TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

DEVELOPING A MULTIPURPOSE MACHINE VISION TEST BENCH WITH A ROBOTIC ARM

ROBOTKÄEGA MITMEOTSTARBELISE MASINNÄGEMISE KATSESTENDI ARENDUS

MASTER THESIS

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Co-supervisor: Viktor Rjabtšikov, Early Stage Researcher

Tallinn 2023

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ABSTRACT

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Abstract:

The main purpose of the thesis is to create a universal machine vision test bench for research, with the help of which it will be possible to reproduce various environmental conditions to study the different ways how an industrial manipulator perceives the world. The idea of this project was born from finding some problems in this field, such as the problem that ambient light creates shadows that are not previously registered, making it a completely unknown object for recognition, or an inappropriate wavelength for the camera which is in use. Therefore, for the development of this project, a detailed search was carried out on what solutions are currently proposed in the market and it was decided to create a test bench right from the start based on the desired requirements and supported by calculations. On the other hand, throughout this project several simulations are carried out in DIALux evo to determine the configuration of the appropriate lighting system based on the cameras that are used. Finally, designs of electrical circuits are also made where different ways of feeding the lights and the camera are proposed.

This project is focused on the UR5 robotic arm located at the Tallinn University of Technology but, in the future, this project can be scalable to any robotic arm that works based on machine vision.

Keywords: robotic arm, design, machine vision, hyperspectral imaging, test bench, lighting system.

LÕPUTÖÖ LÜHIKOKKUVÕTE

Autor: Laura Garrido Cediel *Lõputöö liik:* Magistritöö

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Töö juhendaja(d): Daniil Valme and Viktor Rjabtšikov

Töö konsultant (konsultandid): Toivo Varjas

Sisu kirjeldus:

Lõputöö põhieesmärk on luua teadustööks universaalne masinnägemise katsestend, mille abil on võimalik reprodutseerida erinevaid keskkonnatingimusi, et uurida erinevaid viise, kuidas tööstusmanipulaator maailma tajub. Selle projekti idee sündis selles valdkonnas mõningate probleemide leidmisest, nagu probleem, et ümbritsev valgus tekitab varje, mida pole varem registreeritud, muutes selle äratundmiseks täiesti tundmatuks objektiks või kasutatava kaamera jaoks sobimatu lainepikkus. . Seetõttu viidi antud projekti arendamiseks läbi põhjalik otsing, milliseid lahendusi hetkel turul pakutakse ning otsustati kohe alguses luua soovitud nõuetest lähtuvalt ja arvutustega toetatud katsestend. Teisest küljest tehakse selle projekti jooksul DIALux evo-s mitmeid simulatsioone, et määrata kasutatavate kaamerate põhjal sobiva valgustussüsteemi konfiguratsioon. Lõpuks tehakse ka elektriskeemide projekte, kus pakutakse välja erinevaid viise tulede ja kaamera toitmiseks.

See projekt keskendub Tallinna Tehnikaülikoolis asuvale robotkäele UR5, kuid tulevikus saab seda projekti skaleerida igale masinnägemisel töötavale robotkäele.

Märksõnad: robotkäsi, disain, masinnägemine, hüperspektraalne pildistamine, katsestend, valgustussüsteem.

THESIS TASK

Thesis title in English:	**Developing of multipurpose machine vision test bench with a robotic arm**
Thesis title in Estonian:	**Robotkäega mitmeotstarbelise masinnägemise katsestendi arendus**
Student:	**Laura Garrido Cediel, 214146MAHM**
Programme:	**MSc Mechatronics**
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Validity period of the thesis task:	**Validity period is given by supervisor** 2022/2023 2022/2023 Spring
Submission deadline of the thesis:	**18.05.2023**

Supervisor (signature) Student (signature) Head of programme (signature)

Co-supervisor (signature)

1. Reasons for choosing the topic

Achieving favorable conditions for the machine vision implementation in robotic arms is very important but it is a challenging task since several factors can influence on it, such as lighting or the type of camera used. These factors vary depending on the purpose, such as identifying the position of the object, identifying its color or knowing the material from which it is made. In addition, one of the biggest problems we find in this field is getting the object to be detected under any situation and this is sometimes not possible due to the interference of ambient light or other factors

Currently, in the industry, it is possible to find test benches designed for a specific task, but if that task later changes, this test bench will no longer serve. For this reason, this thesis focuses on designing a multifunctional test bench for a robotic arm that can be used for a wide range of machine vision operations, including the ones mentioned above. In this way, small and large companies could use a single test bench to perform different tasks, instead of having to buy a specific one for each task.

2. Thesis objective

The aim of this thesis is to create a universal machine vision test bench for research, with the help of which it will be possible to reproduce various environmental conditions to study the different ways how an industrial manipulator perceives the world. In this way, we will get the manipulator to be able to deal with any type of object after knowing some aspects of them, such as their size, positioning, and material, among others.

3. List of sub-questions:

How should the design of the test bench of the robotic arm be so that it meets the desired specifications?
What is the suitable location for each camera used in the project to obtain the required results?
What is the needed lighting system for the machine vision to be able to carry out all these tasks?
How to prevent natural light from interfering with the robot's operations when using machine vision?

4. Basic data:

The data needed related to the robotic arm will be found in the documentation provided by the manufacturing company, Universal Robots, as well as its CAD drawings. For getting data related to light sources or the cameras, their datasheets would be especially useful. Also, standards would be taken into account.

In addition, in order to collect information about current applications in the industry related to this topic, it will be used different internet sources such as IEEE, Springer and ResearchGate.

5. Research methods

Based on the literature review it will be possible to conclude which components should be selected and which design patterns must be considered during the development of this project. Also, while designing the test bench, the measurements of the robot and the desired requirements will be taken into account. Also, calculations will be carried out to determine if the final structure is stable.

In addition, simulations would be carried out such as mechanical deflation testing once the test bench design will be finished and also simulations related to the lighting system.

6. Graphical material

For this project, the graphical material will be useful such as the technical drawings of the robotic arm, the CAD file of the test bench design, graphs from the simulations and connection diagrams for the light system.
These graphical elements will be part of the main work and, in addition, they will be attached to the appendixes.

7. Thesis structure

1. Introduction
2. Literature review and background
    - 2.1 Robotic arms
    - 2.2 Test bench for robotic arm
    - 2.3 Implementation of machine vision
        - 2.3.1 Lighting systems used in market
        - 2.3.2 Cameras used in machine vision
        - 2.3.3 Design of a test bench
3. Design of the lighting system
4. Choosing the location for cameras
5. Design of the test bench
    - 5.1 First drawings
    - 5.2 Simulations
        - 5.2.1 Stress test simulation of the test bench
        - 5.2.2 Lighting system simulation
    - 5.3 Final design
6. Building process
7. Tests of the setup and analysis
8. Conclusion
9. References
10. Appendices

8. References

The research will be mainly focused on related articles on the subject as well as on books and scientific reports. European standards and manufacturers' datasheets will also be taken into account. Some of the examples are shown below:

’A parctical guide to machine vision lighting’. Engineer Ambitiously.

UR5 Technical specifications - Universal Robots.

Design of aluminium structures. Introduction to Eurocode 9 with worked examples. Brussels, 2020.

9. Thesis consultants

Toivo Varjas, lighting technology expert at TalTech University.

10. Work stages and schedule

Task	**Month**
Literature review draft	15th Nov – 20th Dec
Literature review definitive	19th Feb
Design of the lighting system	19th Feb – 5th Mar
Choosing location for cameras	19th Feb – 5th Mar
Designing the test bench	5th Mar – 19th Mar
Bill of materials	19th Mar
First draft to supervisors	16th Apr
Building the universal test bench	17th Apr – 1st May
Tests and analysis	17th Apr – 7th May
Last version to supervisors	7th May
Thesis submission	18th May 12:00
Submission of the thesis document	26th May
Thesis defence	3rd – 4th June

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

3D	3 Dimensional
EN	European Standards
HSI	Hyperspectral Imagine
LED	Light Emitting Diode
MDF	Medium Density Fibreboard
RGB	Red, Green and Blue
SCARA	Selective Compliance Articulated Robot Arm
SWIR	Short Wave Infrared

1 INTRODUCTION

Nowadays, the robotics sector is booming and constantly developing since it makes life easier for people. We can find countless cases that affirm this, such as in the industry sector where robotic arms can perform repetitive or dangerous tasks, preventing a human from having to do them for hours.

Currently, attempts are being made to implement other tools on robotics to make it even more interesting and useful, such as machine vision. Machine vision, applied to robotic arms, makes the tasks performed more accurate and efficient, since it can visualize the object and acting on that information. Achieving favourable conditions for the machine vision is very important but it is a challenging task since several factors can influence on it. That is why one of the first questions that arise when designing a machine vision system is which objects are the targets. This is because depending on the colour of the object or the material that is manufactured, it will be necessary to apply certain lighting conditions or a different camera. Currently in the industry, it is possible to find test benches designed for a specific purpose, but if that purpose later changes, this test bench will no longer serve.

In addition, one of the biggest problems we can find in this field is getting the object to be detected under any situation and this is sometimes not possible due to the interference of ambient light or other factors such as wavelength of the light used applied in the camera. This has been verified in previous tests carried out at the university where the natural light that penetrates through the windows created shadows on the test bench, and therefore, machine vision was not capable of relating the image obtained with the real object, making it impossible to identify it. Without this base, as it is understandable, the robotic arm will not be able to continue with the tasks for which it has been programmed.

For this reason, this thesis focuses on designing a multifunctional test bench for a robotic arm that can be used for a wide range of machine vision operations, including the ones mentioned above. This project will be focused on a new robotic arm located at the Tallinn University of Technology but in the future, this project will be scalable to any robotic arm that works based on machine vision.

2 LITERATURE REVIEW AND BACKGROUND

2.1 Robotic arms

A robotic arm is a set of mechanisms that constitute a mechanical arm, usually programmable, capable of performing similar tasks to those of a human arm [1].

Figure 2.1 Robotic arm [2].

In the current market we can find four main types of robotic arms depending on the movement that they can perform. First, we have the articulated robots, which are the most common ones, and they can perform tasks that requires to be operated in non-parallel planes. Second, we have the SCARA robots which are designed to work between parallel planes [3]. Third, we have cartesian robots which are able to perform movements in a 3D coordinate plane due to they are formed by three linear actuators [4]. And the last type, the cylindrical robots which are able to operate in a cylindrical space because they are composed of one vertical axis, one horizontal axis and they are able to rotate around the vertical axis.

The robotic arm on which we are going to work in this project is the UR5 robot of the Universal Robots brand (Figure 2.2) since it is the robotic arm available at Tallinn University of Technology and on which the entire project is focused. This robot belongs to the group of articulated robots previously explained and its main characteristics are shown in Table 2.1.

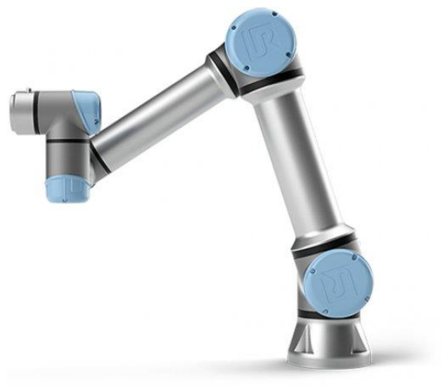


Figure 2.2 UR5 robot from Universal Robots company [5]

Table 2.1 Main characteristics from robot UR5 from Universal Robots company [6]

Parameter	**Value**
Freedom degree	6
Speed	1 m/s
Payload	5 kg
Reach	850 mm
Footprint	Ø 149 mm
Repeatability	±0,1 mm
Weight	18.4 kg
Torque of base joint	150 Nm
Control box size	475 mm x 423 mm x 268 mm
Control box weight	15 kg
I/O power supply	24 V 2 A in control box and 12 V/24 V 600 mA in tool

2.2 Test bench for robotic arm

2.2.1 Current test bench

The robotic arm mentioned in the previous section is currently located on a test bench that was designed for it, but during this project it will be evaluated if this test bench meets all the desired characteristics and, if it doesn't meet them, a market research will be done to find out what are the alternatives that can be found in the market.

Relative to the current test bench, it has measurements of 947 mm x 723 mm and a height of 788 mm. The workbench has 4 idle wheels to facilitate its movement and 4 supports to leave it fixed to the ground. In addition, the control box of the robot is located in the lower zone, more or less at ground level and it carries an emergency button.

Figure 2.3 Current test bench

2.2.2 Desired requirements

The desired requirements for the test bench are the following:

- Being able to be moved without making great efforts.
- Fit through the door frame to be able to move it from one room to another.
- Be stable since the robot makes sudden movements.
- Be a safe environment so that the robot cannot interfere with the operator or with other humans.
- To have a place where it is possible to allocate the touchscreen while the robot is operating, in that way the emergency button will be more accessible.

Since this project is carried out in Estonia, a country of the European Union, in order to meet the requirement to fit through the doors, it is needed to know what the standard door measurements of the European Union are. The standard measurements for doors used in the European Union are 62,5 cm x 203 cm, 72,5 cm x 203 cm, 82,5 cm x 203 cm, 92,5 cm x 203 cm [7]. Here is the narrowest standard door, 62,5 cm, which will determine the maximum width of the test bench.

Taking these requirements into account, it is determined that the current test bench is not valid, since its dimensions are not adequate to fit through the smallest standard door in the European Union.

2.2.3 Test benches in the market

As a solution, in the market we can find from very basic test benches such as common tables, to test benches that are mobile robots, thus allowing the displacement of the robotic arm around a specific environment. In the case of this project, we are going to focus on those test benches that are similar to a table but that also have some system to be able to move it easily.

The first model that could resemble what we are looking for is the one shown in Figure 2.4. It is from the Item company, model EX-01238, and the dimensions can be chosen to what we need so it would not be a problem. In addition, the table is adjustable in height, but this model does not have wheels to facilitate its mobility. Its price is 4625,40€ [8].

Figure 2.4 EX-01238 test bench [8]

This second example is the Vention brand ME-OT-73561 v12 model. It consists of a structure with wheels, dimensions 642 x 675 x 755 mm and priced at 549,53€. It is shown in Figure 2.5.

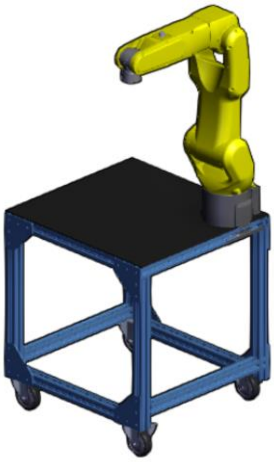


Figure 2.5 ME-OT-73561 v12 test bench [9]

The last proposed example is the EasyDeskAlu model from EasyRobotics company. It has several compartments which makes the design more complex, but it does not have wheels to facilitate movement. Its dimensions are 1200x800mm, its weight is very high, and its price is 6015€ [10].

Figure 2.6 EasyDeskAlu test bench [10]

We can observe the most relevant characteristics of the models previously presented in Table 2.2 in order to make a later analysis and make a decision.

Table 2.2 Comparative table of test bench models

Characteristics	**EX-01238 [8]**	**ME-OT-73561 v12 [9]**	**EasyDeskAlu [10]**
Design	Simple	Very simple	Complex
Dimensions	Adjustable	642x675x755 mm	1200x800mm
Wheels	No	Yes	No
Price	4625,40€	549,53€	6015€

2.2.4 Calculations for the test bench

In order to determine if a test bench is appropriate for this robotic arm, it is necessary to take into a count some calculations to determine the stability of the test bench. For this, the equilibrium condition of a rigid object will be applied [11] where the sum of the external forces of the rigid object must be equal to zero according to formula (2.1) and the sum of the external torques of the rigid object must be equal to zero according to formula (2.2). When both equations are fulfilled, the object is said to be in static equilibrium.

$$\sum F = 0 \tag{2.1}$$

$$\sum \tau = 0 \tag{2.2}$$

Regarding formula (2.1), it should be noted that to know the value of a force we must apply Newton's second law [12] where the definition of a force is described by formula (2.3).

$$F = m \cdot a \tag{2.3}$$

On the other hand, regarding formula (2.2), it should be noted that to know the value of the torque produced by a force, formula (2.4) must be applied, where said force F is multiplied by the distance r between the axis of rotation and the point where the force is produced and by the sine of the angle θ formed between the force vector and the distance vector [13].

$$\tau = F \cdot r \cdot sin\theta \tag{2.4}$$

2.3 Implementation of machine vision

One of the goals of this project is to create an environment to ensure that the robot on which we are going to work is capable of detecting objects by itself through machine vision. Machine vision can be defined as a technology that makes it possible for a computer to be able to recognize objects by analysing images. In short words, it is the ability of a computer to “see” [14].

