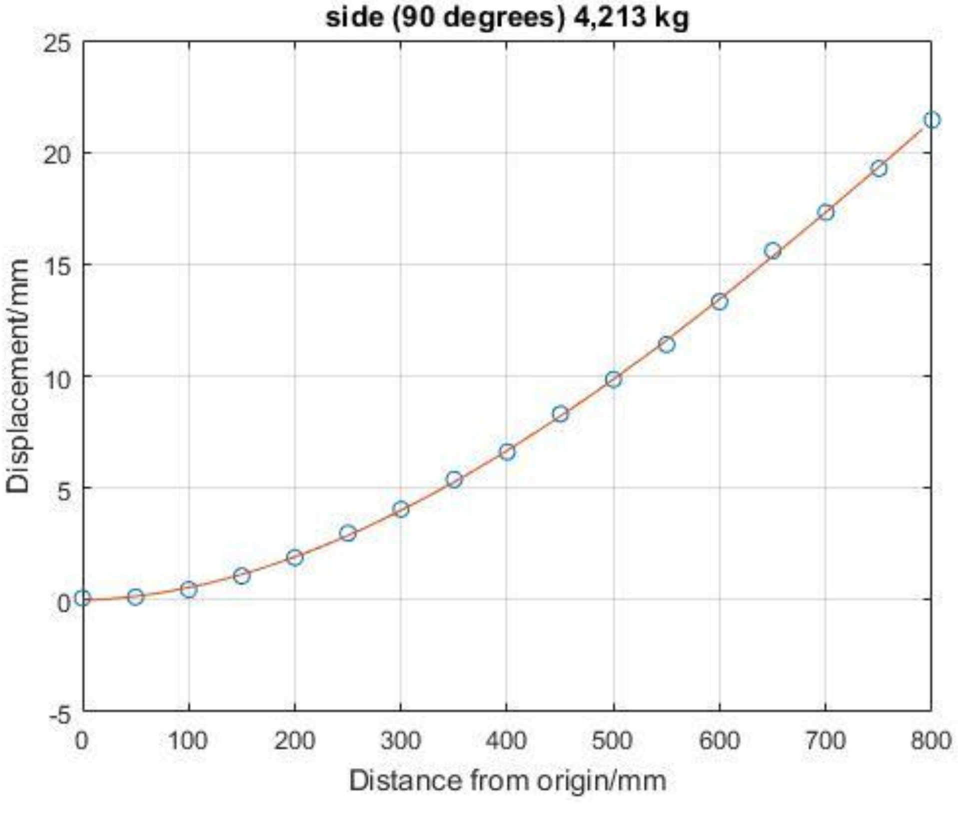


Figure 34

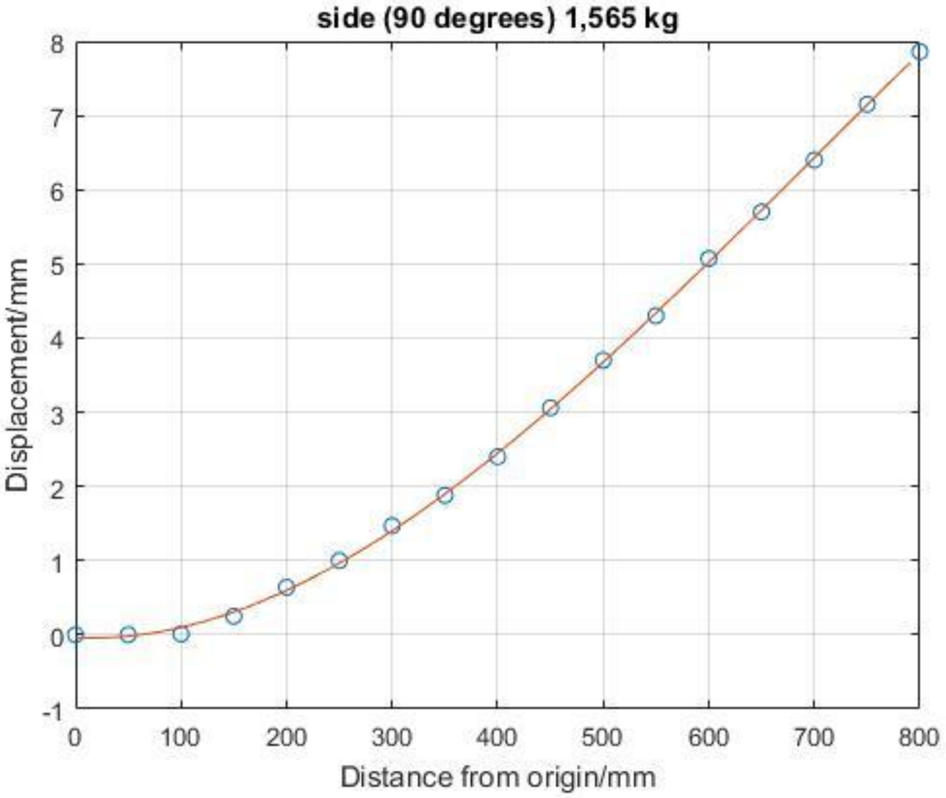


Figure 35

However, the results could not be totally accepted, as they were not satisfactorily accurate. It was observed that one measure taken would differ a lot from the same one taken at other moment. Therefore, a solution for this problem was needed. As a first approach, a new element was added to have the cane fixed better (with less friction) to the original clamp. This new contribution can be appreciated in Figure 36.

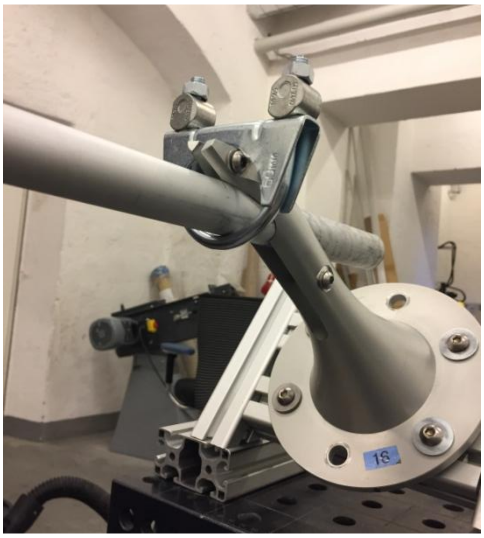


Figure 36. Improved fixation of the cane to the clamp

Having done this, new measurements were taken. The results of the ones taken in the original position, with the 4.213 kg mass, can be seen in Table 5.

Original position, Mass of 4.213 kg		
D fix (mm)	D end 1 (mm)	D end 2 (mm)
0	0.12	0.08
50	0.80	0.95
100	1.65	1.68
150	2.20	2.38
200	3.26	3.30
250	3.85	4.35
300	5.03	5.50
350	6.59	6.90
400	8.25	8.24
450	9.40	9.90
500	11.50	11.48
550	13.00	13.14
600	14.90	14.90
650	16.80	16.85
700	18.40	18.70
750	20.50	20.43
800	23.00	22.30

Table 5. Measures with new fixation

Another Matlab® code was developed to find the polynomial for this new case, as it can be seen in the following Program Code 3.

```
run('get_Data');
figure


p4 = polyfit(CR1,CR2,3)

x1 = 1:10:800;
y1 = polyval(p4,x1);
%figure
plot(CR1,CR2,'o',x1,y1)
title('Front (0 degrees) Random 2 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
% y=p(1)*x2.^3+p(2)*x2.^2+p(3)*x2.^1+p(4)*x2.^0;
% figure
% plot(x2,y);
hold on
p5 = polyfit(CR1,CR3,3)


x2 = 1:10:800;
```

```
y2 = polyval(p5,x2);
%figure
plot(CR1,CR3,'o',x2,y2)
title('Front (0 degrees) Random 2 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on


%Coeff=[p1;p2;p3;p4;p5];
Coeff=[p4;p5];
dlmwrite('Parameters_clamp_F.txt',Coeff,'delimiter','\t','p
recision',4)
```

Program Code 3. "Regression_clamp"

The results of the polynomials for both sets of measurements of the deflection of the end of the clamp in the original position, and under the force of a weight of 4.213kg are:

$$-9.137\mathrm{e}-09 \ast x^{3} + 3.276\mathrm{e}-05 \ast x^{2} + 0.007793 \ast x + 0.2847$$

$$-1.192\mathrm{e}-08 \ast x^{3} + 3.297\mathrm{e}-05 \ast x^{2} + 0.008878 \ast x + 0.2919$$

As it can be appreciated, they are quite similar to one another, but they differ from the first measurements. It makes sense to assume that with the new fixation the body works better, so this were the results to accept and to work with in more details. Figure 37 shows both measurements fitted into the polynomials.

The analysis of this polynomials, the contribution of the terms to each one, and its accuracy will be discussed in further detail in point *1.3.1 Conclusions*.

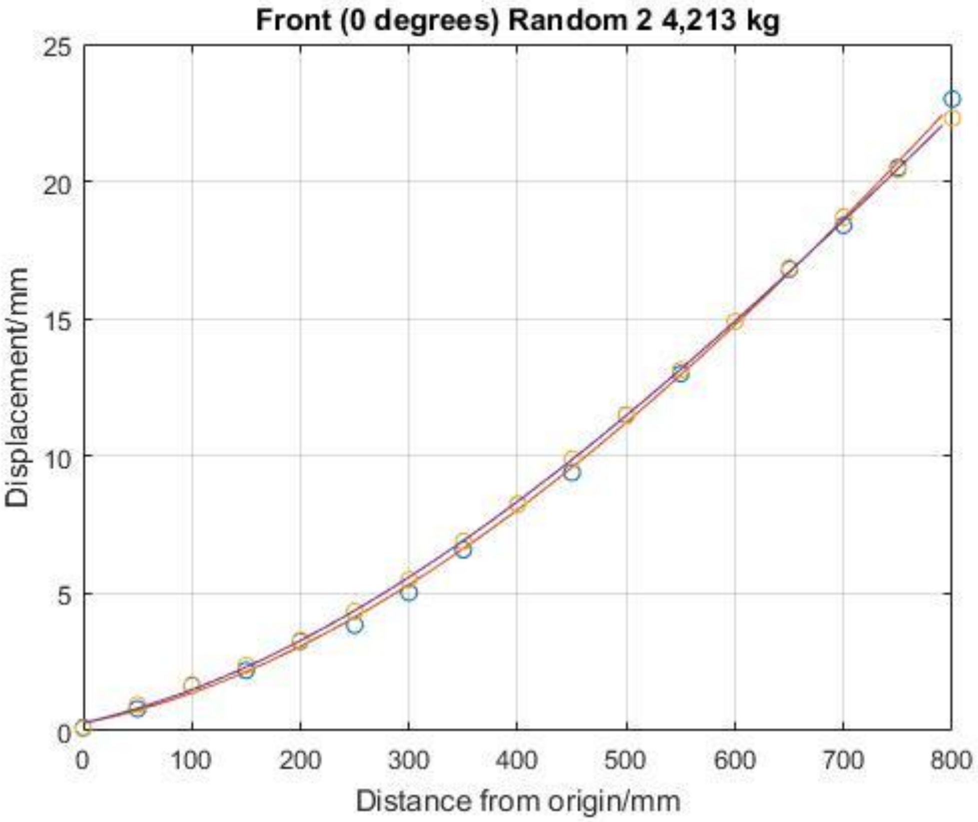


Figure 37. Graph of the deflection of the beam (II)