In today's industry we can find a large number of different models of robotic arms that have machine vision systems implemented. This is due to the fact that its applications in the market are practically infinite, from detecting an object for its subsequent displacement to visualizing a surface where a welding operation must be carried out. For this reason, it has been decided that this technology must be implemented in the robot in which we are going to work in this project. In this way, it will be able to detect by itself the objects with which to carry out a task. To do this, we must take into account various aspects such as the issue of lighting and the lens that will be used, among others.

Given that this robot, as previously mentioned, will be used in different rooms of the university, the lighting will not be the same in one room or another, nor will the incidence of it be the same. This, as has already been verified on certain occasions with the ABB robot located in the mechatronics laboratory of the Tallinn University of Technology, is a problem that will have to be solved throughout this project, since said robot is unable to recognize objects due to the variation of the shadows and reflections that occur on the test bench.

This problem is something widespread that also occurs in all industries due to variation in ambient light intensity. In Figure 2.7 are shown some examples of how the object that is displayed completely changes its shape due to reflections and shadows.

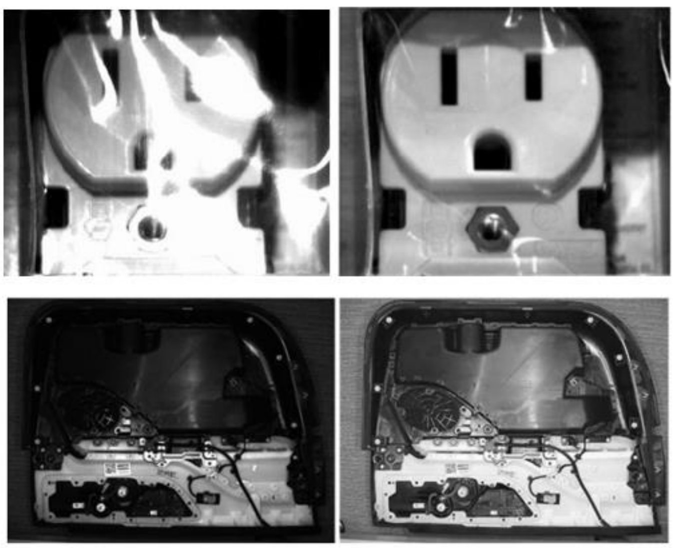


Figure 2.7 Changes due to reflections and shadows [10].

For this reason, an own lighting system for the robot will be designed. In this way, it will not matter in which room the robot operates since we will ensure that the light that falls on the objects and over the test bench is always the same.

2.3.1 Lighting systems used in the market

In order to design a lighting system to implement it in machine vision applications, several factors must be taken into account. Among them is to evaluate which will be the characteristics of the objects that the robotic arm will have to analyse and, in addition, the type of camera that will be used. For this reason, in this section we are going to collect information about the types of lighting sources that are currently on the market and the most used techniques.

Illumination sources. The most used light sources currently in the industry for the field of artificial vision are LED, fluorescent, quartz halogen and xenon lights. In the Figure 2.8 a comparative graph is shown with the most important aspects to take into account when choosing which will be the ideal one for our lighting system.

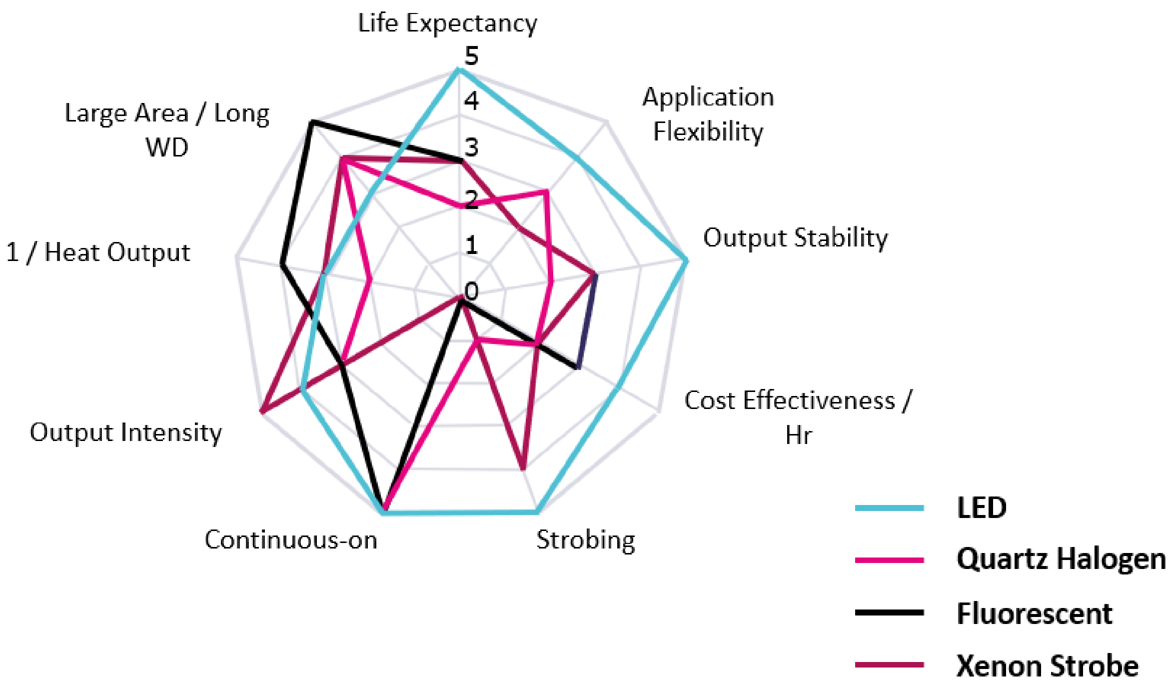


Figure 2.8 Comparative graph of illumination sources [16]

In addition to these characteristics, it is also necessary to take into account the wavelength of each type of light source respect to the relative intensity since it is highly recommended to match the maximum sensitivity of the camera with the maximum wavelength of the light source [17].

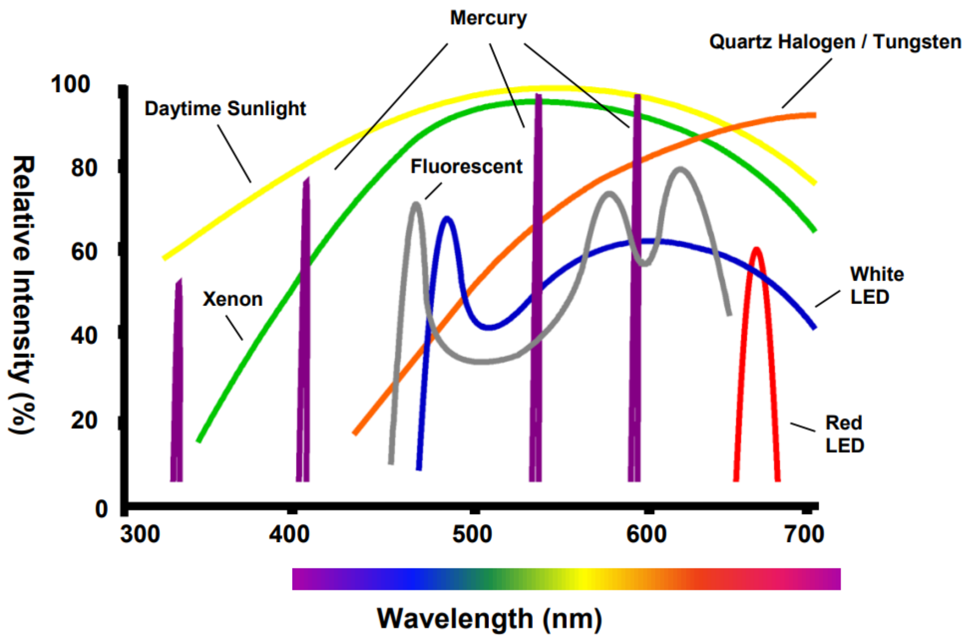


Figure 2.9 Wavelength vs Relative Intensity of light sources [16]

Finally, it will be necessary to take into account the shape of this lighting source, since in the market we can find different types such as bar lights, back lights, dome lights, axial lights, spotlights and ring lights, among others. Bar lights get their name from being linear lights. Back lights produce the silhouette of the object, so they are useful for achieving high levels of contrast. Dome lights are used to identify highly reflective elements. The axial and coaxial lights play with mirrors to illuminate objects on the same axis as the camera. Spotlights are very easy to install and provide multiple options. Finally, ring lights are perfect for removing shadows from objects.

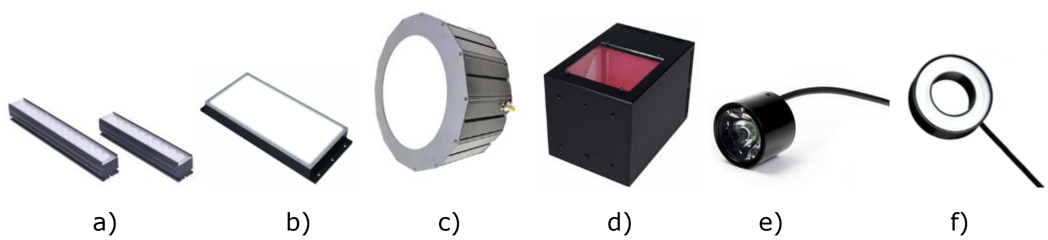


Figure 2.10 Types of lighting sources [18], where a) bar light, b) back light, c) dome light, d) coaxial light, e) spotlight and f) ring light.

Illumination techniques. In relation to the lighting of machine vision systems, not all that matters is the type of lighting source, but its location also plays a very important role. For this reason, the most used techniques in the market are described below.
In the first place, we find the back lighting technique (see Figure 2.11) which consists of placing the light source behind the object to be analysed to create contrast and obtain the silhouette of the object as a result. This technique is commonly used in cases where the objective is to measure objects or determine their orientation.

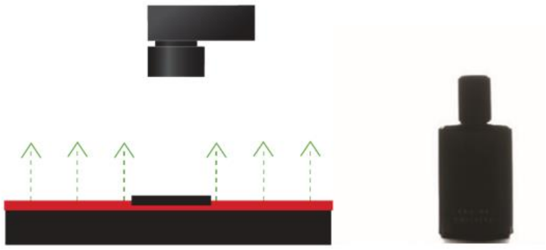
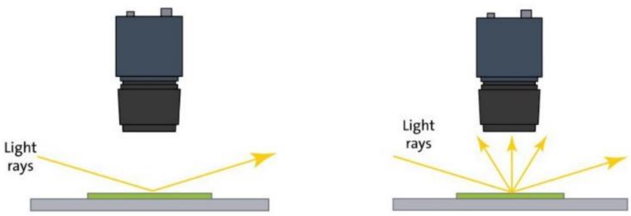


Figure 2.11 Back lighting [19]

Another commonly used technique in the industry is dark field illumination. This technique is mainly used to detect defects or damage in objects and for this the light source is placed with a low angle of incidence. If the surface is completely flat, the light will be reflected without penetrating the camera's field of vision as shown in Figure 2.12 a). However, if any imperfection is found on the surface, the light will be reflected in different directions, penetrating some ray of light in the field of view of the camera, as shown in Figure 2.12 b).



a) b)

Figure 2.12 a) Dark field flat surface, b) Dark field imperfection surface [20]

Finally, the other most used technique in this sector is bright field illumination, which can be divided into two subcategories:

- Partial or directional bright field: in this category we find any light located at a small angle with respect to the vertical axis as shown in Figure 2.13. The most common light sources are bar lights, spotlights, and ring lights [21]. The latter, known as the ring lighting technique, provides shadow-free illumination and good image contrast [22].

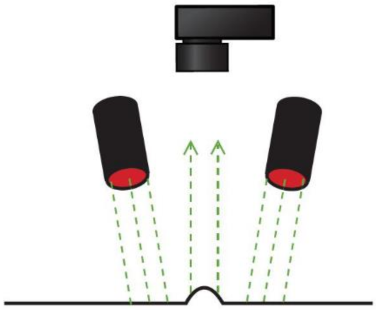
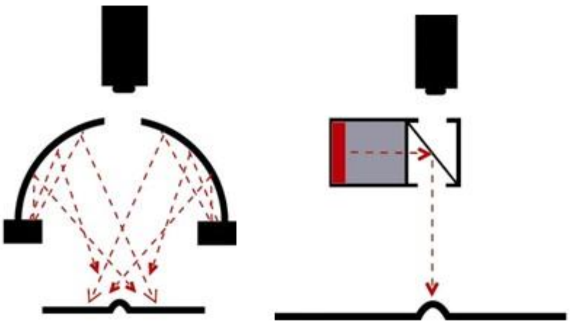


Figure 2.13 Partial bright field [21]

- Full bright field: in this category we find the dome lighting and the diffuse on-axis lighting. Dome lighting provides uniform light from various angles creating a 'cloudy day' effect where shadows disappear and surfaces light up. It is mainly used to smooth rounded surfaces. Finally, the diffuse on-axis technique consists of applying a light perpendicular to the object and using a mirror to change the trajectory of the light making it vertical [22]. It is mainly used with shiny objects.



a) b)

Figure 2.14 a) Dome lighting, b) Diffuse on-axis lighting [16]

2.3.2 Cameras used in machine vision

Next, this section shows the types of cameras that are most used in machine vision and the most common places to place them.

Types of cameras for machine vision. We can mainly find two types of cameras on the market, area-scan and line scan cameras. As the name suggests, area-scans cameras are capable of scanning an entire surface and their scope dimensions are usually displayed as width x height. On the other hand, the line scan cameras are those cameras that only scan a fairly fine line and in order to visualize a surface, the object or the camera has to move to create a total set of captured lines [23].

In addition to this previous classification, we can also base another classification on the information that the camera will receive regarding colours, thus obtaining monochrome, RGB or hyperspectral cameras.

- Monochrome cameras produce images based on the amount of light captured and reproduce it in a grayscale. Their advantages over colour cameras are that they have better performance in low light conditions and are very useful for detecting silhouettes when using the back lighting technique.
- RGB cameras capture light in red, green and blue wavelengths (between 400-700 nm). These cameras normally use the Bayer filter to determine the colour of each pixel in the image. Compared to monochrome cameras they are slower in processing [24].
- Hyperspectral cameras are more complex as they can measure the continuous spectrum of the light for each pixel of the scene [25]. These cameras provide more information than RGB cameras since they are able to identify even the materials of the objects they view based on their chemical composition.

A comparative table is shown below where you can see the advantages and disadvantages of each of these types of cameras. The number 1 is equivalent to 'not relevant', the number 2 is equivalent to 'poor' and the number 3 is equivalent to 'good'.

Table 2.3 Characteristics of different camera types

Parameters	**HSI**	**RGB**	**Monochromatic**
Speed	3	3	3
Colour Interference	3	1	1
Material	3	1	1
Contactless	3	3	3
Versatile	3	2	2
Quantitative	3	1	1
Qualitative	3	1	1

Locations for the camera. Finally, it is going to be analysed the most common locations of the cameras for machine vision in robotic arms used in the industry. In the first place we find the option that the camera itself is integrated into the robotic arm, being able to move simultaneously with it. This technique is called Eye-in-Hand camera and we can visualize it in Figure 2.15.

On the other hand, we find the option of placing the camera fixed at an external point and in this way it will not depend on the movement made by the robot. This method is called Eye-to-Hand camera.