1.3.1 Tolerances

It is clear that not all measurements taken would be exactly the same if this experiment was repeated several times, so with the ones obtained, it was decided to find out a range of tolerances. Again, another Matlab® code was developed to fulfill this task. It is Program Code 4. In it, the average values of the two sets of measurements is calculated. Afterwards, the standard deviation of each value from this average is found. Once having this deviations, they are multiplied by 3 (giving 3σ) and summed to the average. The results are plotted in Figure 38.

```
clear

%% Calculate the Tolerances
run('get_Data');
p4 = polyfit(CR1,CR2,3)

x1 = 1:10:800;
y1 = polyval(p4,x1);
%figure
%plot(CR1,CR2,'o',x1,y1)
% title('Front (0 degrees) Random 2 4,213 kg')
% xlabel('Distance from origin/mm')
% ylabel('Displacement/mm')
% grid on
% hold on

p5 = polyfit(CR1,CR3,3)


x2 = 1:10:800;
y2 = polyval(p5,x2);
%figure
%plot(CR1,CR3,'o',x2,y2)
% title('Front (0 degrees) Random 2 4,213 kg')
% xlabel('Distance from origin/mm')
% ylabel('Displacement/mm')
% grid on

%%
Meas1=CR2;  %Measurements 1
Meas2=CR3;  %Measurements 2
Ap1=zeros();
%Ap2=zeros();

% Create Average between the 2 Measurements
for i=1:17

    Ap1(i)=(Meas1(i)+Meas2(i))/2;


end

Ap1=Ap1';
```

```
%%% Create Distances from average to measurement points
Measurment1=zeros();%Measurement 1
for i=1:17
   Measurment1(i)=Meas1(i)-Ap1(i);

end

Measurment2=zeros();%Measurement 2
for i=1:17
   Measurment2(i)=Meas2(i)-Ap1(i);

end


% Create the Tolerances with Standard deviation 3 Sigma
TSigma1=abs(Measurment1)*3;
TSigma2=abs(Measurment2)*3;



Upper=zeros();
Lower=zeros();



%Define the Tolerance out of the Biggest tolerance Value

 for i=1:17
    Upper(i)=Ap1(i)+TSigma1(i);
    Lower(i)=Ap1(i)-TSigma2(i);
end
%% Plot the Sigma Tolerances according to the measurement Points
Upper=Upper';%Upper border
Lower=Lower';%Lower border
p1 = polyfit(CR1,Upper,3);

x1 = 1:10:800;
y1 = polyval(p1,x1);
figure
plot(x1,y1)
title('Front (0 degrees) Random 2 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
hold on



p2 = polyfit(CR1,Lower,3);

x1 = 1:10:800;
y1 = polyval(p2,x1);
%figure
plot(x1,y1)
title('Front (0 degrees) Random 2 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
hold on
```

```
%Plot Measurements in the tolerance field

p4 = polyfit(CR1,CR2,3)
x1 = 1:10:800;
y1 = polyval(p4,x1);
%figure
plot(x1,y1)
title('Front (0 degrees) Random 2 4,213 kg')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
grid on
hold on

p5 = polyfit(CR1,CR3,3)
x5 = 1:10:800;
y5 = polyval(p5,x5);
%figure
plot(x5,y5)
%plot(CR1,CR3,'o',x5,y5)
title('Measurements front with 4,213 kg and tolerances')
xlabel('Distance from origin/mm')
ylabel('Displacement/mm')
legend('upper border','lower border','measurement
1','measurement 2')
grid on
hold on
```

Program Code 4. "Standart_dev_1"

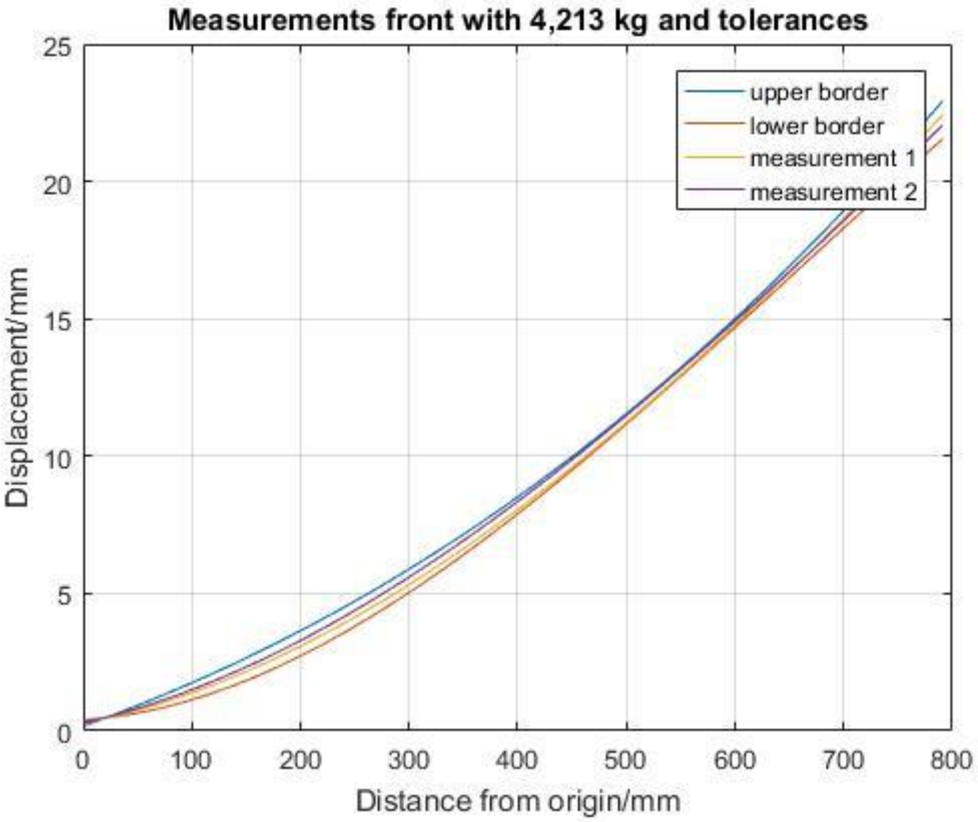


Figure 38. Tolerances of the measurements of deflection of the beam (I)

As it can be seen, certain problems occur when approximating these tolerances to a polynomial; some values collapse with the limits. Thus, a new method was developed. It is shown in the extract of another Matlab® code, Program Code 5. It only differs on the previous code in the chosen 3 σ. In this case, the biggest deviation of all is taken, giving a wider range of tolerances, assuring all of the values are inside it.

```
% Create the Tolerances with Standard deviation 3 Sigma
TSigma1=abs(Measurment1)*3;
TSigma2=abs(Measurment2)*3;

SigmaBig=zeros();

%Search for the Biggest Tolerance Value
for i=1:17
   if TSigma1(i)>TSigma2(i)
       SigmaBig(i)=TSigma1(i);
   else
       SigmaBig(i)=TSigma2(i);
   end
end

Final1=zeros();
Final2=zeros();
maxSigma=max(SigmaBig);

%Define the Tolerance out of the Biggest tolerance Value

 for i=1:17
    Final1(i)=Ap1(i)+maxSigma;
    Final2(i)=Ap1(i)-maxSigma;
end
```

Program Code 5. Standart_dev_2"

The final result is satisfactory, as it can be seen in Figure 39.

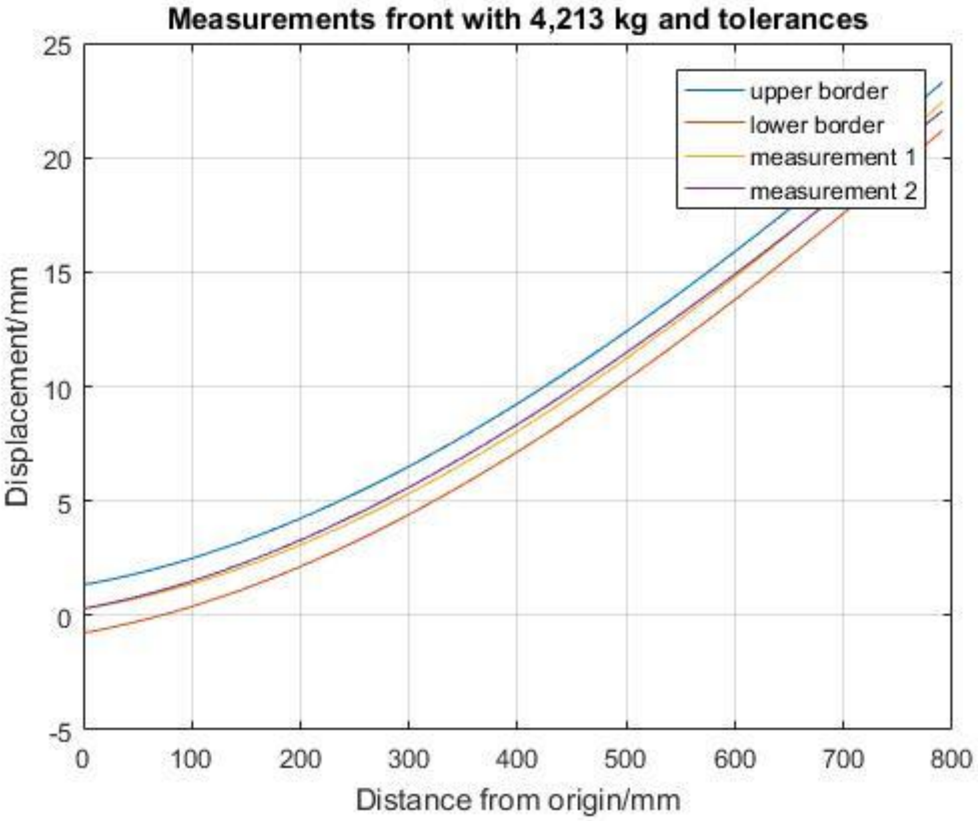


Figure 39. Final tolerances of the measurements of deflection of the beam

It can be appreciated how the error evolves from small to bigger distances between the point of application of the force and the fixation. When the force is applied close to end of the cane (bigger distances from origin), the accepted error is quite small. However, when the force is applied closer to the fixation (smaller distances from origin), this error grows, getting much bigger in comparison. The tolerances were designed this way because it is very difficult to measure the behavior of the cane under forces close to the fixation, as the deflection is very small. The errors, therefore, can be much bigger.

1.4 CONCLUSIONS

Analyzing in more detail the mathematical model found for the mass of 4,213kg, it is clear the predominance of the second order term, which corresponds to the spring behavior influence, in either of both polynomials:

$$-9.137\mathrm{e}-09 * x^3 + 3.276\mathrm{e}-05 * x^2 + 0.007793 * x + 0.2847$$

$$-1.192\mathrm{e}-08 * x^3 + 3.297\mathrm{e}-05 * x^2 + 0.008878 * x + 0.2919$$

For example, using the first one, if the mass is applied at 700mm from the fixation it produces a deflection of 18.644mm, and the contribution of each of the terms are (in absolute value):

$$9.137\mathrm{e}-09 * 700^3 = 3.134$$

$$3.276\mathrm{e}-05 * 700^2 = 16.038$$

$$0.007793 * 700 = 5.455$$

$$0.2847$$

In the second case, with the mass applied at 700mm from the fixation, the deflection is of 18.573mm, and the contribution of each of the terms are (in absolute value):

$$1.192\mathrm{e}-08 * 700^3 = 4.089$$

$$3.297\mathrm{e}-05 * 700^2 = 16.155$$

$$0.008878 * 700 = 6.215$$

$$0.2919$$

As it can be seen in Table 5, attached previously in the document, the experimental measures for the mass of 4.213kg at a distance from the fixation of 700mm, produced a deflection of 18.40mm and of 18.70mm, which is in accordance to the results obtained with the polynomials.

As two polynomials were found because two sets of measurements were taken, it was decided to find the average polynomial between them, getting a final one of:

$$\boxed{-1.053\mathrm{e}-08*x^3+3.287\mathrm{e}-05*x^2+0.008336*x+0.2883}$$

It is needed to mention that it is clear that different masses would produce different deflections, but the relation between the terms of the polynomials are expected to be alike. This behavior with other masses is not separately studied in this project because the experimental study of the cane has limitless possibilities, and having found the mentioned model, it is not considered of interest to repeat the experiment all over again for different masses to prove it. Therefore, as the cane is expected to behave in a linear elastic way, the deflection of it under the effect of other forces rather than 41,33N can be found as:

$$\boxed{\mathrm{w}=\left(-1.053\mathrm{e}-08*x^3+3.287\mathrm{e}-05*x^2+0.008336*x+0.2883\right)*\frac{\mathrm{F}}{41.33}}$$

Finally, comparing the theoretical and experimental measures, it is satisfactorily seen that the values obtained in the laboratory do not overpass the maximum analytical ones. The maximum deflection of the end of the cane, under a the effect of the mass of 4.213kg applied at its end was of 26.579mm, as it could be seen in Figure 19 attached previously in the document.

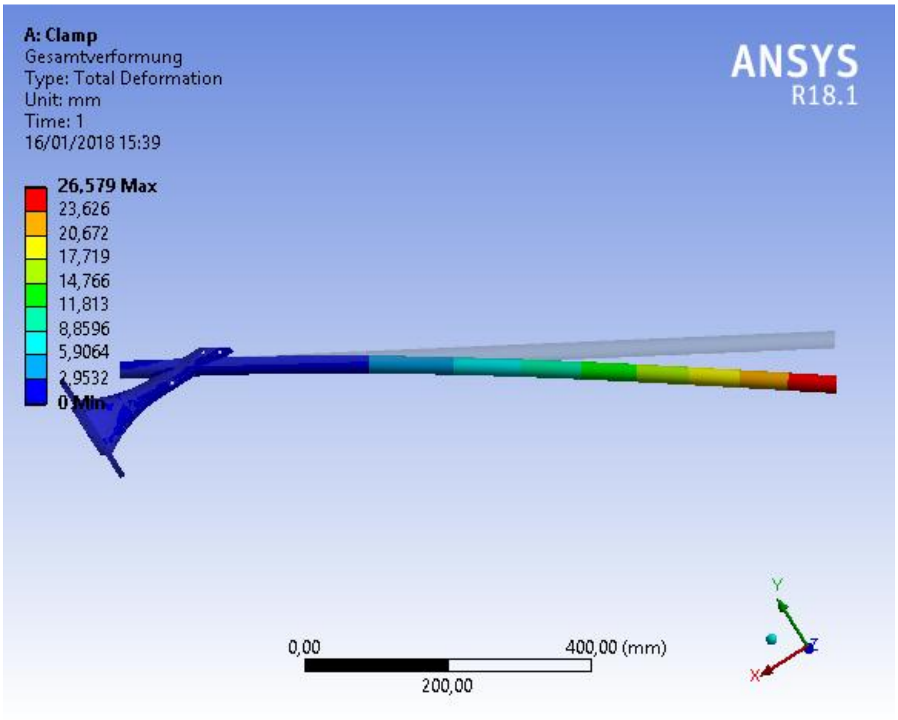


Figure 19. Maximum displacement of the end of the cane in the scenario of study

The obtained values in the laboratory for this scenario were of (in different experiments, with the cane-clamp body in its original position - 1): 23.00mm, 22.30mm, and 24.10mm, this is, satisfactorily smaller than the previous theoretical maximum value of 26.579mm.

PART 2

DETERMINATION OF THE POINT OF COLLISION

After having studied the elastic behavior of the cane-clamp object, it was considered interesting for the whole robot to be able to detect the point of the cane where the collision with the certain object is produced; this is, the point in which the force is applied to the cane.

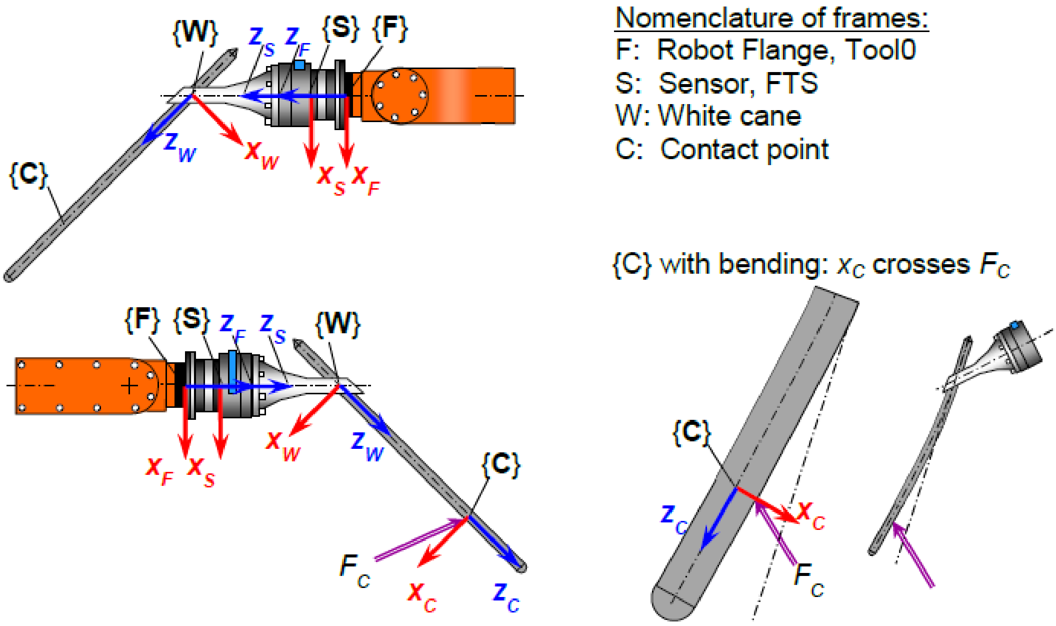


Figure 40. Cane under the effect of force applied at a certain point [10]

The sensor in the robot {S}, can measure the force that the impact with the object produces at the cane, the torque that this force generates, and the deflection that the cane suffers. However, it has been proved that due to the noise, the force that the sensor measures cannot be accepted, but the torque and the deflection are accurate enough.

Therefore, to find the point of the cane where the collision is produced, it was necessary to use simplified mechanical models.

First of all, as a first approach, the cane was considered to be a cantilever beam, and the model for finding the point of collision was derived.

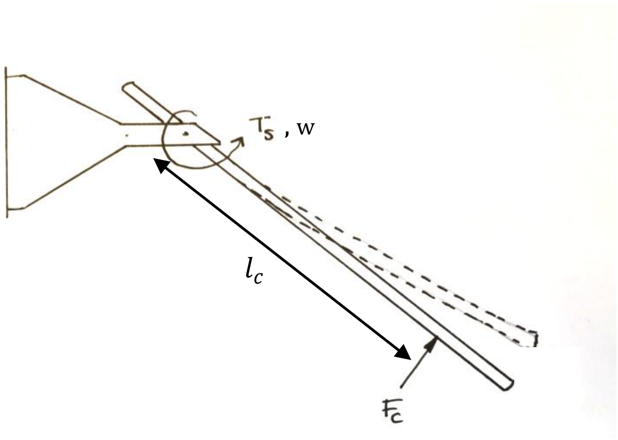


Figure 41. Simple model of the deflection of the cane under a force

The deflection (w) of a cantilever beam follows the equation:

$$w = \frac{1}{3 * E * I} * F_c * l_c^3$$

The torque (T_s) that the sensor situated in the robot measures, is equal to:

$$T_s = F_c * l_c$$

And combining both equations:

$$w = \frac{1}{3 * E * I} * T_s * l_c^2$$

Therefore, as the sensor is able to measure T_s and being w also known thanks to the robot motion controller, the distance from the application of the force to the fixation, as well as the force, can be derived.

$$l_c^2 = \frac{w * 3 * E * I}{T_s}$$

$$F_c = \frac{T_s}{l_c}$$

Knowing the Tensile modulus of the used aluminum alloy $E = 71GPa$, and the area moment of inertia (I) of the cylindrical cane,

$$I = \frac{\pi}{4} * \left(r_{out}^4 - r_{in}^4\right) = \frac{\pi}{4} * (12{,}5^4 - 11{,}5^4) = 5.438{,}1mm^4$$

numerical values can be given.

For example, being the measured torque $T_s = 30Nm$, and the deflection $w = 14{,}5mm$, the corresponding l_c and F_c would be:

$$l_c = \sqrt{\frac{0{,}0145 * 3 * 71 * 10^9 * 5{,}4381 * 10^{-9}}{30}} = 0{,}748m = 748mm$$

$$F_c = \frac{30}{0{,}748} = 40{,}107N$$

Values that are more or less in accordance to the results obtained analytically as well as experimentally in the other parts of the project, but that differ a bit from them. It was measured that, for a force of 41,33N applied at a distance to the fixation of 750mm, the deflection of the end of the cane was of approximately 20mm. With the model developed above, the obtained deflection under the effect of a slightly smaller force, at a very similar point of application is considerably smaller (a 27,5%). This makes sense, as it is not true that the cane totally behaves as a cantilever beam; it is not as rigid. The real deflection has to be, indeed, bigger than the one obtained by this method.

Therefore, the same study will be now done, considering the mathematical model of the deflection of the cane previously found:

$$w = \left(-1.053\text{e} - 08 * {l_c}^3 + 3.287\text{e} - 05 * {l_c}^2 + 0.008336 * l_c + 0.2883\right) * \frac{F_c}{42{,}13}$$

Having T_s and w, l_c and F_c can be found once more, this time with the help of mathematical tools; in particular with the HP Prime Graphic Calculator.

$$w = \left(-1.053\text{e} - 08 * {l_c}^3 + 3.287\text{e} - 05 * {l_c}^2 + 0.008336 * l_c + 0.2883\right) * \frac{T_s}{42{,}13 * l_c}$$

$$T_s = \frac{w * 42{,}13 * l_c}{-1.053\text{e} - 08 * {l_c}^3 + 3.287\text{e} - 05 * {l_c}^2 + 0.008336 * l_c + 0.2883}$$

Giving an example, having measured that the torque is $T_s = 30Nm$, and the deflection $w = 19{,}25mm$, the result of the distance from the collision of the object to the fixation is $l_c = 725{,}23mm$, produced by a force of

$$F_c = \frac{30}{0{,}725} = 41{,}38N$$

This model, as proven above, is much more accurate than the simple cantilever beam, as the results (the force, and its distance to the fixation, in relation to the deflection) are much closer to the real ones.

PART 3

REDESIGN OF THE CLAMP

Finally, After developing the whole model and analyzing the obtained results, although they were satisfactory and close to what was expected, it was decided to improve once more the fixation. It was thought that a clamp with which the cane was fixed symmetrically would make the elastic behavior of the cane more linear, not so direction-dependant, and therefore more reliable and predictable. For this purpose, several supplements for the original clamp were designed and simulated with Solid Edge®. The first suggested one can be seen in Figures 42 and 43.