Finally, there is the option of placing the camera on the test bench pointing up. This method is called Upward-looking camera and it is usually used as an auxiliary camera which comes into play when the robotic arm has already taken the object and it is necessary to examine the underside of it or its positioning.

Figure 2.15 Locations for the camera [26]

Next, in the Table 2.4, a comparative table is shown on the advantages and disadvantages of these different techniques.

Table 2.4 Advantages and disadvantages of locations techniques of cameras [26]

Camera location	Advantages	Disadvantages
Eye-in-Hand camera	• More flexibility of the picture point. • No additional pre-set is needed.	• The arm has to stop for taking pictures. • It spends more time.
Eye-to-Hand camera	• Photos can be taken while the robot is moving. • Shorter cycle time.	• Previous configuration needed: It is necessary a fixed connection between the camera and the robot.
Upward-looking camera	• Very precise. • Used for secondary operations.	• The arm has to stop for taking pictures. • It spends more time.

2.4 Conclusion of the literature review

After carrying out a detailed search on the different aspects that this project encompasses, it is concluded that the test bench that was designed for the robotic arm is not enough to achieve the objective of this project. In addition, the test benches that can be found on the market do not meet the requirements, either because the issue of displacement is a problem, inadequate measures, or very high costs. Therefore, finally we proceed to design a custom test bench, which will meet all the necessary requirements and will take into account the system of lights and cameras that will be finally chosen.

Regarding cameras, the monochromate camera JAI GOX-3201M-USB and the hyperspectral camera Ximea xiSpec MQ022HG-IM-LS150 VISNIR will be used. This last camera is capable of predicting the material the object is made of, which will allow to select the correct pressure with which the robot grips the object, making the test bench a multipurpose test bench since it will be able to work with any required object. In addition, the eye-to-hand camera position will be used since its advantage that photos can be taken while the robot is moving will save time.

Lastly, regarding the lighting system, for the moment it is considered that the most appropriate source will be halogen lights due to the advantage of being continuous in the visible spectrum (see Figure 2.9), while the lighting technique that will be used will be the bright illumination technique since one of our objectives is to be able to predict the material as previously mentioned and this is the only technique that provides us with that possibility.

3 DESIGN OF THE TEST BENCH

3.1 Preliminary design of the test bench

To start designing the test bench where the robot will be located later, many factors must be considered, from the dimensions of the robot and its reach, its weight and its payload to the size of its control box. All these data can be found in the Table 2.1. Also, keep in mind the requirements that the test bench must meet, which can be found in item "2.2.2. Desired requirements". SolidWorks software will be used to carry out the design.

First place, the measurements that the table must have are established. The width is established taking into account the minimum standard door width in the European Union, 625 mm. To ensure that the table will fit across the width, it is given a width of 500mm. The robot will be located in the middle of this distance. In addition, to determine the length of the test bench, the reach distance of the robot is considered. Although the robot can reach 850 mm, it is decided that this range is unnecessary and that 650 mm will be enough for the robot to work. It is also necessary to take into account that the robot needs to have space behind it since when making the movements it acts as an elbow as shown in Figure 3.1.

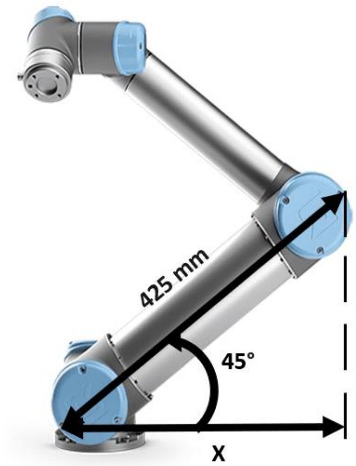


Figure 3.1 Rest position of UR5 robot, where
X - length of the projection of the robotic arm in the horizontal plane.

To do this, we calculate the space that it invades using the Pythagoras' theorem by the formula (3.1), obtaining that the length needed X is equal to 300,52 mm.

$$X = \cos\theta \cdot L \tag{3.1}$$

where X – length of the projection of the robotic arm in the horizontal plane, m;

θ – angle between the robotic arm and horizontal plane in rest state, rad;

L – half of the length of the robotic arm, m.

Therefore, the table must be at least 950 mm long, but keeping in mind that an arch would be designed to locate the lights and cameras there and that a methacrylate box would be also designed to prevent the robot from colliding with any person, the length of the table will be of 1400 mm.

On the other hand, given that the robot has a range of 850 mm to the right and another 850 mm to the left, it is decided to add two wings to expand the space on both sides. These will be 320 mm each, creating a surface with a total width of 1140 mm. The wings will be held by three full overlay hinges each like the ones that appear in Figure 3.2. In addition, the table will have a height of 874 mm formed by 120 mm of caster wheels [27], 725 mm of aluminium profile and 19 mm of MDF wood board. All this structure will be made by 60x60 mm aluminium profiles from the MiniTec manufacturer [28] as shown in Figure 3.3.

Figure 3.2 Full overlay hinges for the wings of the table [29]

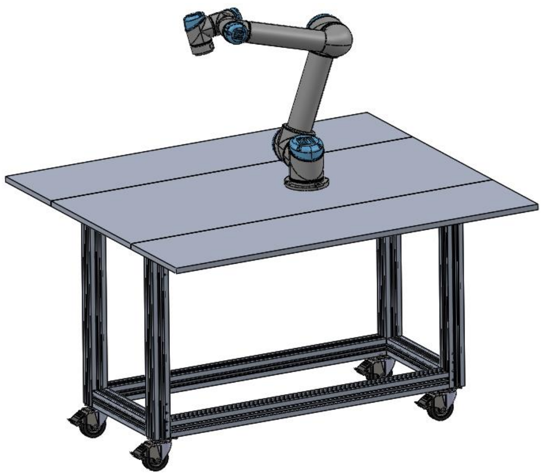


Figure 3.3 Preliminary design of the test bench

3.1.1 Calculations based on first draft

As in any structure, before continuing with the design, some calculations must be carried out to guarantee its stability. For this, the most unfavourable case is going to be assumed, in which the robot is extended towards one of the sides and is acting with the maximum torque and with the maximum payload in the grip. The formulas presented in "2.2.4 Calculations for the test bench" will be applied, where the sum of the vertical forces and the sum of the moments will be equalled to zero (formulas 2.1 and 2.2).

First, the vertical forces exerted on the robotic arm are calculated (Figure 3.4). For this, it is assumed that the centre of mass of the robot is located in the centre of it once it is extended, at the same distance from the grip as from its base. On the other hand, the maximum load that the robot can grip is taken into account, 5 kg, located at the end of the grip. With these two forces we can calculate the reaction produced at the base of the robot in formula (3.2).

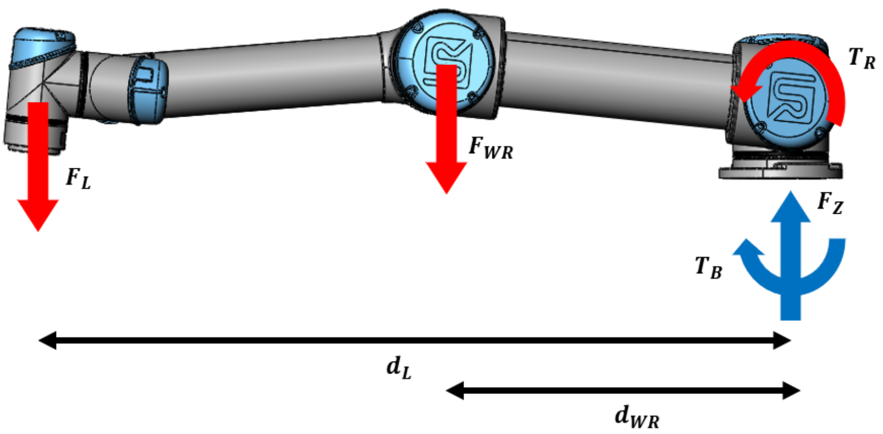


Figure 3.4 Internal forces of robotic arm
F_L – force produced by the payload of the robot, F_{WR} – force produced by the weight of the robot, T_R – torque of the base joint of the robot, F_Z – vertical reaction force produced in the base of the robot, T_B – reaction torque in the base of the robotic arm, d_L – distance from the payload force to the base of the robot, d_{WR} – distance from the weight force to the base of the robot.

$$\sum_{vertical\ forces} = 0 \qquad (3.2)$$

$$F_z = F_L + F_{WR} = 229{,}55\ N$$

where F_Z – vertical reaction force produced in the base of the robot, N;

F_L – force produced by the payload of the robot, N;

F_{WR} – force produced by the weight of the robot, N.

To compute the moment generated at the base, the formula (3.3) is used.

$$\sum_{momments\ base} = 0 \tag{3.3}$$

$$T_B = F_L \cdot d_L + F_{WR} \cdot d_{WR} + T_R = 268{,}4\ Nm$$

where T_B – reaction torque in the base of the robotic arm, Nm;

F_L – force produced by the payload of the robot, N;

d_L – distance from the payload force to the base of the robot, m;

F_{WR} – force produced by the weight of the robot, N;

d_{WR} – distance from the weight force to the base of the robot, m;

T_R – torque of the base joint of the robot, Nm.

Once we know the values of F_z and T_B we begin to apply this last formula based on point A of the test bench (see Figure 3.5) in the design of the test bench in order to determine if in the most unfavourable case the table would overturn.

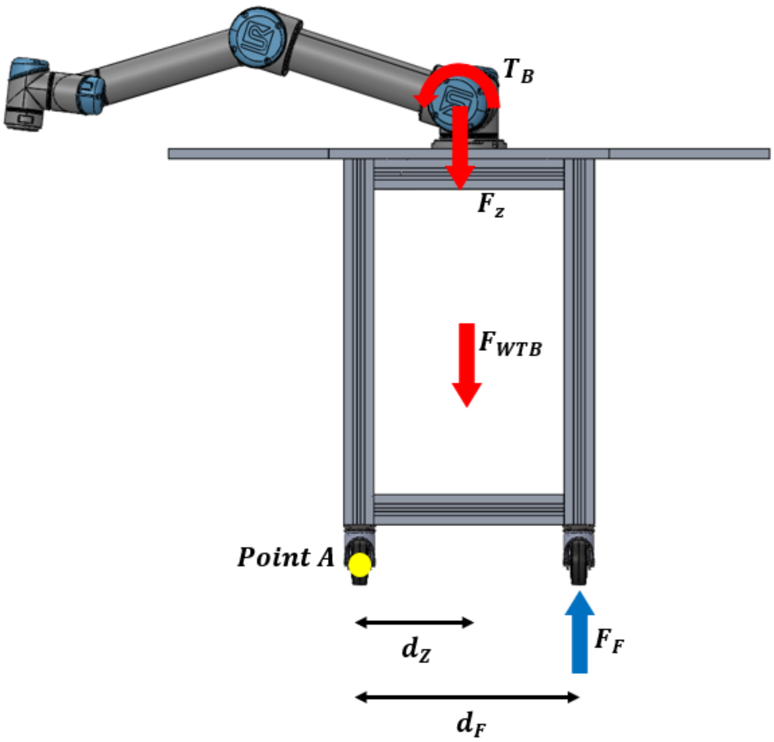


Figure 3.5 Internal forces of test bench for first draft
T_B – reaction torque in the base of the robotic arm, F_Z – reaction force produced by the robot, F_{WTB} – force produced by the weight of test bench (incl. controller box), F_F – reaction force produced in the floor, A – point where the moment calculation is applied, d_Z – distance from the reaction force F_Z to point A, d_F – distance from the reaction force F_F to point A.

In this case, we assume that the centre of mass is located in the centre of the structure, since it is symmetrical. The weight to take into account will be the weight of the test bench which is assumed to be at least 20 kg plus the weight of the controller box, 15 kg. In addition to the centre of mass, to carry out this calculation, the robot's reactions located in the centre of the test bench and a new force F_F are taken into account, whose value will be the one that determines if the test bench would overturn or not.

$$\sum_{momments\ A} = 0 \tag{3.4}$$

$$F_{WTB} \cdot d_{WTB} + F_Z \cdot d_Z - F_F \cdot d_F - T_B = 0$$

$$F_F = -278{,}26\ N$$

where F_{WTB} – force produced by the weight of test bench (incl. controller box), N;

d_{WTB} – force produced by the payload of the robot, m;

F_Z – reaction force produced by the robot, N;

d_Z – distance from the reaction force F_Z to point A, m;

F_F – reaction force produced in the floor, N;

d_F – distance from the reaction force F_F to point A, m;

T_B – reaction torque in the base of the robotic arm, Nm.

F_F should be positive and in this case it is negative. This means that with this design, la test bench could overturn. Given this, different solutions are presented to solve this problem:

- Fix a maximum torque of the robot base joint lower than the current one.
- Set a maximum reach distance of the robot lower than the current one.
- Establish a maximum payload that the robot can lift lower than what is allowed.
- Add an extra weight at the bottom of the test bench to get a lower point of gravity.
- Improve the design of the test bench.

The last option is chosen, improving the design of the test bench to make it more stable. The first three options are discarded because it is not desired to establish limits lower than the maximum allowed by the manufacturer in order to use the robot at its maximum performance. The option of adding weight to the lower part of the test bench is also discarded since this would require a greater effort when transporting it.

3.2 Modified draft of test bench

Therefore, it was decided to add four legs under the wings to gain stability (see Figure 3.6) built by 45x45 mm aluminium profiles [30]. These legs will be retractable since they will be attached to the structure by two hinges each [31], remaining hidden when the wings are not unfolded. To do this, the longitudinal profiles of the table structure are also moved inwards to leave space for when the legs are folded, as shown in Figure 3.7. During the operation of the robotic arm, these legs will be unfolded and levelled thanks to four levelling pads [32].

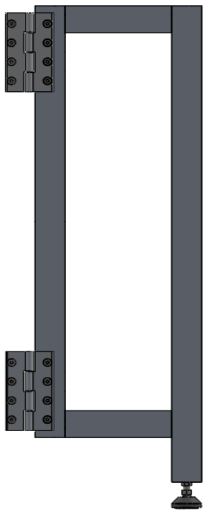


Figure 3.6 Legs for supporting the wings

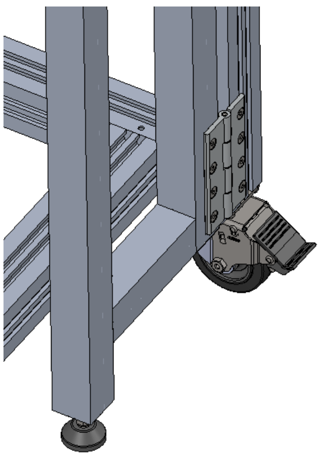


Figure 3.7 Retracted leg position

3.2.1 Calculations based on modified draft

The reactions from the robot are not affected by the change in the test bench design, so the ground reaction is recalculated from the new model as shown in Figure 3.8 with help of formula (3.5).

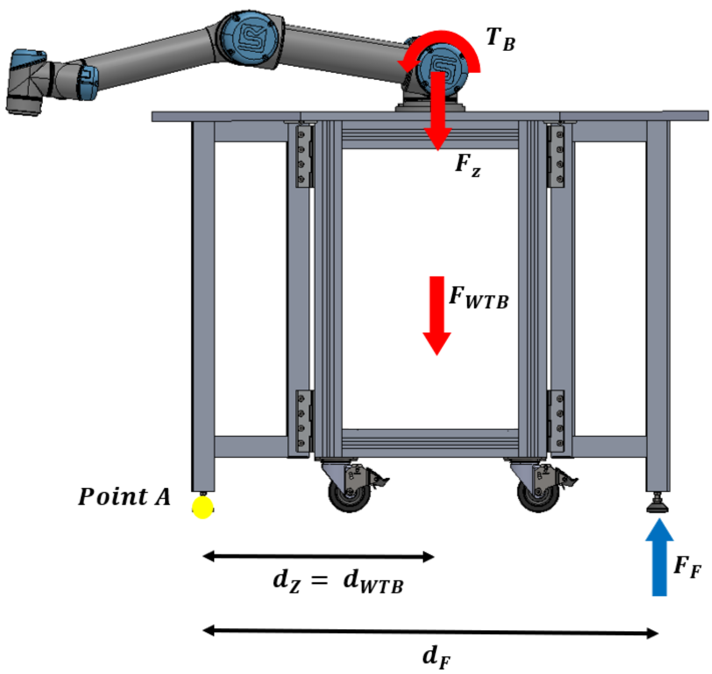


Figure 3.8 Internal forces of test bench for modified draft
T_B – reaction torque in the base of the robotic arm, F_Z – reaction force produced by the robot, F_{WTB} – force produced by the weight of test bench (incl. controller box), F_F – reaction force produced in the floor, A – point where the moment calculation is applied, d_Z and d_{WTB} – distance from the reaction force F_Z and F_{WTB} to point A, d_F – distance from the reaction force F_F to point A.

$$\sum_{momments\ A} = 0 \qquad (3.5)$$
$$F_{WTB} \cdot d_{WTB} + F_Z \cdot d_Z - F_F \cdot d_F - T_B = 0$$
$$F_F = 14{,}54\ N$$

In this case, F_F is positive which means that the test bench is stable.