Figure 42 . Whole body with added clamp (D1) simulation

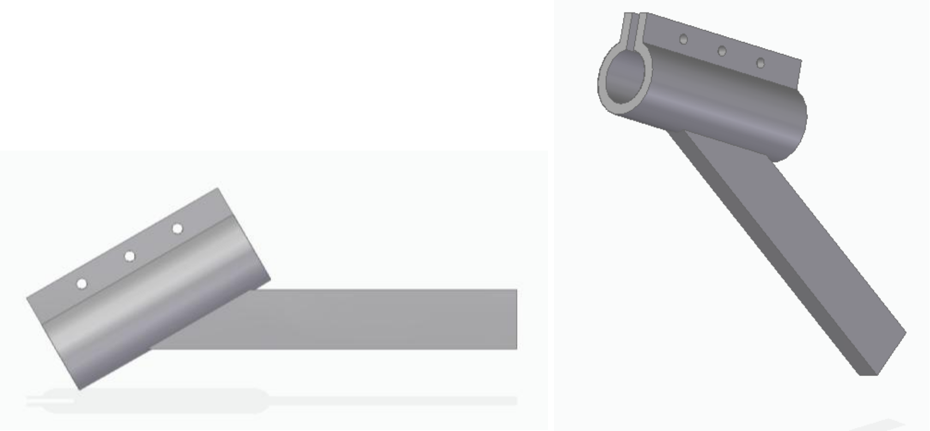


Figure 43. New added clamp (D1) simulation

However, manufacturing it would have been more expensive and taken more time than desired. Thus, a new model, easier to manufacture as it just consisted in plates, screws, boring and milling, was designed. It is shown in Figure 44.

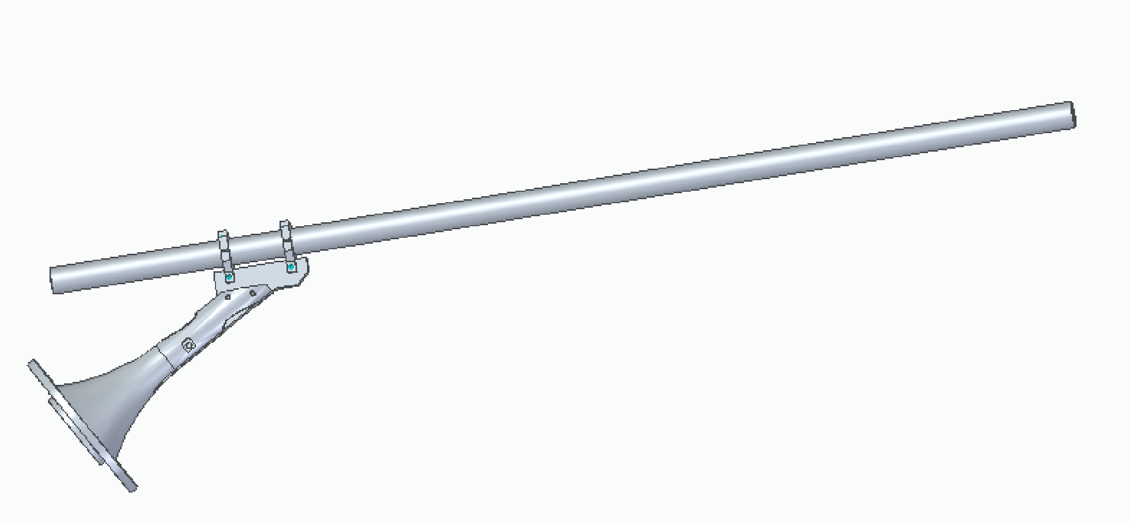
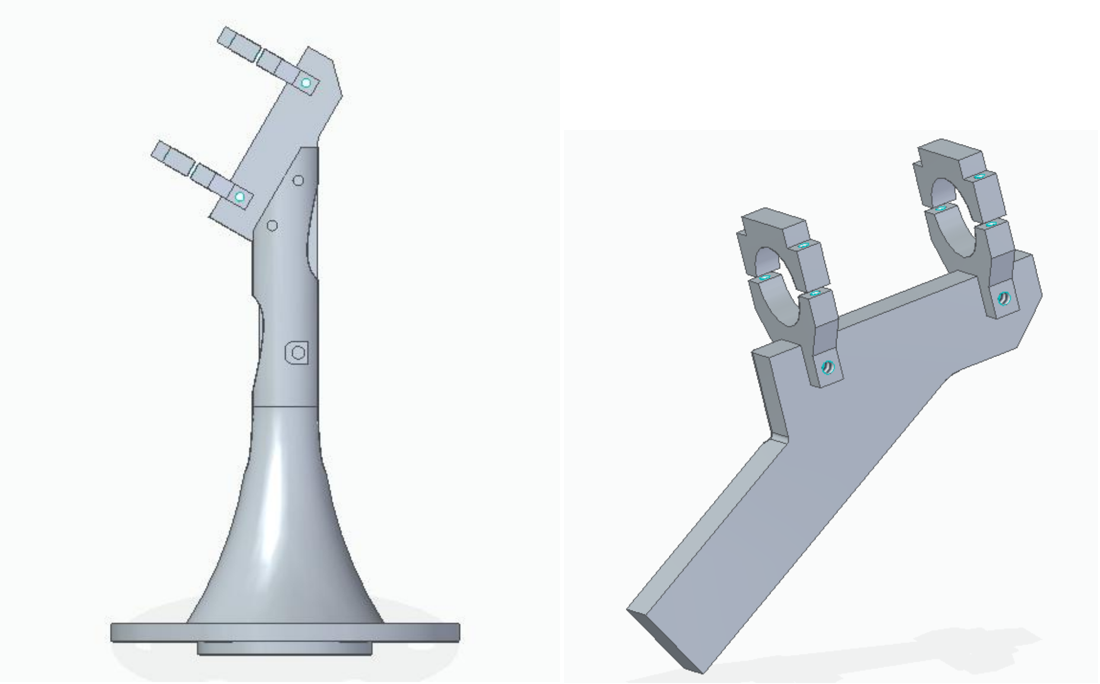


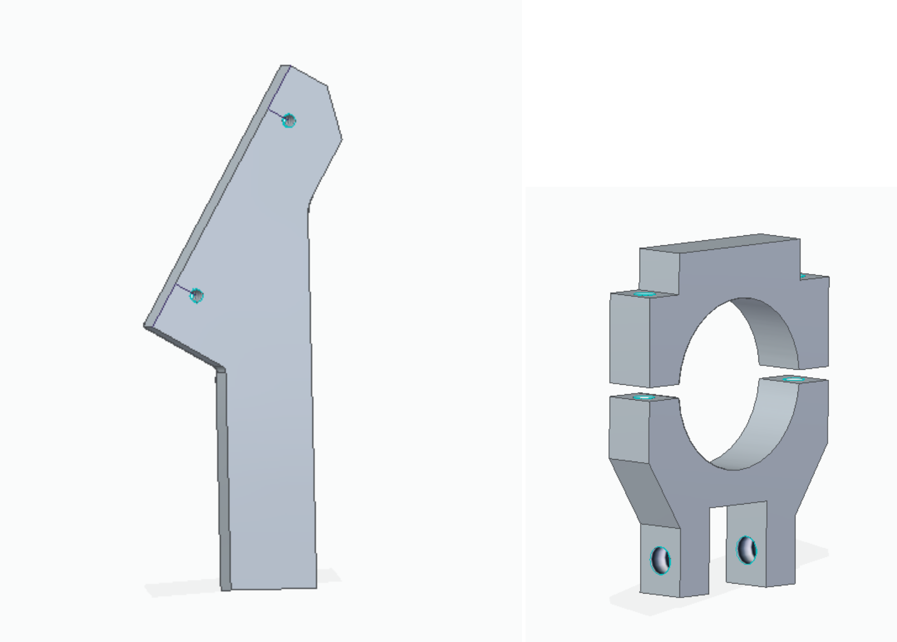
Figure 44. New added clamp (D2) whole body' simulation

More in detail, it consists in the following add-on, fixed to the original clamp shown in Figures 45 and 46.



Figures 45 and 46. New slot plate (D2)

This add-on, is, in particular, composed of the following parts shown in Figures 47 and 48, held to each other by M5 screws. Each of the parts of the upper fixation are connected by M4 screws.



Figures 47 and 48. New slot plate + upper fixations in detail (D2)

The first intention was to have it conveniently manufactured, but there was not as much time as expected, and therefore it was not possible to re-do the studies with this new, more elegant, more accurate fixation. This new task will be left for the following students of the MCI.

The detailed measurements and isometric views of each component, and of the whole bodies, can be seen in the structural plans attached at the end of the document

DOCUMENT II

-

STRUCTURAL PLANS

INDEX OF DOCUMENT II – STRUCTURAL PLANS

1. STRUCTURAL PLANS OF THE WHOLE ROBOT *[11]*

1.1 Overview

KR60HA is a 6-axis articulate arm robot made by KUKA Company, see Figure 1-1:

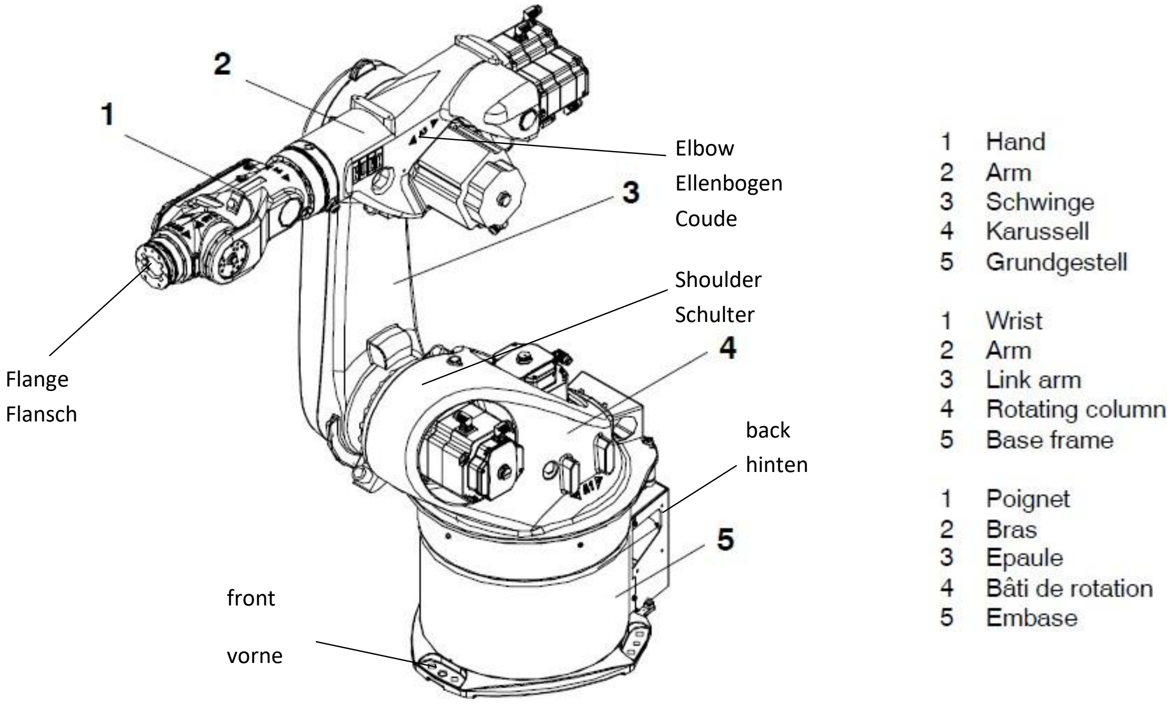


Figure 1-1: KUKA KR60 robot mechanical configuration

1.2 Dimensions and Frames

Figure 1-2 shows the KR60 robot and its main dimensions in a configuration where all joint angles Θ_1 to Θ_6 have zero value following the original Denavit-Hartenberg convention.

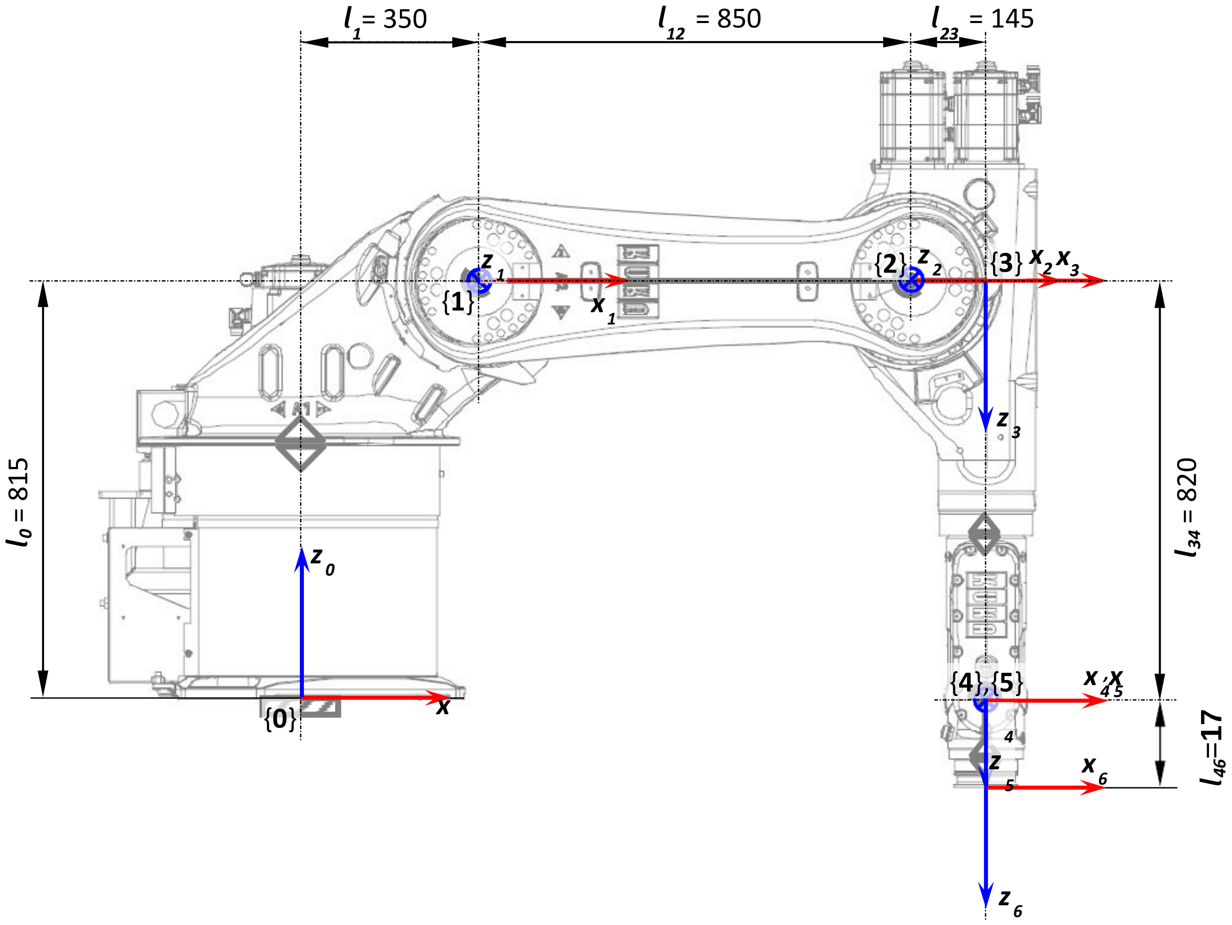
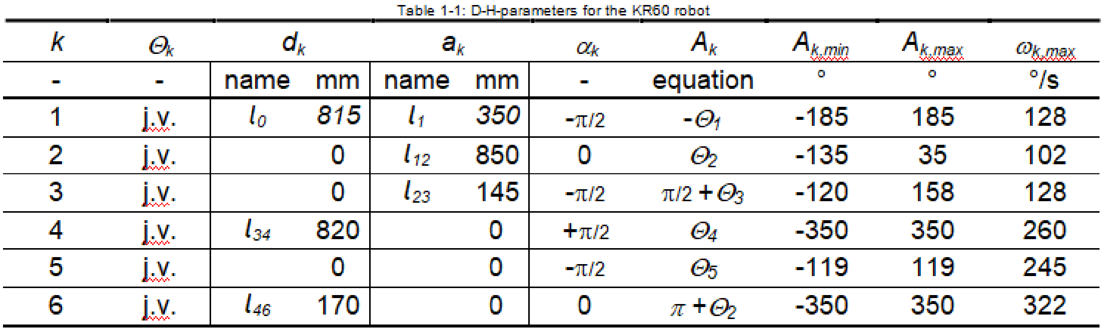


Figure 1-2: Frames and Dimensions in D-H-Configuration

Denavit-Hartenberg parameters

The following table gives the Denavit-Hartenberg parameters Θ, d, a, α for the joints k=1…6 along with the robot axis angles A, angular ranges A_{min}, A_{max} and max angular speed ω_{max}.

Table 1-1: D-H-parameters for the KR60 robot



k	Θ_k	d_k		a_k		α_k	A_k	$A_{k,min}$	$A_{k,max}$	$\omega_{k,max}$
-	-	name	mm	name	mm	-	equation	°	°	°/s
1	j.v.	l_0	815	l_1	350	$-\pi/2$	$-\Theta_1$	-185	185	128
2	j.v.		0	l_{12}	850	0	Θ_2	-135	35	102
3	j.v.		0	l_{23}	145	$-\pi/2$	$\pi/2+\Theta_3$	-120	158	128
4	j.v.	l_{34}	820		0	$+\pi/2$	Θ_4	-350	350	260
5	j.v.		0		0	$-\pi/2$	Θ_5	-119	119	245
6	j.v.	l_{46}	170		0	0	$\pi+\Theta_2$	-350	350	322

1.3 Kinematics and frames in 2D views

The corresponding kinematic schematic is drawn in Figure 1-3.