Once the test bench is stable, the deflation produced in the upper longitudinal profiles of the test bench by the weight of the robot is calculated to determine if these aluminium profiles are adequate or if the profiles section should be increased. In this case it is a simply supported beam with a point load [33] displaced to the right with respect to the central axis as shown in Figure 3.9. Therefore, to obtain the deformation, the specific formula for this case will be used (see formula (3.6)).

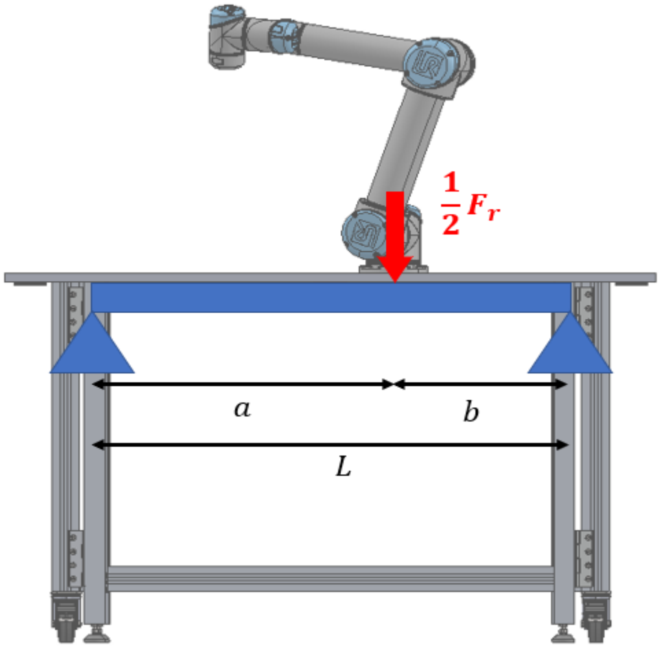


Figure 3.9 Scheme of forces to calculate deflation
a and b – length from the point load to one end of the beam, E – modulus of elasticity of the material, I – moment of inertia based on the shape of the extrusion, L – total length of the beam.

$$\frac{\frac{1}{2}F_r \cdot b}{9 \cdot E \cdot I \cdot L \cdot \sqrt{3}} \times (L^2 - b^2)^{\frac{3}{2}} \quad (3.6)$$

where b – length from the point load to one end of the beam, m;

E – modulus of elasticity of the material, N/mm²;

I – moment of inertia based on the shape of the extrusion, cm^4;

L – total length of the beam, m.

In order to apply this formula, it is necessary to know the modulus of elasticity and the moment of inertia of the profiles used. This information is provided by the manufacturer, in this case, MiniTec. The modulus of elasticity depends on the material they are made of and in this case is 70000 N/mm², while the moment of inertia depends on the geometry of the extruded profile, being 40,715 cm^4, for MiniTec profiles of 60x60 mm. In addition, it is necessary to know the dimensions of the test bench, with the distance a being 680 mm and b being 400 mm. Finally, the applied force will be the reaction F_r previously calculated divided by 2 since this force will be supported by two parallel aluminium profiles.

The result obtained is a deflection of 0,279 mm. According to the European standard 'EN 1990 – Basis of structural design', the deflection limits will be established for each project [34]. In this case, a limit value of L/400 will be considered after collecting different standardized values such as floor aluminium beams, bridge aluminium beams or roofs aluminium beams. Therefore, the limit will be a value of 2,7 mm and the value obtained from the calculations is lower than it.

3.3 Final design

After making the test bench stable, we start with the design of the upper part. It is decided to add two arches on which the lights and cameras will be located. These arches will be formed by 45x4 5mm aluminium profiles as shown in Figure 3.10. The height of this structure is 900 mm.

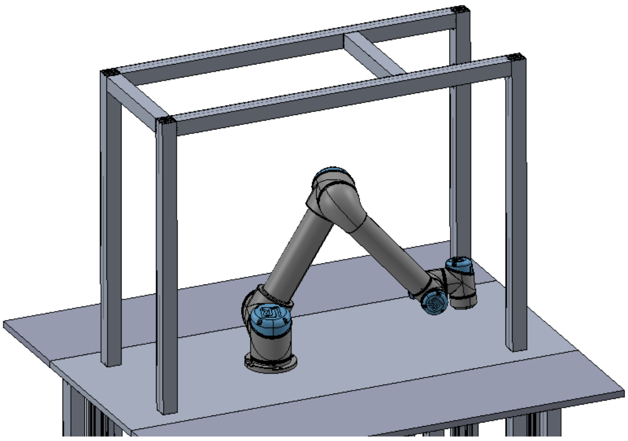
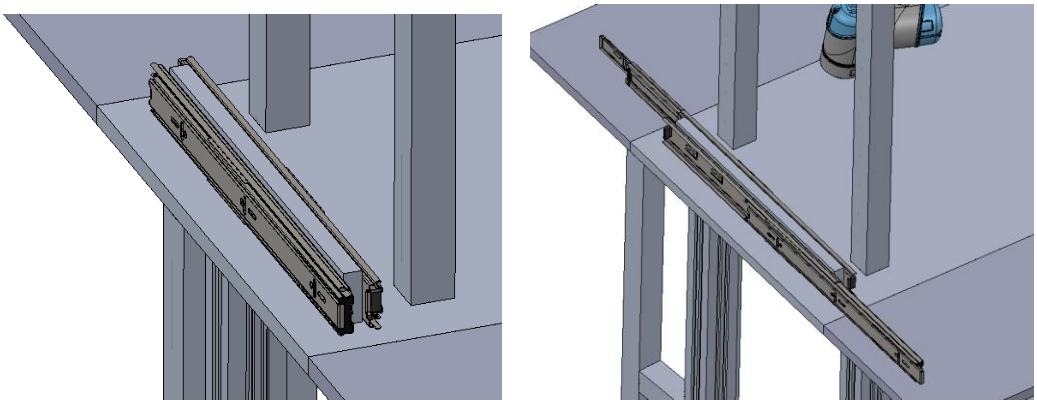


Figure 3.10 Arches to place lights and cameras

The next step is to create a cover that serves as protection to prevent the robot from colliding with an external object or even with a person. Since the test bench has to fit through the doors as previously discussed, the cover cannot be fixed. For this purpose, a system with slides is designed (see Figure 3.11) that will allow the cover to remain closed while the robot is not operating and to unfold when it goes to work. These telescopic slides must be 250 mm closed and 500 mm opened [35].



a) b)

Figure 3.11 Sliding system, a) slider closed and b) slider opened

Therefore, a cover divided into two halves is designed (see Figure 3.12), one slightly larger than the other so that they can fit inside each other when closed. These structures are made up of 30x30 mm aluminium profiles [36] and in the rectangles that are formed, methacrylate crystals are placed that fit into the rails of the profiles. For fixing them, a specific seal from the manufacturer MiniTec is used [37]. In addition, these two structures will have a handle each to facilitate their movement [38].

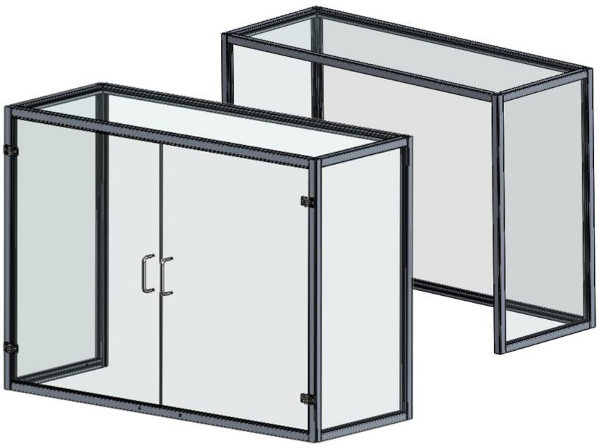


Figure 3.12 Two halves of the cover

In the larger half, there are also methacrylate doors (see Figure 3.13) to access the interior of the test bench to place the objects with which the robot will work. These doors are attached to the structure through two hinges each [39]. In addition, each door will have an aluminum handle to facilitate its use [40].

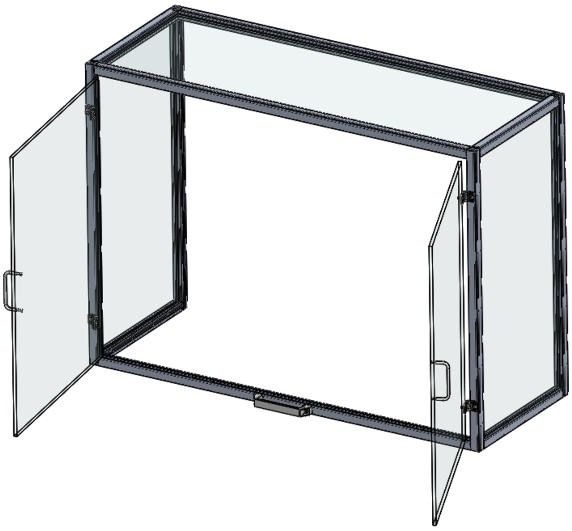


Figure 3.13 Doors of the big cover

On the other hand, it was decided to place another MDF wood board in the lower area of the test bench to be able to place the robot's control box and a third wing was also created (see Figure 3.14), with dimensions of 300 mm x 340 mm, to rest the touchscreen on it while the robot is in operation. This wing will also be attached to the structure through two full overlay hinges as previously mentioned.

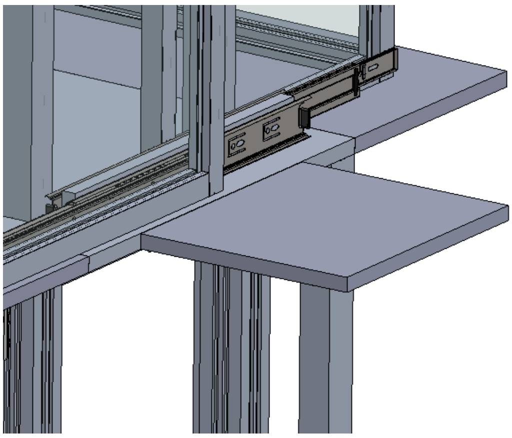
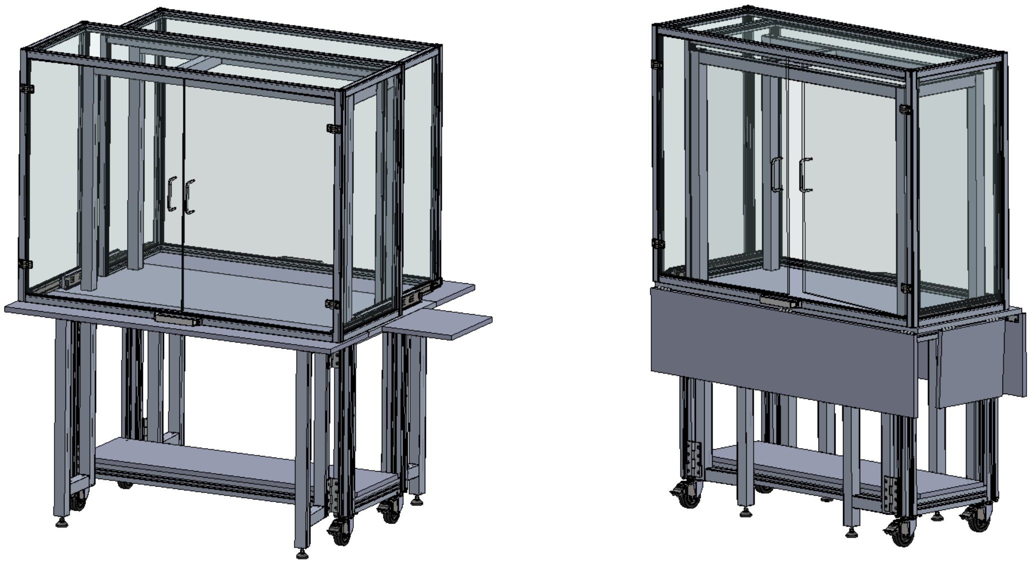


Figure 3.14 Wing to place the touchscreen

To finish the design, the respective end caps are added for the ends of the 30 x30 mm profiles [41] and the 45 x 45 mm profiles [42] that remain uncovered and in plain sight. Figure 3.15 shows the final design of the fully open test bench (operation mode) and closed (transportation mode) while Figure 3.16 shows the robot workspace with dimensions of 660 mm x 1000 mm and 800 mm of height.



a) b)

Figure 3.15 Final design where a) Full opened test bench, b) Closed test bench

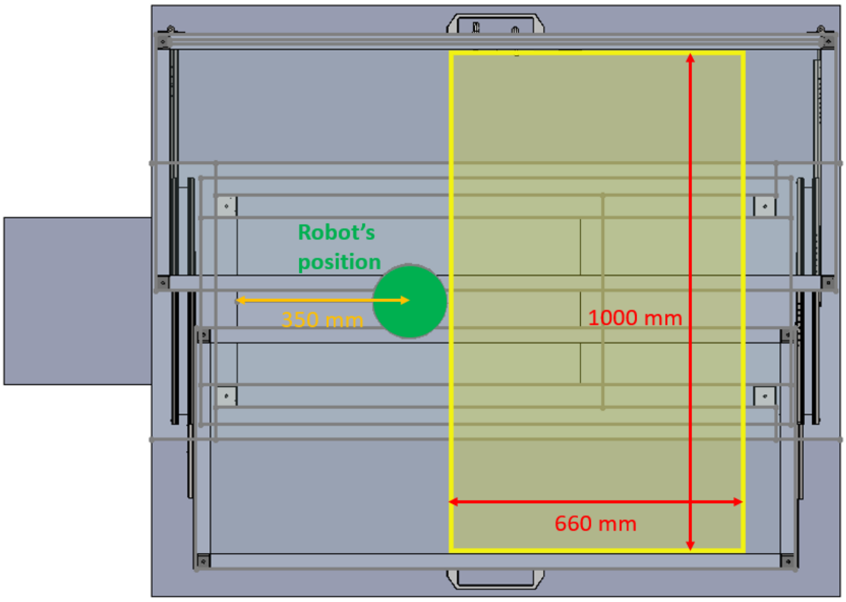


Figure 3.16 Robot workspace

3.3.1 Specifications of final design

In this chapter, an estimate of the weight and cost of the final structure will be carried on. For the final weight estimation of the test bench would be taken into account the values provided by the respective providers as shown in Table 3.1 and Table 3.2. For the aluminium profiles, the values provided by MiniTec are considered, while for the methacrylate is obtained from the supplier Ibermetal [43] and for the MDF plates from BAUHAUS [44].

Table 3.1 Profile weights by MiniTec

Profile type	m	kg/m	kg
60x60 (Base)	10,915	3,655	39,89
45x45G (Arch)	6,380	1,997	12,74
45x45G (Extra legs)	7,380	1,997	14,73
30x30 2G (Cage)	14,806	0,695	10,29

Table 3.2 Methacrylate and MDF plates weights

Material	m2	kg/m2	kg
Methacrylate	5,389	4,760	25,65
MDF plates	2,190	14,630	32,04

The total amount of the weights shown above is 135,35 kg. This weight favours the stability and robustness of the test bench. Thanks to the four caster wheels, the weight will not affect the movement of the test bench from one room to another.