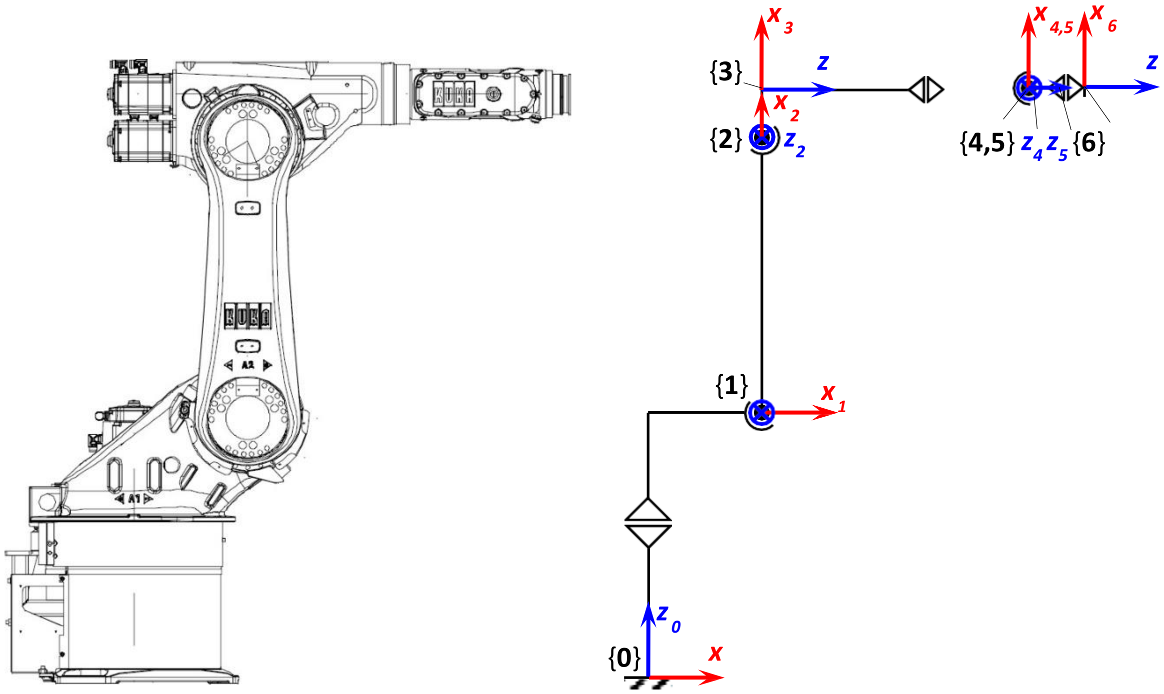


Figure 1-3: standard robot pose: view from right side, kinematics and frames

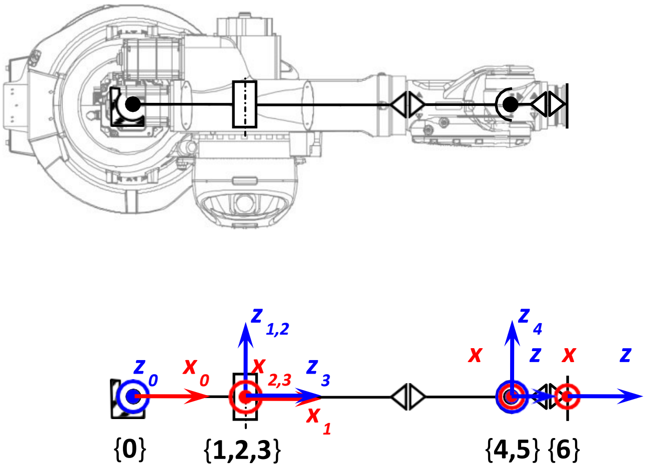


Figure 1-4: standard robot pose: top view with kinematics

1.4 Frames in 3D

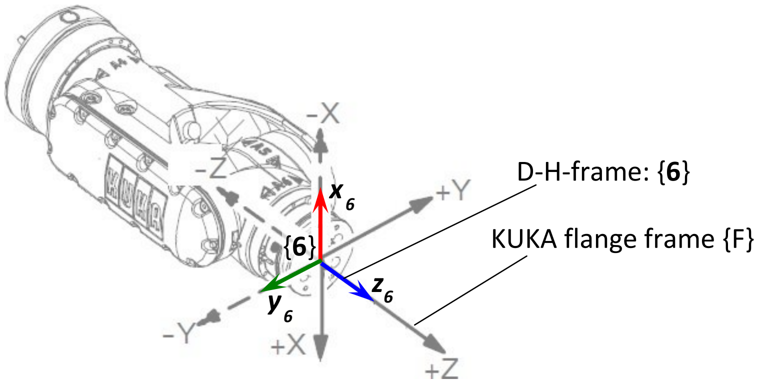


Figure 1-5: KUKA flange frame vs. D-H-frame {6}

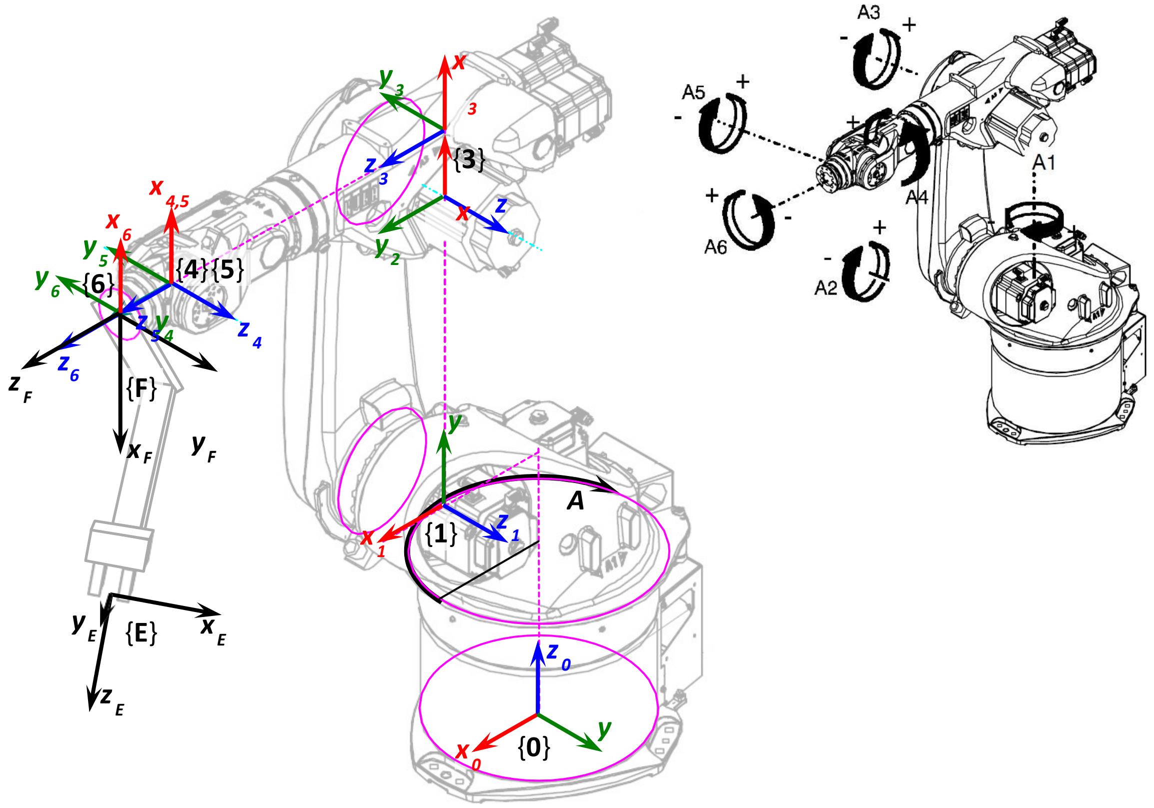


Figure 1-6: ISO view with 3D frames and anomalies: Axis 1 angle, Flange-frame

The complete chain of 3D frames:

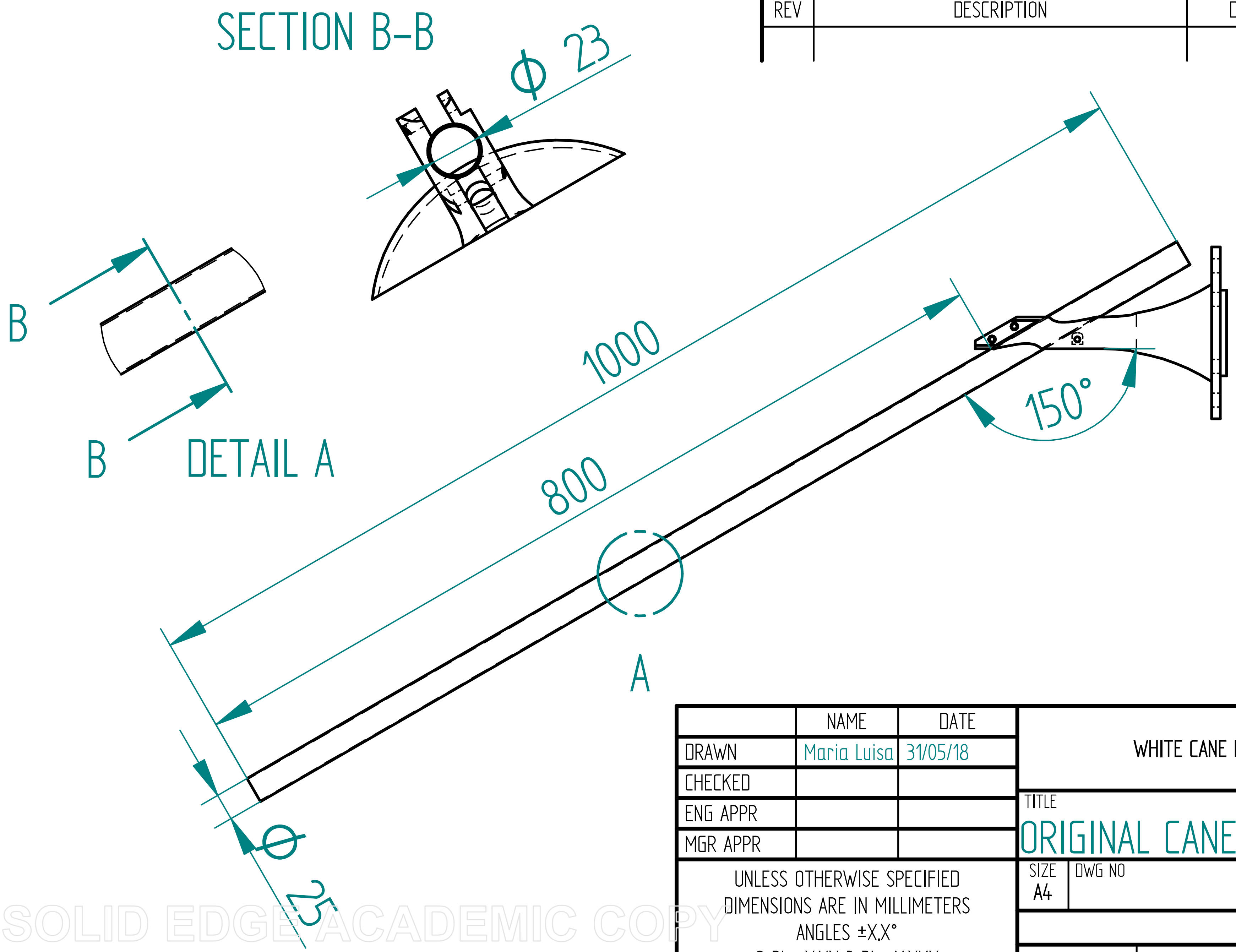
$$\{0\} \rightarrow \{1\} \rightarrow \{2\} \rightarrow \{3\} \rightarrow \{4\} \rightarrow \{5\} \rightarrow \{6\} \rightarrow \{F\} \rightarrow \{E\}$$

2. STRUCTURAL PLANS OF THE ORIGINAL CLAMP + CANE

In the following pages, the structural plans of the original cane-clamp body are shown, They consist in a plan of the whole assembly of the body, and another one, more detailed, of the clamp. In this last one, and due to its very complex structure, only the most relevant dimensions are included. The aim is not to be able to manufacture an equal one, but to understand its structure.

REVISION HISTORY

REV	DESCRIPTION	DATE	APPROVED



	NAME	DATE
DRAWN	Maria Luisa	31/05/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

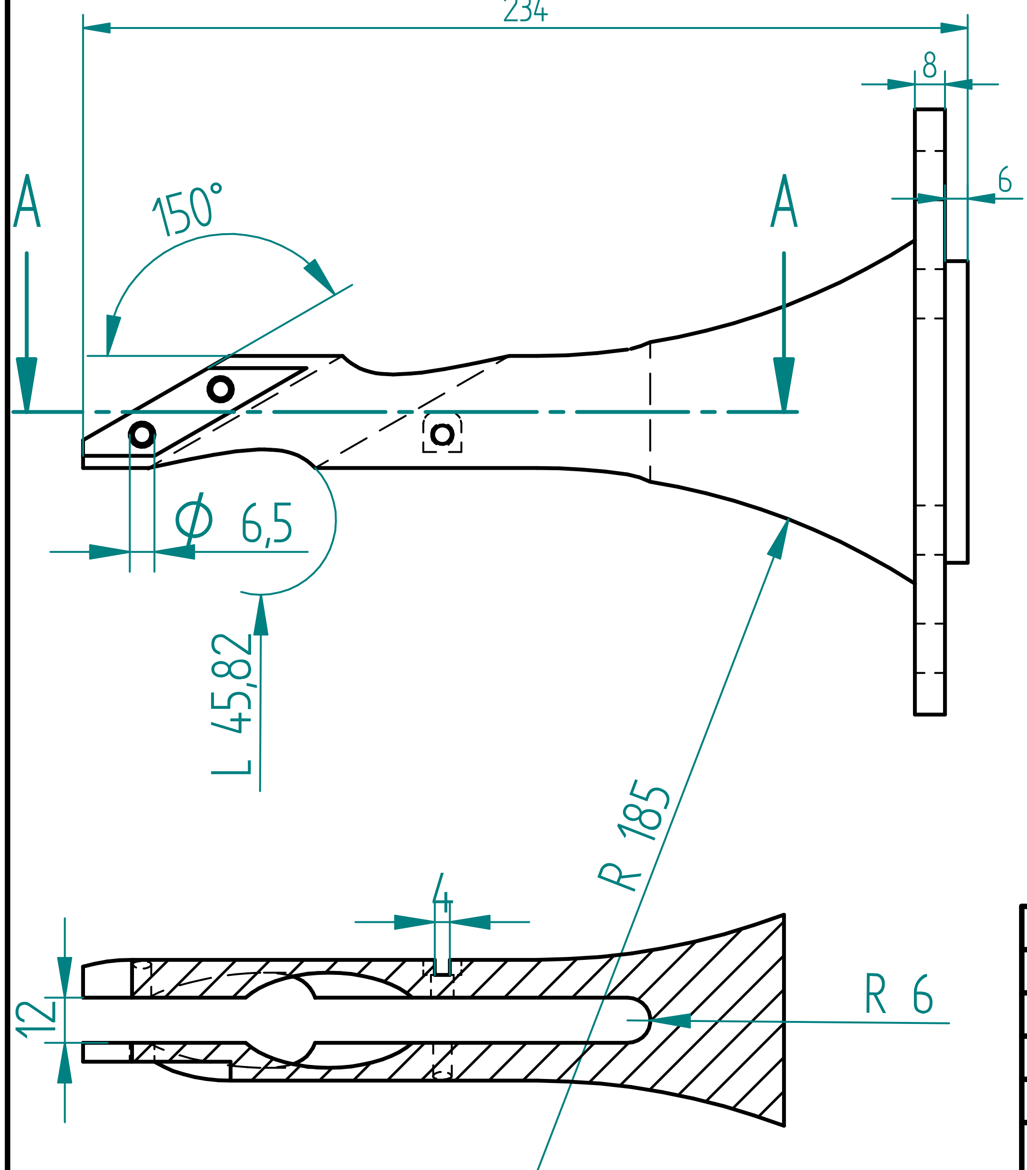
TITLE
ORIGINAL CANE-CLAMP BODY

SIZE	DWG NO	REV
A4		

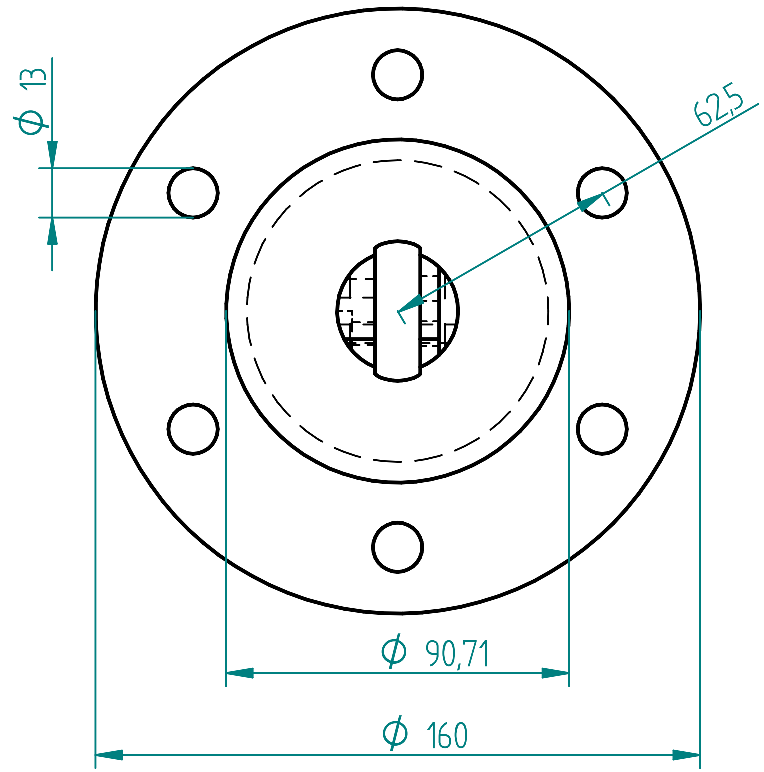
SCALE: 1:5

SHEET 1 OF 1

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED



SECTION A-A



	NAME	DATE
DRAWN	Maria Luisa	11/06/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