In addition, it should be taken into account an estimation of the final price of the test bench. To do this, a list of all the materials that the test bench is composed of is created (see Appendix 3), where the necessary quantity, the price, and the manufacturer are detailed. Below is shown a summary of the most significant costs (see Table 3.3), being the total amount of 2365,20 €.

Table 3.3 Estimated final cost of test bench

No	Materials	Price (€)
1	60x60 (Base), profile	531,78
2	45x45G (Arch), profile	183,41
3	45x45G (Extra legs), profile	230,71
4	30x30 2G (Cage), profile	197,58
5	Methacrylate	148,00
6	MDF plates	123,98
7	Caster wheels	170,60
8	Rest of the materials (hinges, end caps, handles, links, etc.)	777,34
	Total	2363,85

4 DESIGN OF THE TEST BENCH

4.1 Selection of light source

To choose the light source to be used in this project, it must be considered that the cameras used in the project are hyperspectral and monochromatic, with a range of 470nm-900nm and 400nm-100nm respectively. For this reason, it will be needed a light source that is continuous in the 400nm-1100nm spectrum.

Based on the item "2.3.1 Lighting systems used in the market", three possible light sources are proposed to apply in this project:

Halogens: In this case, all halogen lights are continuous in the spectrum from 400 nm to 2500 nm[45], so it would be possible to buy anyone in the market. This light source can be bought for 2,99€ [46].

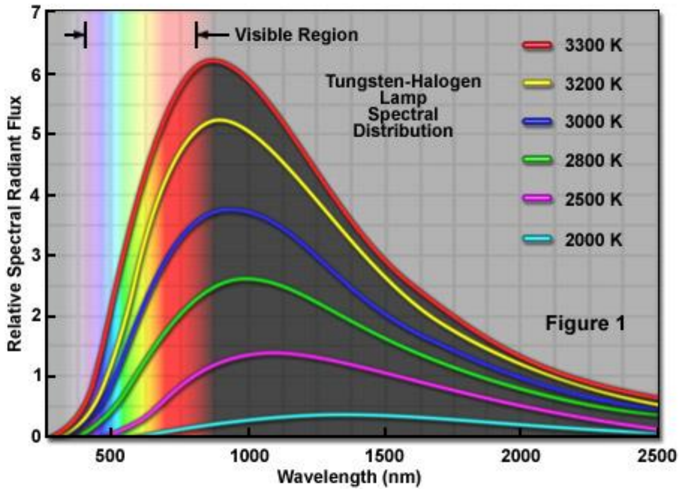


Figure 4.1 Spectral distributions of halogen lights [47]

HSI LED [48]: This is a novel LED created by the company CCS Inc. They have been able to create an LED light that is continuous in the spectrum between 400nm and 1000nm with a distribution similar to sunlight. Since this is quite consistent with the requirements of the cameras used in this project, it was decided to request a quote from the company that supplies it in Europe, EFFILUX. For this, the datasheet provided by the manufacture must be taken into account where the characteristics that the costumer can choose are shown. The quotation obtained by the company for a 300 mm long bar light, with transparent glass and a 45 degrees lens position (product code EFFI-FLEX-HSI-300-TR-P1) is a net price of 1117,93 €.

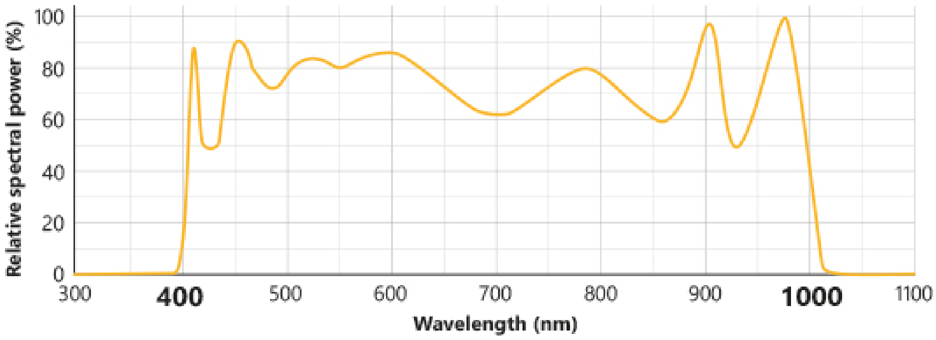


Figure 4.2 Spectrum of HIS LED of CC Inc. manufacturer [49]

SuperK EVO Laser [50]: As the name suggests, this is a laser, but unlike conventional lasers, this is a supercontinuum laser in the 400 nm to 2500 nm spectrum designed specifically for hyperspectral imaging applications. It is manufactured by the NKT Photonics company, and the manufacturer provides a line generation optics to convert the point of light into a line. The budget obtained by the company is a net price of 20000€ plus 5000€ for line generation optics.

Among these three options, SuperK EVO Laser option is discarded because for this project it would be necessary to install a linear mobile system where the hyperspectral camera moves at the same time as the laser to be able to evaluate the entire work area. In addition, both devices would have to be calibrated so that the reflectance line coincides as shown in Figure 4.3. Even so, it could be a good option to apply it in situations where it is required to use the range of SWIR wavelengths for line scan hyperspectral cameras.

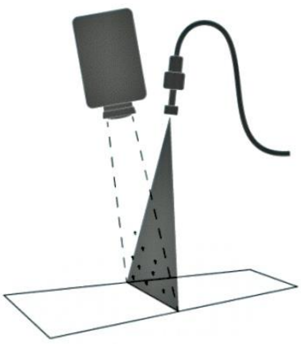


Figure 4.3 Reflectance line

Between the other two options presented, it is considered that the best solution would be to use the HSI LED light source since halogen lights are in decline, have a higher consumption, develop heat and have a shorter life compared to LED lights. Even so, for projects with a lower budget, the option of halogen lights can be implemented since they are much cheaper and therefore more accessible to all audiences.

4.2 Lighting simulations

To carry out the light simulation, it was decided to use DIALux Evo software, one of the most widely used light simulators in lighting projects. This program allows to calculate and visualize the lighting in exterior and interior spaces [51]. This means that thanks to this program it is possible to determine where to place the lights and how many units will be necessary to illuminate the surface where the robotic arm will operate.

To start using this software, the first thing to do is design the workspace. For this, a standard room is designed where this robot could operate. The measurements of this room are 10 m x 6 m, with a height of 3 m. Within it, the test bench is designed in a simplified way since it is not possible to import the SolidWorks design. The most significant of this design will be the dimensions of the test bench and the arches where the lights will be placed. On this test bench, the surface to be examined during the simulation is selected, this being the robot's work area called robot workspace (see Figure 4.4) with measurements of 660 mm x 1000 mm.

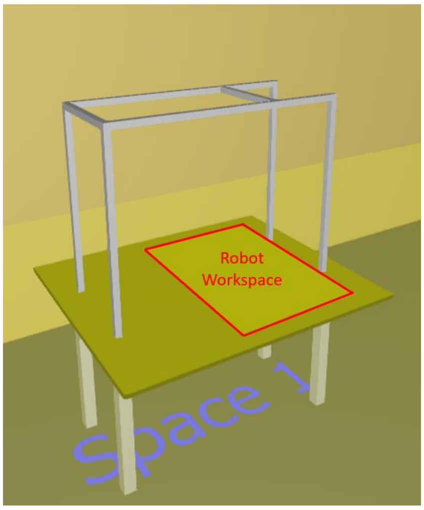


Figure 4.4 Test bench in DIALux Evo software

The location of the test bench within the room is set randomly and therefore the final environment is shown in Figure 4.5.

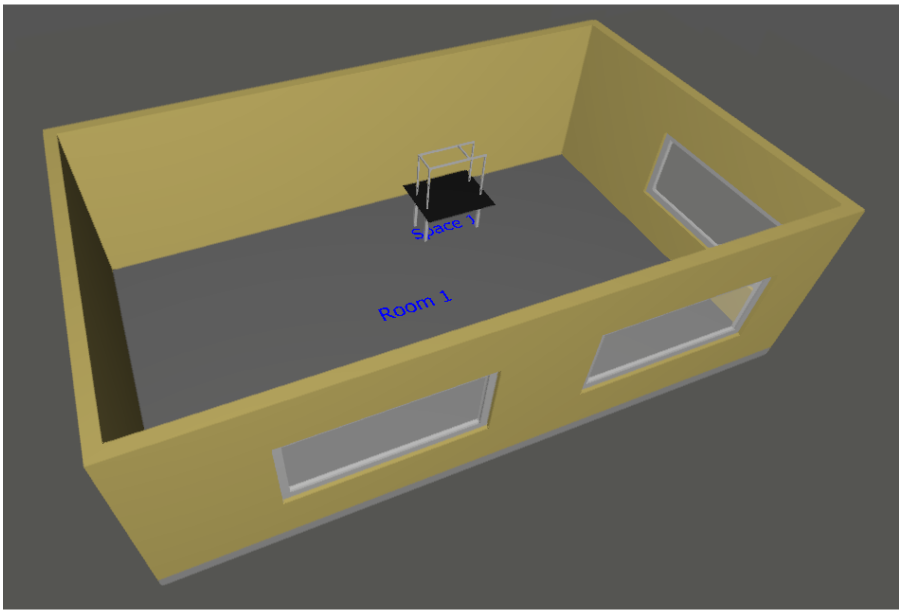


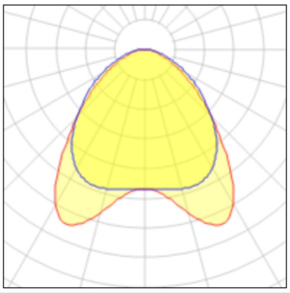
Figure 4.5 Room design in DIALux Evo

Once the workspace is defined, we proceed to search for the light sources for their subsequent installation. For this, DIALux Evo has a wide catalogue with different manufacturers, and within each brand there is the option to choose between different models proposed. In this case, the goal is to simulate the HSI LED option and the halogen lights option. However, when searching for the EFFILUX supplier to select the HSI LED model, no results are obtained. This is because DIALux Evo charges brands for publishing their products in the software and therefore in this case this option is not available and cannot be simulated. A solution before this would be to buy a light and test it in the lighting laboratory of the university thanks to the goniometer that is available, but these tests will not be carried out throughout this project because the light source is a large financial outlay and because carrying out these tests is tedious and long-lasting work.

Therefore, we proceed to search for halogen lights within the software. As discussed above, as far as halogen lights are concerned, no specific manufacturer is required, unlike HSI LED, that as it is an innovation, they are the only provider of continuous LED light across the entire visible spectrum. Therefore, to carry out the simulation, it is decided to select the model F24380/QT-12/35W/101° from FLOS manufacturer and in Figure 4.6 is possible to observe its specifications.

Light output 1

Available equipment	Nominal lamp power	Lamp flux	Luminous efficacy	CCT	CRI
1 x Halogen low voltage lamp without reflector	35 W	600 lm	11 lm/W	3000 K	99



Socket:	Gy6.35
LOR:	74%
Total flux:	444 lm
Total power:	39 W

Mounting mode

Ceiling mounted, Contact rail

Shape and measurements

Length: 43 mm
Width: 68 mm
Height: 119 mm

Adjustability

Free

Electric

System power: 39 W

Protection

IP: 20

Figure 4.6 F24380/QT-12/35W/101° specifications from FLOS manufacturer [52]

Once we have selected the halogen light source, we proceed to locate them in different positions to evaluate the illuminance values and light distribution. The illuminance is the quantity of light that falls on a surface [53] and is measured in lux (lumens per square meter). According to the European standard EN 12464-1, the illuminance values of an office must be 500 lx, while for hospital operating theatres it must be 1000 lx [54]. For this project, a minimum optimal illuminance value of 550 lx and a maximum value of 1000 lx will be considered, based on the values shown for 'inspection areas' of different types of materials such as wood, metals or plastics in the previously mentioned European standard.

The first chosen arrangement consists of two light units placed in parallel at the intersection of the two arcs and the perpendicular profile as shown in Figure 4.7.

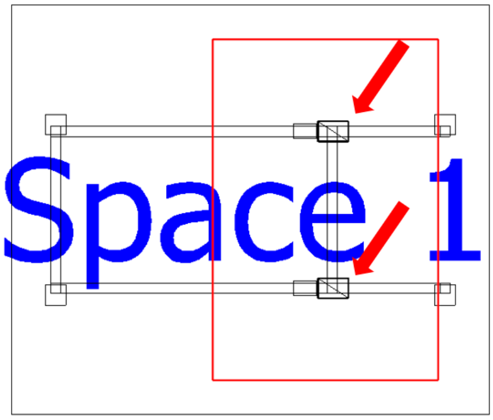


Figure 4.7 First arrangement for simulation

After carrying out the simulation, the results shown in Figure 4.8 were obtained, where the average illuminance in the plane of the robot workspace is 318 lx, with its minimum value being 259 lx and its maximum value being 381 lx. These values are lower than the optimal minimum illuminance value that has been established for this project, therefore this arrangement is rejected and it is decided to increase the number of lighting units.

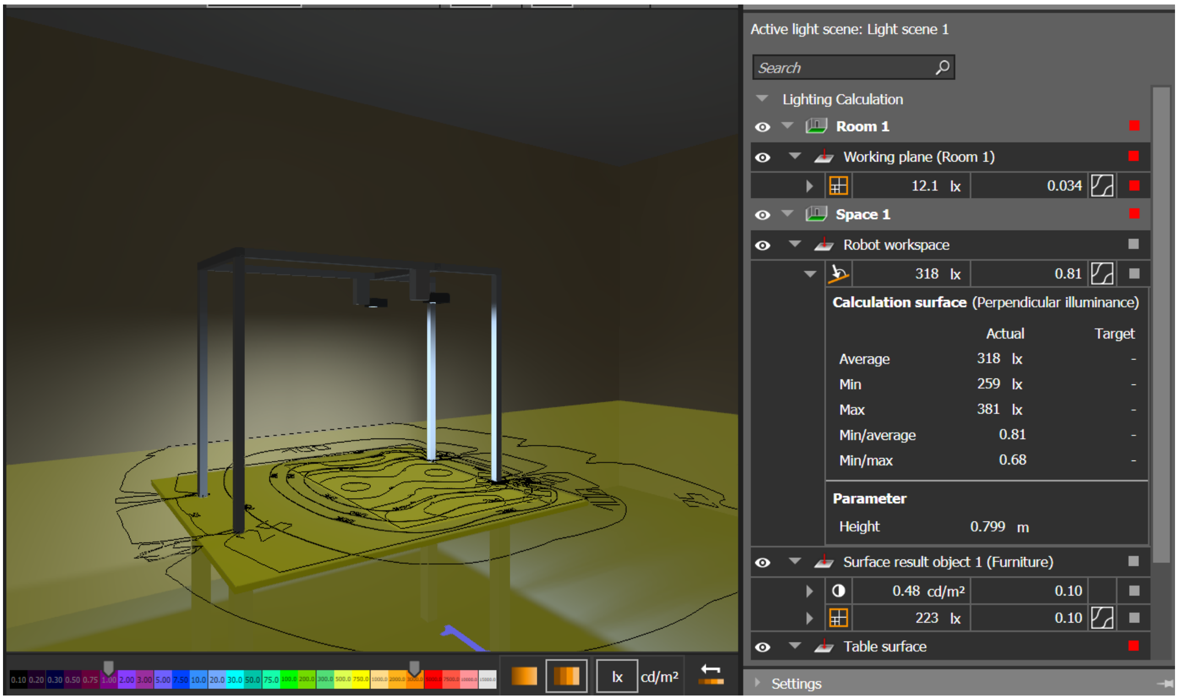


Figure 17.8 Results obtained for the first simulation

To do this, four light units will be placed, centred on the robot's work plane, separated by 220 mm between them and forming a rectangle as shown in Figure 4.9.

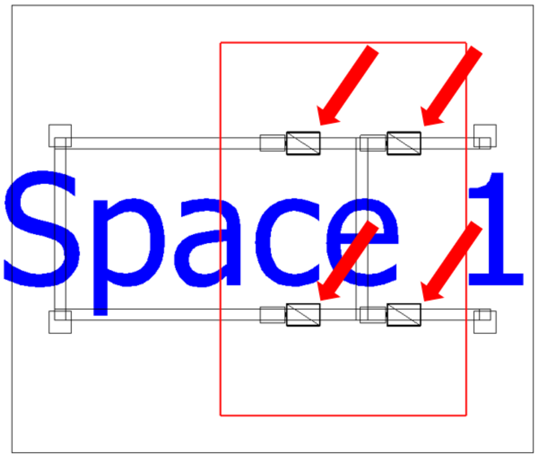


Figure 4.9 Second arrangement for simulation

The results obtained from this simulation are shown in Figure 4.10, with an average illuminance value of 615 lx, where the minimum value is of 510 lx and the maximum value is of 715 lx. The average illuminance value for this configuration is higher than the minimum illuminance value established for this project, so this lighting configuration is considered acceptable.

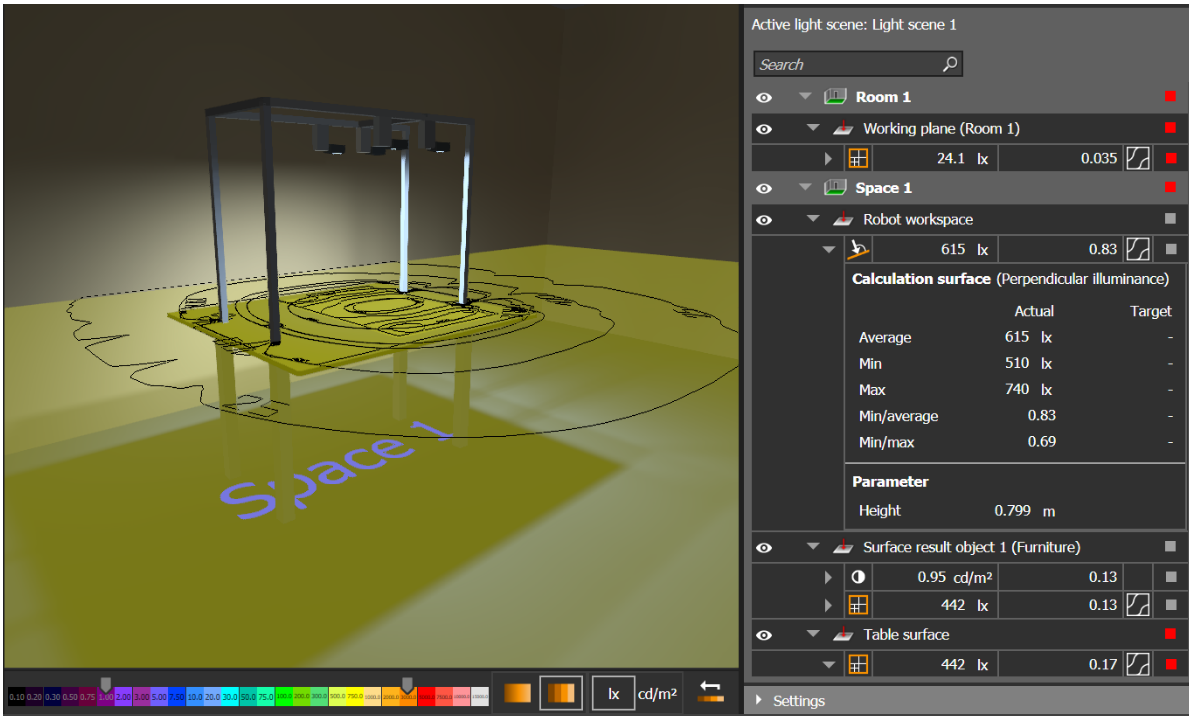


Figure 4.10 Results obtained for the second simulation

These simulations have been carried out without taking into account other external light sources such as the room's own lighting or the sunlight that penetrates through the windows. In this case, only the light generated by the room's own lighting source will be added, since although the robot could operate with the light in the room turned off and depending only on the lighting of the test bench itself, it is considered that in the most common cases, the room will be lit. Sunlight is neglected since it depends on external agents such as whether it is a sunny or cloudy day or the orientation of the windows, among others. It is also understood that the robot could operate in a room where there are no windows or where they are covered by blinds or curtains.

For this last simulation, twelve LED lights of the model DSP52-18-041 Optima EM3 940 from the ASTZ manufacturer (see Figure 4.11) are placed in a uniform distribution on the ceiling of the room.

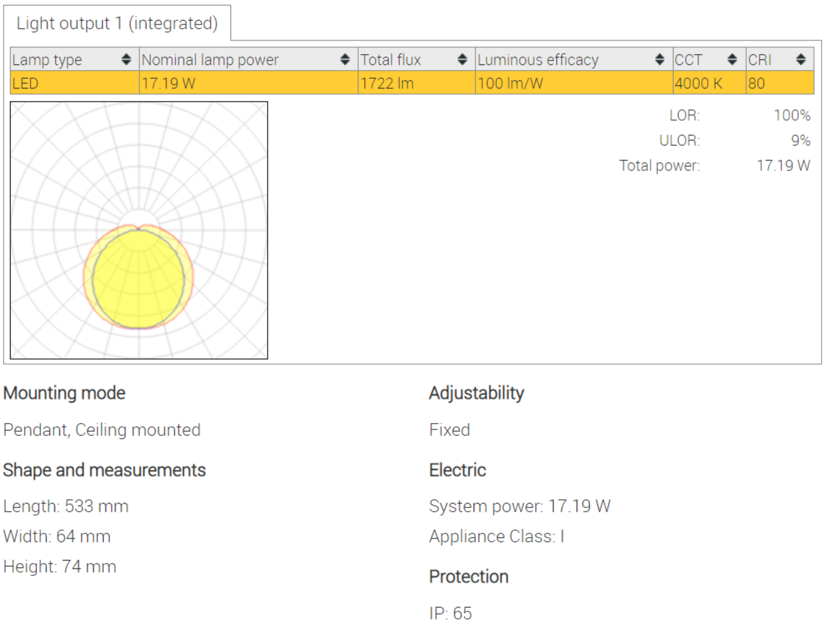


Figure 4.11 DSP52-18-041 Optima EM3 940 specifications from the ASTZ manufacturer [55]

The results obtained from this simulation are shown in Figure 4.12, with an average illuminance value of 829 lx, a minimum value of 737 lx and a maximum value of 974 lx. The average illuminance value for this configuration is within the suggested optimal range of 550-1000 lx, so it is considered acceptable.

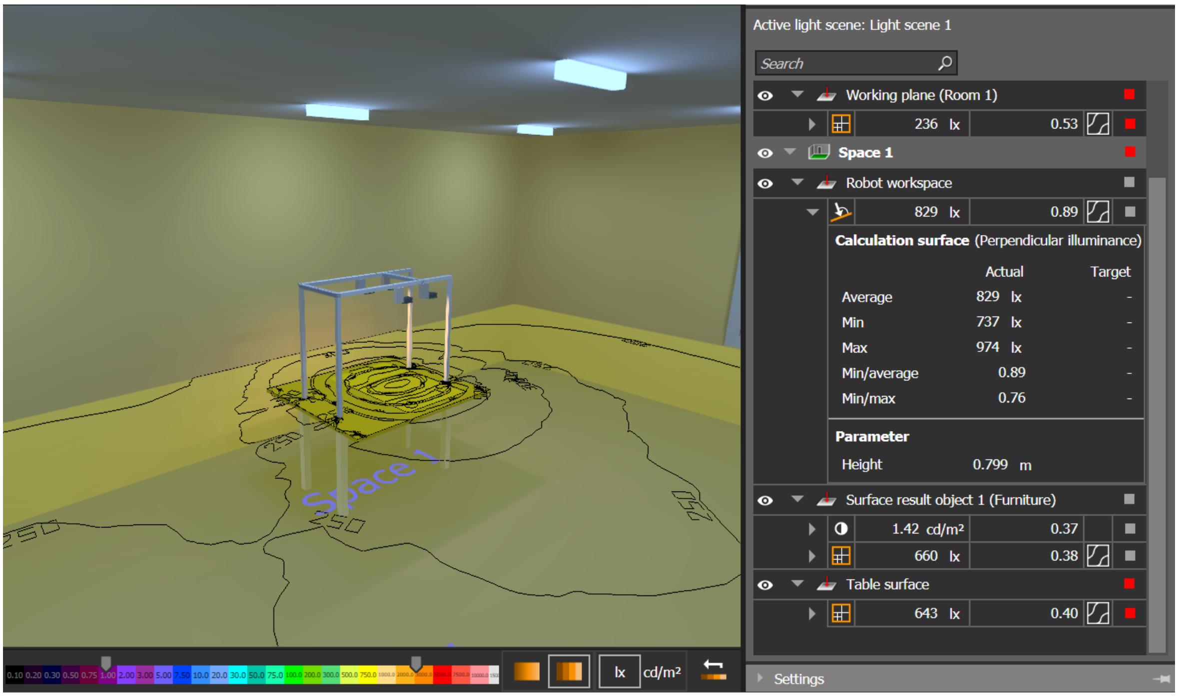


Figure 4.12 Results obtained when the light of the room is added

Finally, these simulations are repeated with the same model of halogen lamps as before, but with a higher power of 50W (see Figure 4.13). The results obtained are shown in Table 4.1 together with the results shown above for comparison.

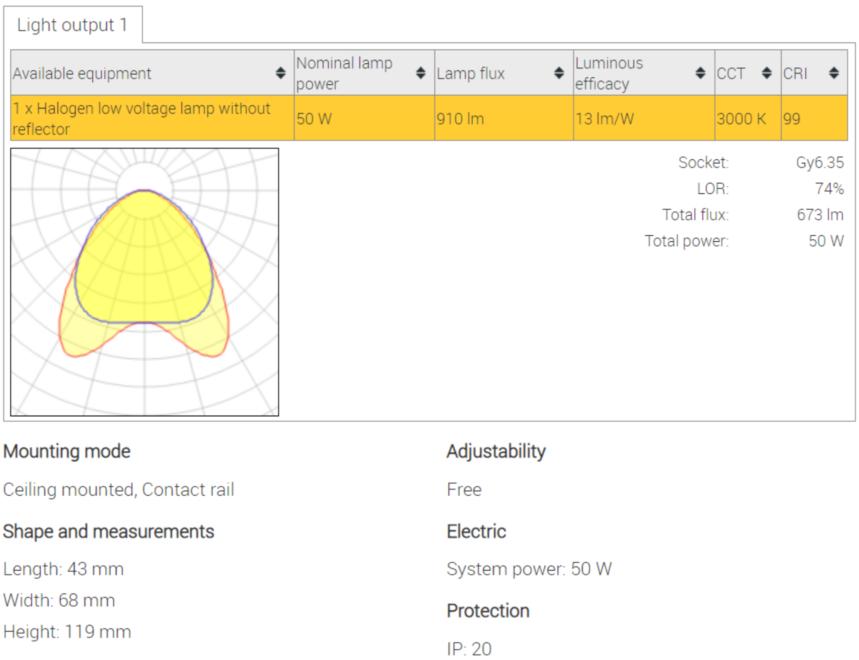


Figure 4.13 F24380/QT-12/50W/101° specifications from FLOS manufacturer [56]

Table 4.1 Comparative chart of simulations results

No	**Number of pieces**	**Power (W)**	**Room light**	**Average (lx)**	**Minimum (lx)**	**Maximum (lx)**	**Acceptable?**
1	2	35	No	318	259	381	No
2	2	50	No	483	393	578	No
3	4	35	No	615	510	740	Yes
4	4	35	Yes	829	737	974	Yes
5	4	50	No	933	774	1122	Yes
6	4	50	Yes	1147	1001	1356	No

Once the results obtained after carrying out the different simulations have been compared, the conclusion is reached that it is best to use four halogen lamps distributed uniformly over the robot's work space and adjustable 50W. In this way, by using a dimmer switch we can modify the power of these lights depending on the external conditions that it exist, such as more or less lighting in the room or solar lighting, among others.

5 LIGHT AND CAMERA CONNECTION DIAGRAMS

In this chapter the electrical diagrams necessary to feed the lights and the camera will be designed. For this, different scenarios are taken into account depending on which light sources are used.

For HSI LED lights, since it has not been possible to carry out the simulations, the optimal number of units is unknown, therefore two scenarios are considered. For the first case, the use of two light units is contemplated. For this, it is taken into account that each HSI LED of 300 mm length consumes a power of 20W, so the total sum is 40W and that this type of light requires a voltage of 24V. On the other hand, the power consumed by the cameras used in this project must be considered, being 1,8W for the Ximea hyperspectral camera and 4,3W for the JAI monochrome camera. This would make a total of 46,1W, although both cameras are not going to be running at the same time. Knowing this value, we can propose the idea of connecting all these elements to the robot's controller box, since it has 16 digital inputs and 16 digital outputs with 24V and 2A. This means that it can admit up to a maximum power of 48W, so it would be viable. To do this, the connection diagram is shown below in Figure 5.1, where SW1 corresponds to Lamp 1, SW2 to Lamp 2 and SW3 to Camera.

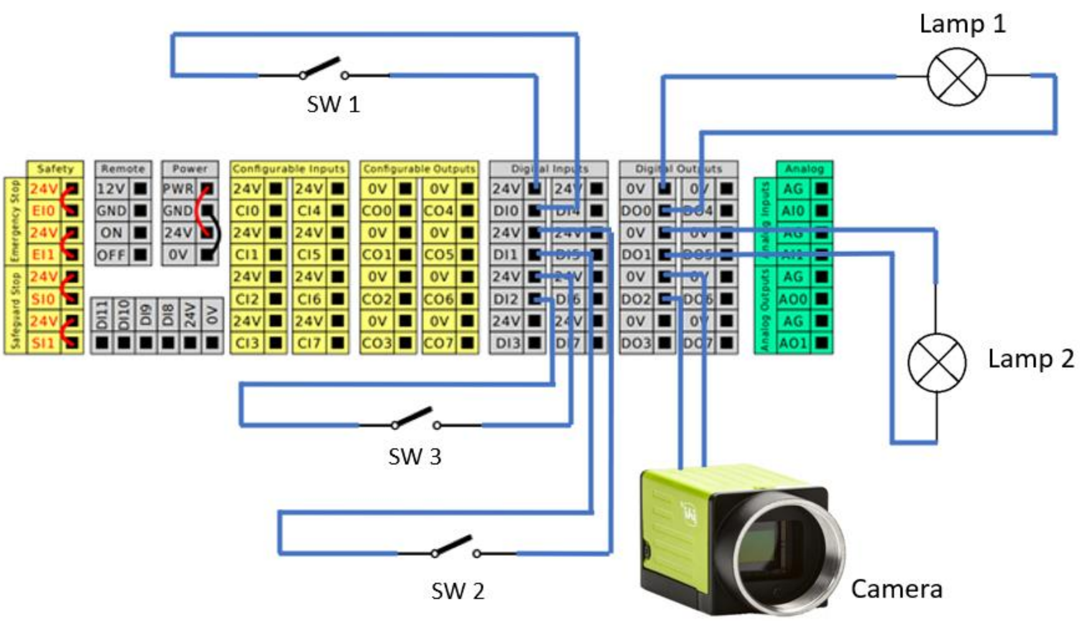


Figure 5.1 Electrical circuit for two HSI LED

In the second case, if four HSI LED units are needed, it will be needed to resort to the connection of an external power supply. In this case, Universal Robot explains how to connect it to the robot's control box in the User Manual [57] and sets a maximum of 6A external power supply to be used. This connection is shown in Figure 5.2, where SW1 corresponds to Lamp 1, SW2 to Lamp 2 and SW3 to Lamp 3, SW4 to Lamp 4 and SW5 to Camera.