TITLE ORIGINAL CLAMP

SIZE A4
DWG NO
REV

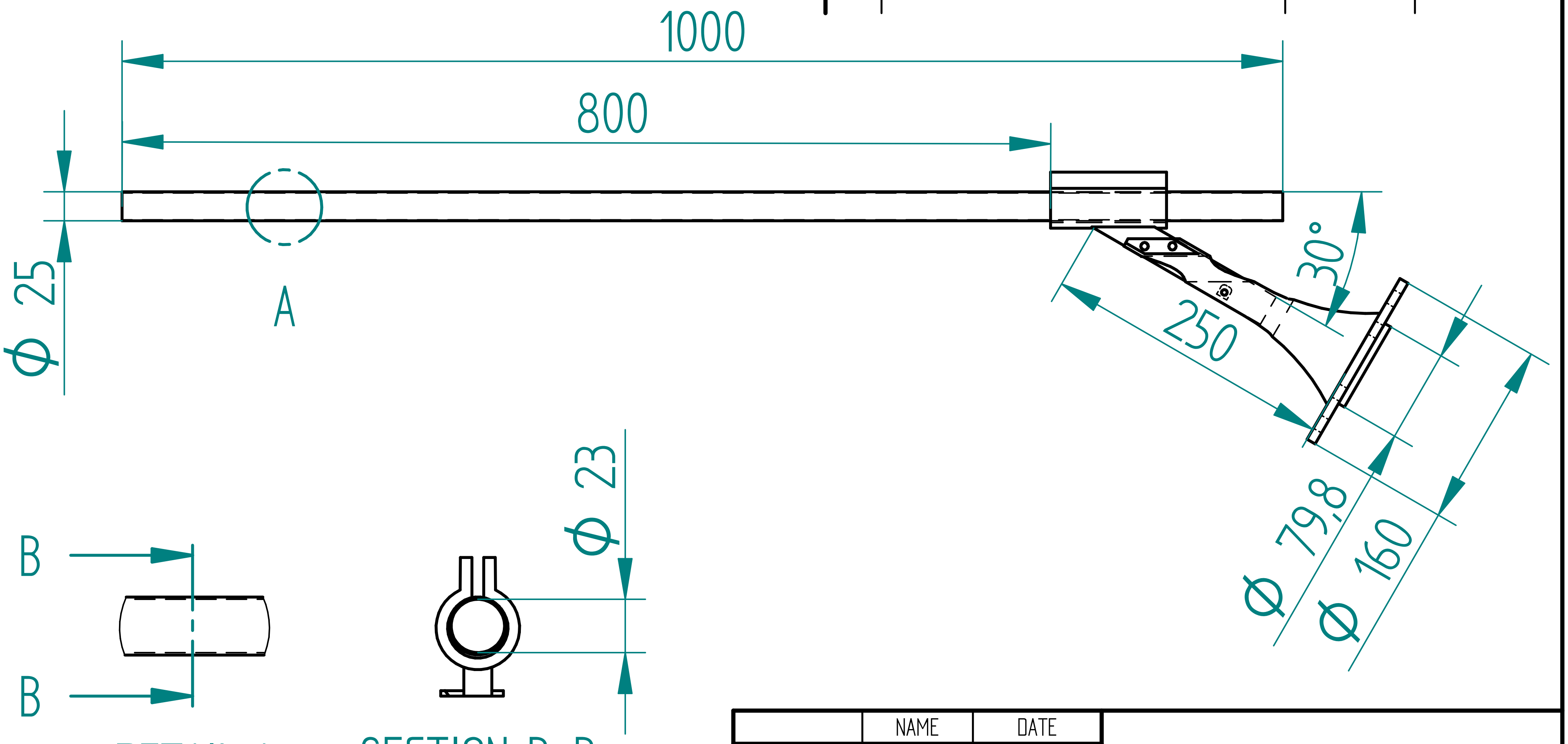
FILE NAME: Adapterflansch.dft

SCALE: 1:2
SHEET 1 OF 1

3. STRUCTURAL PLANS OF THE FIRST REDESIGN OF THE CLAMP + CANE

In the following pages, the structural plans of the first redesign done of the clamp are shown, They consist in a plan of the whole assembly of the body, and another, more detailed, of the designed piece.

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED



DETAIL A

SECTION B–B

	NAME	DATE
DRAWN	Maria Luisa	31/05/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

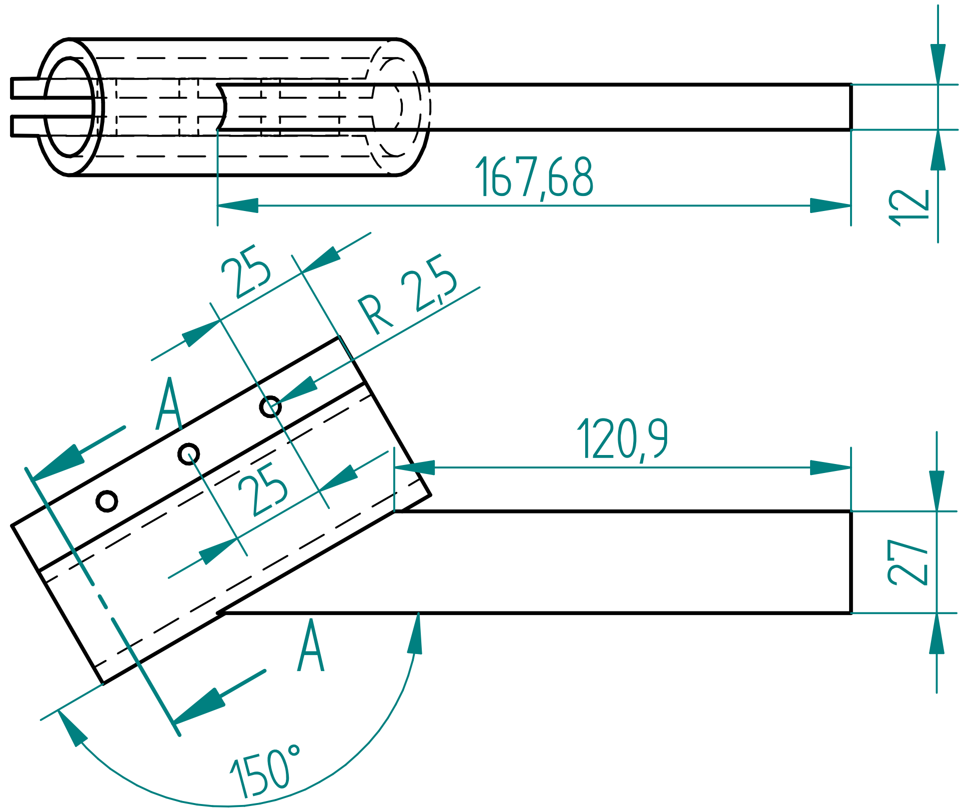
TITLE
WHOLE BODY (DESIGN I)

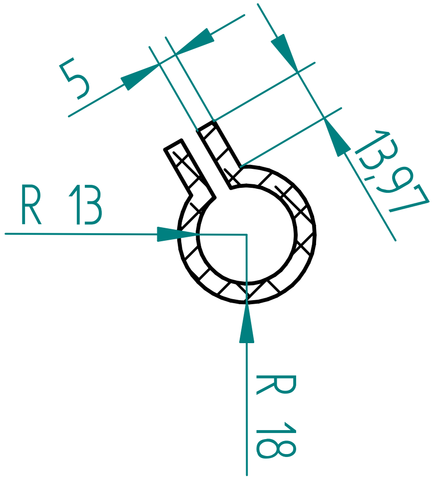
SIZE	DWG NO	REV
A4		

SCALE: 1:5	WEIGHT:	SHEET 1 OF 1

REVISION HISTORY

REV	DESCRIPTION	DATE	APPROVED





SECTION A-A

	NAME	DATE
DRAWN	Maria Luisa	11/06/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

TITLE
ADDED CLAMP (DESIGN I)

SIZE	DWG NO	REV
A4		

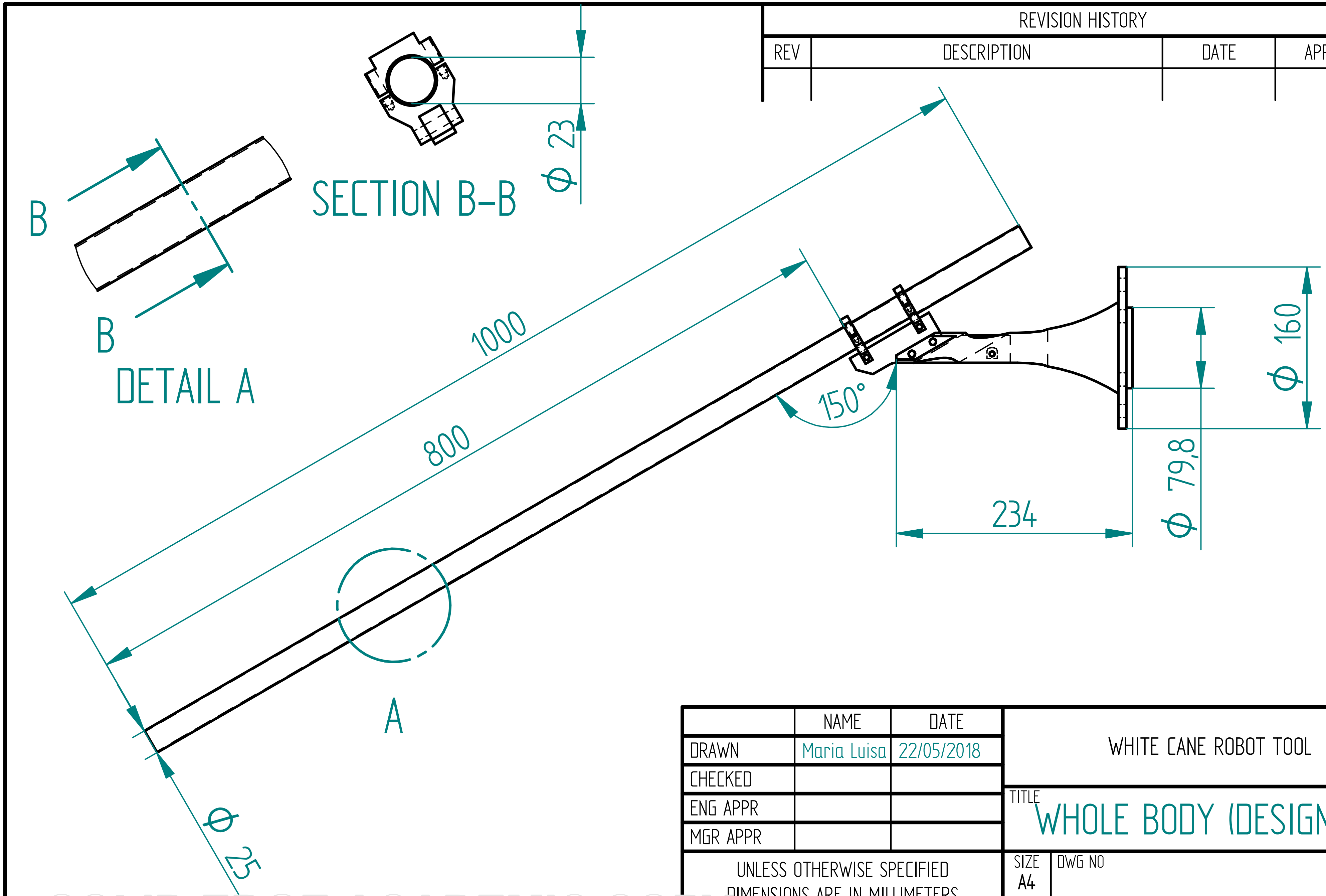
FILE NAME: new clamp (I).dft

SCALE: 1:2
SHEET 1 OF 1

4. STRUCTURAL PLANS OF THE SECOND REDESIGN OF THE CLAMP + CANE

In the following pages, the structural plans of the second redesign done of the clamp are shown, They consist in a plan of the whole assembly of the body, and two others, more detailed, of the designed pieces (slot plate and clamps for the slot).