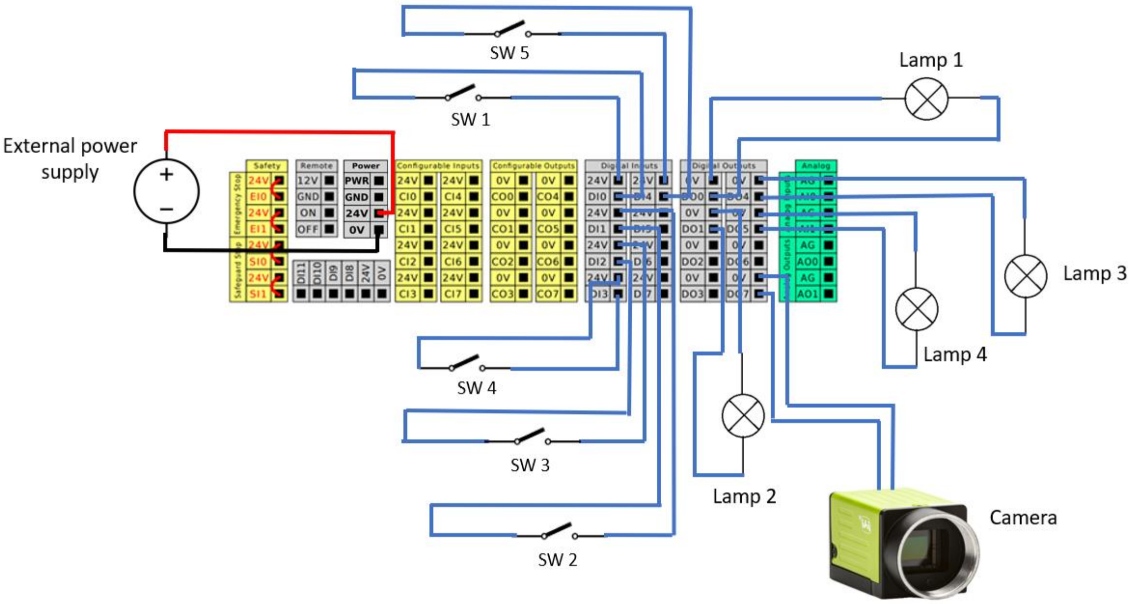


Figure 5.2 Electrical circuit for four HSI LED

On the other hand, for the halogen lights, four units of 50W each are required, as discussed in Chapter 4, making a total of 200W. The maximum power that the external power supply connected to the controller box can support will be of 144W. Therefore, this idea is rejected and a 24V 10A power supply is used, where the four lights can be connected in parallel to conserve the 24V for each of them (see Figure 5.3). In addition, a dimmer switch is connected that will allow to adjust the voltage that passes through the lamps, allowing to increase or decrease the intensity produced. Finally, the camera will be connected to the controller box of the robotic arm.

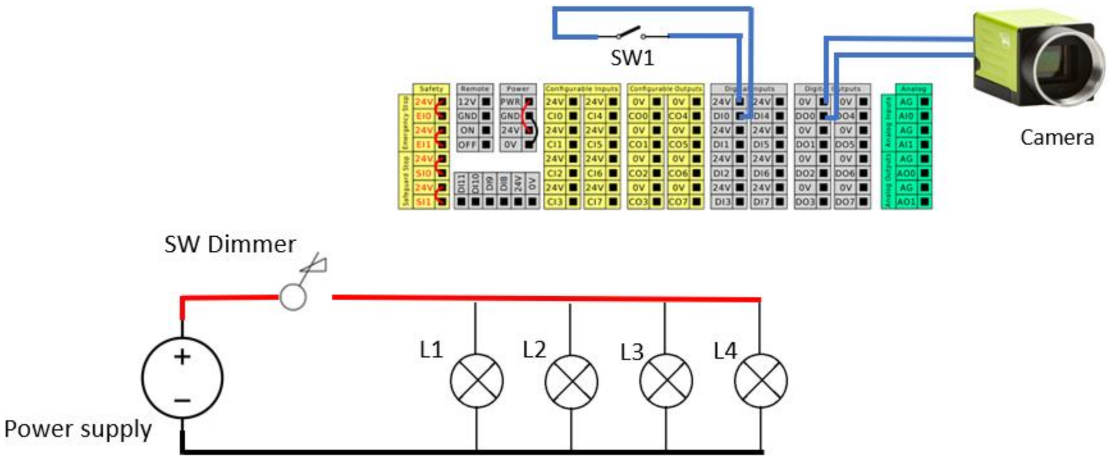


Figure 5.3 Electrical circuit for four halogen lamps

In addition, for all the previous configurations, it should be noted that in the case of needing to connect a camera to the tool of the robot, it has two digital inputs and two digital outputs of 12V/24V and 600mA in the tool, so a camera that consumes up to 14,4W can be connected.

Finally, it is intended that all the wires for the lights and cameras go inside the profiles since the extrusion of the profiles that make up the arches have four squares of 11,7 mm of side (see Figure 5.4) that are not used for assembly. Therefore, the wires could have a section of up to 10 mm.

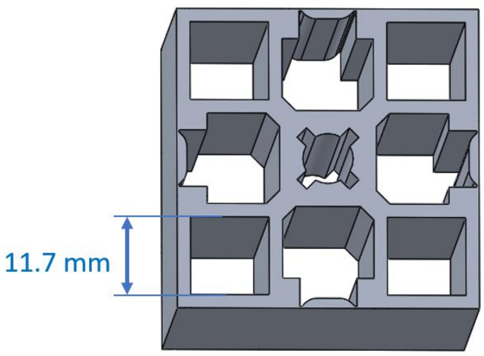


Figure 5.4 Extrusion of 45x45 G aluminium profiles of MiniTec.

Regarding the location of the lamps and camera on the test bench, it is shown in the Figure 5.5 that they will be located on the two arches and the distance between them will vary depending on the size of each lamp. Here it is shown a configuration for four lamps and the camera is located in the middle of them.

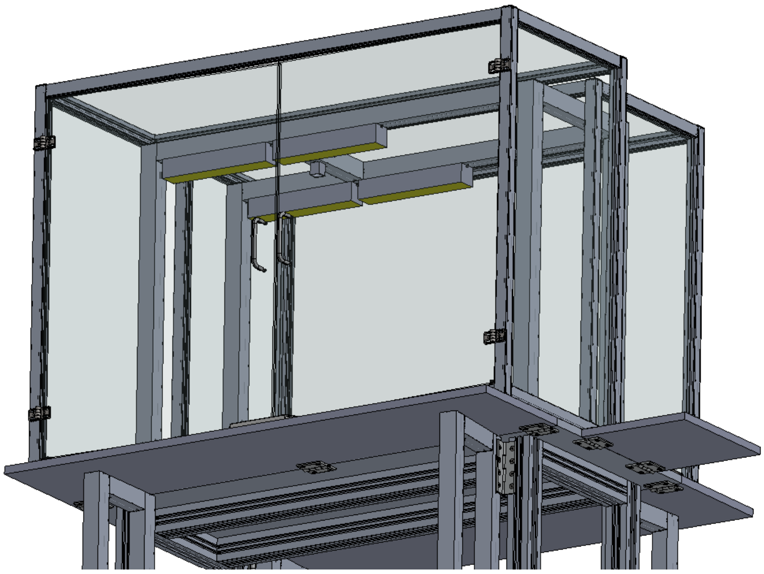


Figure 5.5 Location of the camera and light sources in the test bench.

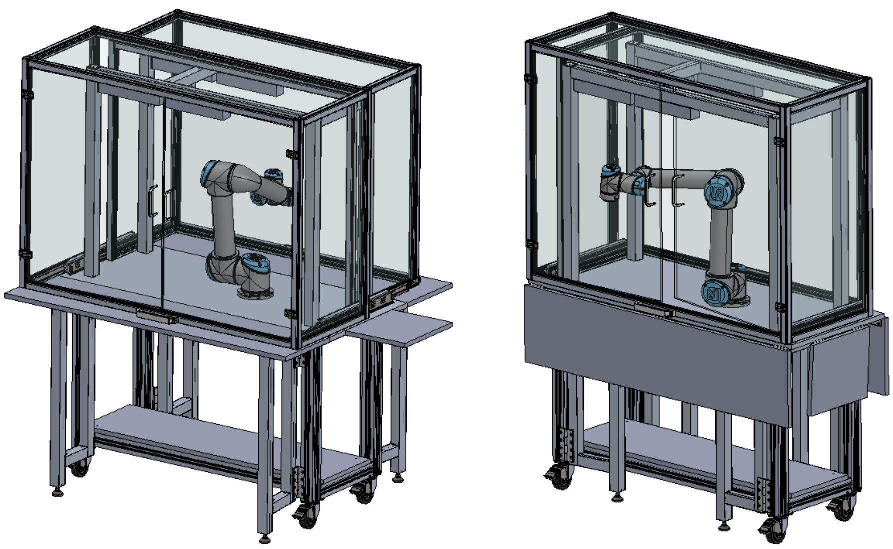
6 RESULTS OBTAINED

This chapter shows the results that have been obtained throughout the thesis, such as the final dimensions of the test bench, its weight or the cost of the project.

The final design of the test bench has overall dimensions of 1420,91 mm x 520 mm and 1857,45 mm in height when closed and 1700 mm x 997,52 mm and 1857,45 mm when unfolded. These final measures fulfil the desired requirements so that it can be transported from one room to another through the doors. In addition, its weight will be approximately 170 kg taking into account its own weight, plus the weight of the robot, the control box and an approximate weight of 1 kg for the lighting system. Since the test bench has a system of wheels, the weight will not be a problem when it comes to being transported, so it also meets the previously established requirements.

On the other hand, the total cost of the project resulted from the type of light source that was finally chosen and could vary between approximately 2370 € in the case of selecting four halogen lights, approximately 4600 € in the case of selecting two units of HSI LED lights and 6835 € when selecting four HSI LED lights.

Finally, the final design is shown in Figure 6.1 where you can see the installation of the lights and camera and the robot already located in its place.



a) b)

Figure 6.1 Location of the camera and light sources in the test bench where a) opened test bench and b) closed test bench

7 FUTURE JOBS

Once this project is finished, an evaluation is carried out to detect problems and improvements that could be carried out as future works. One of these improvements could be to create a system that ensures the safety of the operator and that of the robot itself. For this, the idea of introducing some sensors in the cover doors and in the sliding system of the covers is raised, thus ensuring that the robot will not start operating until the doors are closed and the cover fully expanded. In addition, if the cover doors are opened during its operation, the robot will stop immediately to avoid a collision with the operator.

On the other hand, regarding the HSI LED lights, the fact of buying a lamp and testing it in the lighting laboratory of the university to measure the light distribution using the goniometer could be considered as future work. With this information it could be determined how many light units would be needed for this project and its distribution, making its implementation possible with all the advantages mentioned in Chapter 4 that this entails.

Finally, another future job would be to carry out the manufacture of the test bench and thus be able to turn this project into something tangible and very useful.

8 SUMMARY

During the development of this project, a universal test bench has been designed that allows a robotic arm, UR5 from Universal Robots, to be able to operate through the application of machine vision. For this, the design is carried out based on the previously established desired requirements and after carrying out different calculations to ensure its stability and resistance, the final design is obtained. This final design consists of a main expandable worktable with two arches where the cameras and lights are located. In addition, it has a cover to avoid collisions of the robot with objects or people that are around it.

On the other hand, a market search is carried out to determine which lighting source is the most suitable for this project so that it meets certain requirements based on the cameras with which the robot is going to work, considering that one of them is one hyperspectral camera and the other monochrome. To complete this process, different simulations are carried out in the DIALux evo software to determine the ideal configuration and the number of lamps needed based on the illuminance obtained in each simulation. In this way, it is concluded that the best light sources that can be applied to this project are halogen lights and a novel light source called HSI LED, which, as its name indicates, is an LED light and therefore has greater advantages over halogen lights but it is more expensive.

Next, several connection diagrams are designed that show how the installation of the lights and cameras should be carried out, depending on the type of light source chosen when the project is manufactured, taking into account the most efficient way to power them in each situation, using the control box or an external power supply if necessary.

Finally, after carrying out the project, it is concluded that the main goal of the project has been achieved, developing a multipurpose machine vision test bench with a robotic arm, which can be used to operate with different objects of different sizes, materials and colours and thanks to the lighting system that it has, the problems that usually arise related to the shadows produced by the ambient light or an inappropriate wavelength for the camera which is in use will be avoided.

Overall, as main future job it will be to carry out the manufacture of the test bench and thus be able to turn this project into something tangible and very useful.

9 KOKKUVÕTE

Selle projekti raames kavandati universaalne test/töölaud, mis võimaldab robotkäel, Universal Robots UR5, masinnägemise abil töötada. Lähtudes eelnevalt kehtestatud ja soovitud nõuetest viidi läbi projekteerimine ning pärast erinevate arvutuste tegemist, töölaua stabiilsuse ja vastupidavuse tagamiseks, jõutigi lõpliku tulemuseni. Lõplik disain koosneb reguleeritavast, kahe kaarega põhitöölauast; kaartel asuvad kaamerad ja valgustid. Lisaks on sellel kate, vältimaks roboti kokkupõrkeid töölaua ümber olevate objektide või inimestega.

Teisalt viidi läbi turu-uuring, selgitamaks välja, milline valgusallikas on selle projekti jaoks kõige sobivam. Valgusallikas peab vastama teatud nõuetele, lähtudes kaameratest, millega robot töötab. Arvesse tuli võtta, et kaameratest üks on mitme- ning teine ühevärviline. Selle protsessi lõpuleviimiseks viidi DIALux evo tarkvaras läbi erinevaid simulatsioone - igas simulatsioonis saadud valgustustiheduse põhjal sai määrata kindlaks ideaalse konfiguratsiooni ja vajaliku lampide arvu. Nii jõutigi järeldusele, et parimad valgusallikad, mida antud projektis kasutada saab, on halogeenvalgustid ning uudne valgusallikas nimega HSI LED. Nagu nimigi ütleb, on tegemis LED-valgustiga ja seetõttu on sellel halogeenvalgustitega võrreldes suuremad eelised, kuid see on kallim.

Järgmise etapina koostati mitmed ühendusskeemid, mis näitavad, kuidas tuleks valgustite ja kaamerate paigaldamine läbi viia võttes arvesse projekti valmistamisel valitud valgusallika tüüpe ning pidades silmas kõige tõhusamat viisi nende töötamiseks igas olukorras, kasutades vajadusel juhtpulti või välist toiteallikat.

Pärast projekti läbiviimist jõuti lõpuks järeldusele, et projekti põhieesmärk on saavutatud - välja on töötatud mitmeotstarbeline masinnägemise ja robotkäega töölaud, mida saab kasutada erineva suuruse, materjali ja värvi objektidega töötamisel. Tänu erilisele valgustussüsteemile, välditakse tavaliselt tekkivaid probleeme, mis on seotud ümbritseva valguse poolt tekitatud varjudega või kasutatava kaamera jaoks sobimatu lainepikkusega.

Kokkuvõtvalt - tulevikus on peamiseks eesmärgiks selle töölaua valmis tegemine ning muuta see projekt seeläbi millekski reaalseks ja ühtlasi väga kasulikuks.

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APPENDICES

Appendix 1 Ximea xiSpec MQ022HG-IM-LS150 VISNIR Datasheet

xiSpec

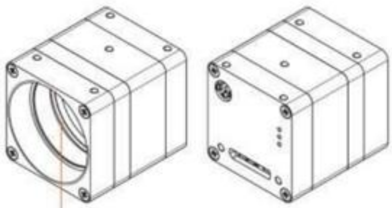
[sci-spek]
or [ksi-spek]

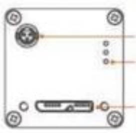
The unique **xiSpec** series offers linescan and snapshot mosaic hyperspectral cameras, being smallest in class by far and combining extreme low power consumption and acquisition of hyperspectral imaging (HSI) raw data at very high frame rates. This camera is implemented in a plethora of applications where chemical differentiation is required: e.g. medicine, agriculture, food processing, waste disposal and many more. The small size, low weight and robustness make it an ideal choice for mobile environments such as drones or handheld devices.