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED



	NAME	DATE
DRAWN	Maria Luisa	22/05/2018
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

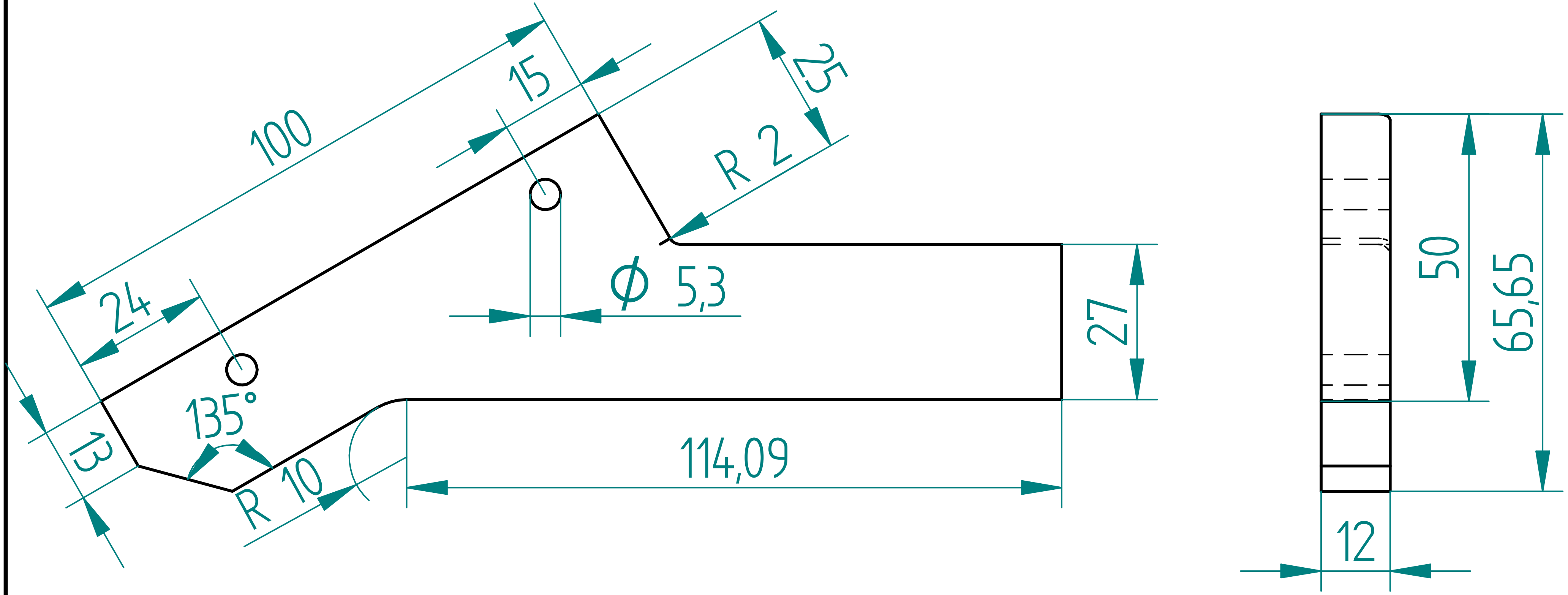
WHITE CANE ROBOT TOOL

TITLE
WHOLE BODY (DESIGN II)

SIZE	DWG NO	REV
A4		

SCALE: 1:5
SHEET 1 OF 1

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED



	NAME	DATE
DRAWN	Maria Luisa	11/06/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

TITLE
SLOT FOR CLAMPS (DESIGN II)

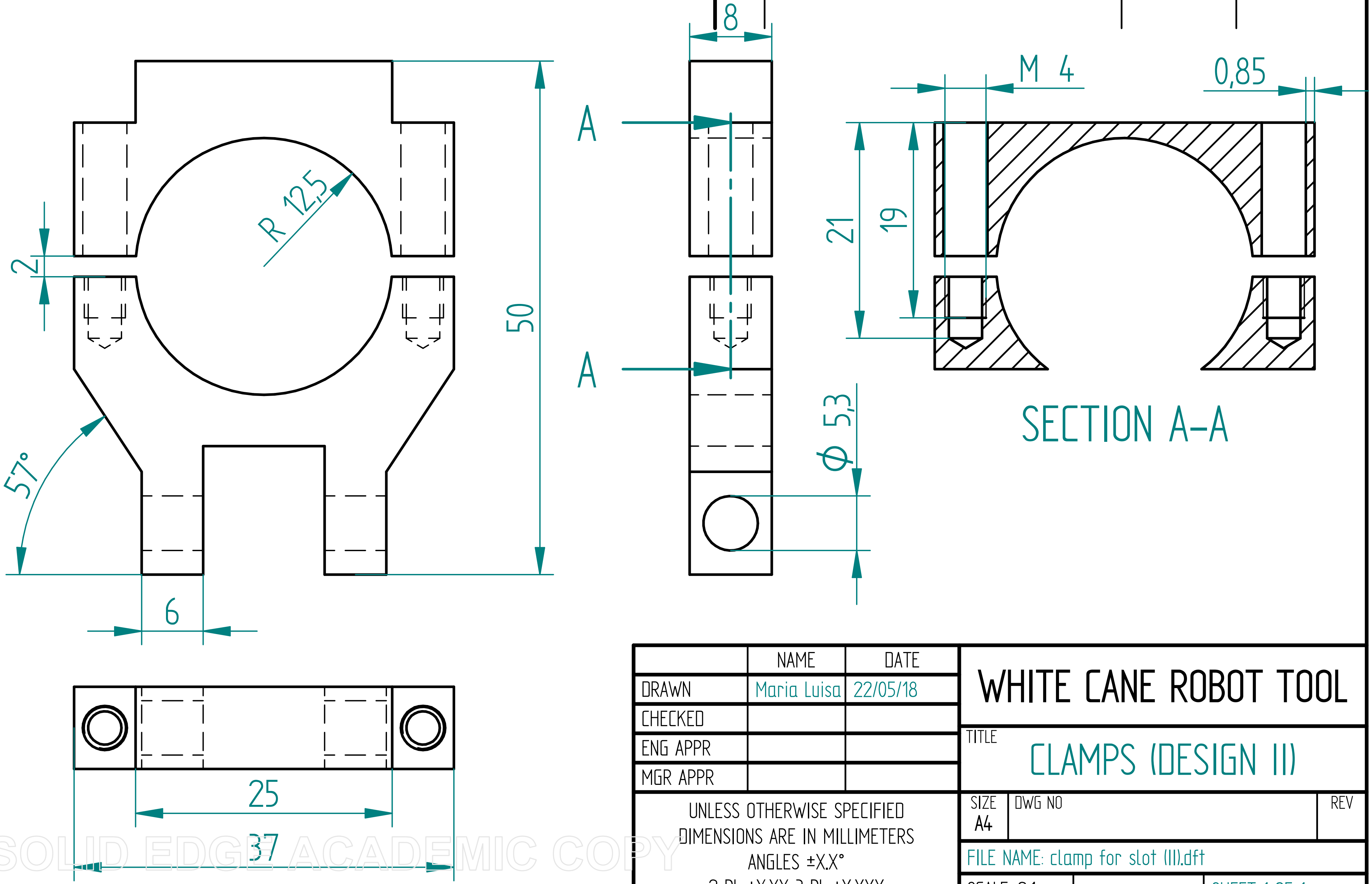
SIZE	DWG NO	REV
A4		

FILE NAME: slot plate.dft

SCALE: 1:1
SHEET 1 OF 1

REVISION HISTORY

REV	DESCRIPTION	DATE	APPROVED



	NAME	DATE
DRAWN	Maria Luisa	22/05/18
CHECKED		
ENG APPR		
MGR APPR		

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

WHITE CANE ROBOT TOOL

TITLE
CLAMPS (DESIGN II)

SIZE A4
DWG NO
REV

FILE NAME: clamp for slot (II).dft

SCALE: 2:1
SHEET 1 OF 1

DOCUMENT III

-

BUDGET

The robot was built in 2008 and bought by Management Center Innsbruck in 2010. The price of it, including FTS, pedestal, manual tool changer was of approximately 40.000,-€.

Around the robot, there is a safety zone built, which consists in several walls of glass with an electric door that opens with a remote control. This safety zone robot was built for approximately 20.000,-€, in 2014. One year later it was necessary to do some repair work, for the cost of 1.000,-€.

Summing it all up, the investments on the robot and the projects that revolve around it have been of about 61.000,-€.

At the moment there is no budget and no planned investment on the robot.

REFERENCES

[1] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "171002 Project Architecture.pdf", 2017

[2] Yield Strength Diagram: *http://www.gunook.com/schritte-zur-analyse-der-eigenschaften-eines-materials-aus-seiner-belastungs-dehnungs-kurve/*

[3] Basic mechanics/Wikispace (esfuerzo normal y de corte) *https://basicmechanics.wikispace.com/Tema+5+Esfuerzo+normal+y+de+corte*

[4] Universidad Pontificia de Comillas – ICAI – Engineering of Materials Department's Documents.

[5] Auckland University Department of Mechanical Engineering Repository *http://slideplayer.com/slide/9995638/*

[6] Tactile Robot – Project Architecture S. Repetzki, October 2017

[7] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "Elastic Behavior.pdf", 2017

[8] Mathworks help: polyfit *https://es.mathworks.com/help/matlab/ref/polyfit.html?searchHighlight=polyfit&s_tid=doc_srchtitle*

[9] Mathworks help: polyval *https://es.mathworks.com/help/matlab/ref/polyval.html?searchHighlight=polyval&s_tid=doc_srchtitle*

[10] Sebastian Repetzki, Management Center Innsbruck. Internal draft documentation "Elastic Behavior.pdf", 2017

[11] MCI – Mechatronik – Course: PRO2 – WS17/18 S. Repetzki, 05.11.2017. Document: "KUKA KR60HA. Denavit-Hartenberg parameters, direct, inverse and pseudo-inverse kinematics"