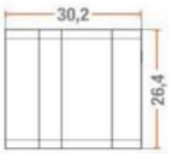
Quick facts

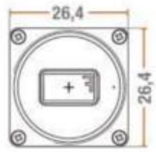
- Smallest and lightest HSI camera
- Single PCB, board-level versions available
- Lowest power consumption, only 1.8 W
- 16 to 150 bands, 170 HSI data cubes or up to 1360 lines per second
- USB3 Vision compliant

Housed cameras









Sensors and models

Model	Sensor type	Spectral range [nm]	Bands
MQ022HG-IM-LS100-NIR	Linescan	600-975	100+
MQ022HG-IM-LS150-VISNIR	Linescan	470-900	150+
MQ022HG-IM-SM4X4-VIS	Snapshot Mosaic	470-630	16
MQ022HG-IM-SM5X5-NIR	Snapshot Mosaic	600-975	25

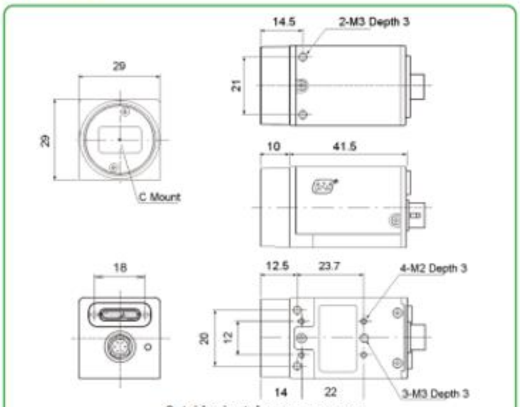
Appendix 2 Ximea xiSpec MQ022HG-IM-LS150 VISNIR Datasheet

Specifications for GOX-3201-USB

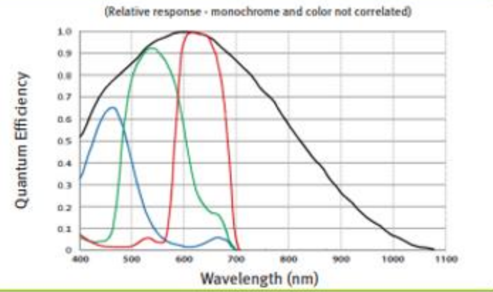
Go-X Series

Specifications	GOX-3201-USB
Sensor	1/1.8" CMOS global shutter (IMX265)
Active pixels	2048 (h) x 1536 (v)
Frame rate, full frame	55 frames/sec. @ 8-bit mono/Bayer
Active area	7.07 mm (h) x 5.3 mm (v) - 8.83 mm diagonal
Pixel size	3.45 µm x 3.45 µm
System clock	74.25 MHz (for pulse generator)
Read-out modes Full ROI (single) Binning	 2048 (h) x 1536 (v) up to 55 fps H: 96 to 2032 pixels in 16 pixel steps V: 8 to 1534 lines in 2 line steps 1x2, 2x1, 2x2
EMVA 1288 Parameters Absolute sensitivity Maximum SNR	10-bit output format Mono: 3.29 p Color: 3.59 p (λ = 527 nm) Mono: 39.7 dB Color: 39.7 dB
Traditional SNR*	>60 dB mono, >60 dB color (0 dB gain, 10-bit)
Video signal output	Monochrome: 8/10/12-bits† Color: 8/10/12-bit Bayer†
Gain	Manual/auto 0 dB to +42 dB
White balance	Off, presets, or one-push/continuous AWB
Gamma/LUT	0.45 to 1.0 (9 steps) or 257-point programmable LUT
Synchronization	Internal
Video modes	Normal/Single ROI, Sequencer (Trigger & Command)
Trigger input	Opto In, Pulse Generators (4), Software, NAND Out (2), User Output (4)
Exposure modes	Timed/EPS, RCT, Trigger Width, Auto
Electronic shutter	Timed: 14.73 µs to 8 sec. in 1 µs steps Auto: 100 µs to 18.1 ms at full resolution
Auto Level Control (ALC)	Shutter range from 100 µs to 18.1 ms, gain range from 0 dB to +42 dB. Tracking speeds and max. values adjustable.
Shading correction	Flat shading, color shading (color model)
Pre-processing functions	H & V flip (mirroring), blemish compensation, H & V decimation
Operating temp. (ambient)	-5°C to +45°C (20 to 80% non-condensing)
Storage temp. (ambient)	-25°C to +60°C (20 to 80% non condensing)
Vibration	10G (20 Hz to 200 Hz, XYZ directions)
Shock	80G
Regulations	CE(EN 55032:2015(CISPR32:2015), EN 55035:2017(CISPR35:2016)), FCC Part 15 Class A, RoHS/WEEE, KC
Power 6-pin USB 3.0	+10V to +25V DC. 4.3 W typical @ +12 V +5V DC. 4.2 W typical @ +5 V
Lens mount	C-mount
Dimensions (H x W x L)	29 mm x 29 mm x 51.5 mm
Weight	62 g

Dimensions



Spectral Response



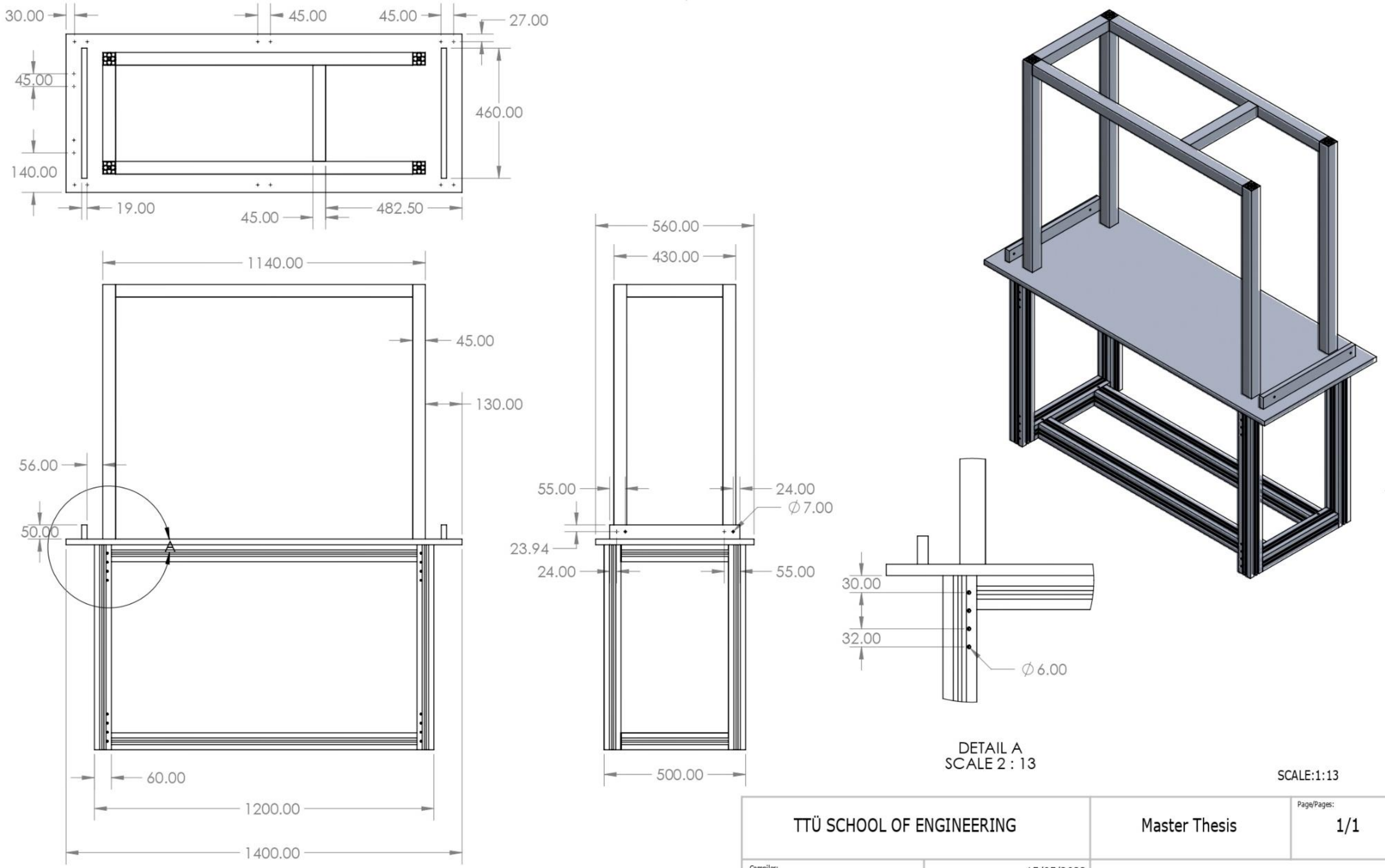
Appendix 3 Bill of materials of the test bench

Table A3.1 Bill of materials of the test bench

Part	Material	Quantity	Characteristics	Price/unit	Total price (€)
Base	Profile 60x60	4	Aluminium profile 60x60 MiniTec Length: 725 mm	42,24€/m	493,28€ 14 cuts x 2,75= 38,5€
	Profile 60x60	4	Aluminium profile 60x60 MiniTec Length: 1080 mm		
	Profile 60x60	4	Aluminium profile 60x60 MiniTec Length: 380 mm		
Arch	Profile 45x45	4	Aluminium profile 45x45 G MiniTec Length: 900 mm	25,3€/m	348,13€ 24 cuts x 2,75= 66 €
	Profile 45x45	2	Aluminium profile 45x45 G MiniTec Length: 1050 mm		
	Profile 45x45	2	Aluminium profile 45x45 G MiniTec Length: 340 mm		
Legs	Profile 45x45	8	Aluminium profile 45x45 G MiniTec Length: 160 mm		
	Profile 45x45	4	Aluminium profile 45x45 G MiniTec Length: 725 mm		
	Profile 45x45	4	Aluminium profile 45x45 G MiniTec Length: 800 mm		
Big Cage	Profile 30x30	4	Aluminium profile 30x30 2G MiniTec 990 mm	9,63€/m	85,68€ 22 cuts x 2,5= 55€
	Profile 30x30	3	Aluminium profile 30x30 2G MiniTec 1323.26 mm		
	Profile 30x30	4	Aluminium profile 30x30 2G MiniTec 460 mm		

Part	Material	Quantity	Characteristics	Price/unit	Total price (€)
Small Cage	Profile 30x30	4	Aluminium profile 30x30 2G MiniTec 950 mm	9,63€/m	57,12€ 11 cuts x 2,5= 27,5€
	Profile 30x30	3	Aluminium profile 30x30 2G MiniTec 1158.74 mm		
	Profile 30x30	4	Aluminium profile 30x30 2G MiniTec 430 mm		
	Hinges Leg	8	Door hinge large MiniTec	31,45€/u	251,6 €
	Hinges Wing	6	Full overlay hinge Leroy Merlin	1,99€/u	11,94 €
	Hinges Window	4	Hinge 30 S MiniTec	8,87€/u	35,48 €
	Caster wheels	4	Cater 3.5" MiniTec	42,65€/u	170,6 €
	End Caps	8	45x45 End cap MiniTec	0,85€/u	6,8 €
	End Caps	8	30x30 End Cap MiniTec	0,95€/u	7,6 €
	Foot Pad	4	45x45 Foot Pad MiniTec	2,21€/u	8,84 €
	Levelling Pad	4	45 diameter Levelling Pad MiniTec	6,40€/u	25,6 €
	MDF plates	2	2440 x 60 mm plate Bauhaus 3€/cut (8 cuts)	49,99€/u	99,98 € 8 cuts x 3= 24 €
	Handle Window	2	Handle AL MiniTec	10,03€/u	20,06 €
	Handle Cage	2	Handle 180 MiniTec	8,3€/u	16,6 €
	Telescopic slide rails	2	250 mm telescopic slide rails Amazon	22,41€/u	44,82 €
	Methacrylate	3 m2	4 mm Methacrylate Rotulatumismo	49,3€/m2	148 €
	Seal	20 m	Insert Seal 6 MiniTec	1,8€/m	36 €
	Links	68 + 10 extra	Links MiniTec	4€/u	312 €
TOTAL					**2363,85 € (no VAT)**

Appendix 4 Drawings of test bench design



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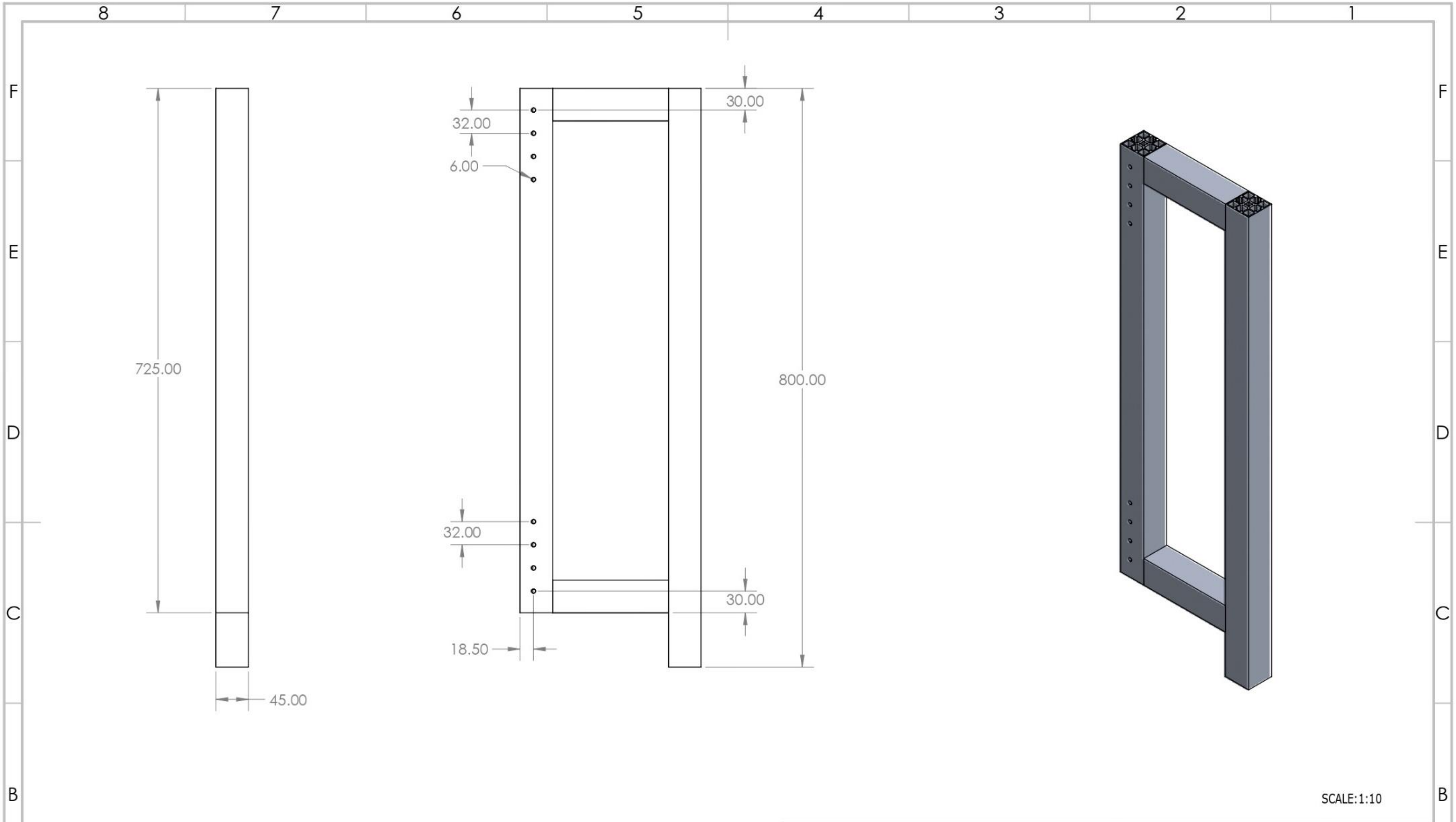

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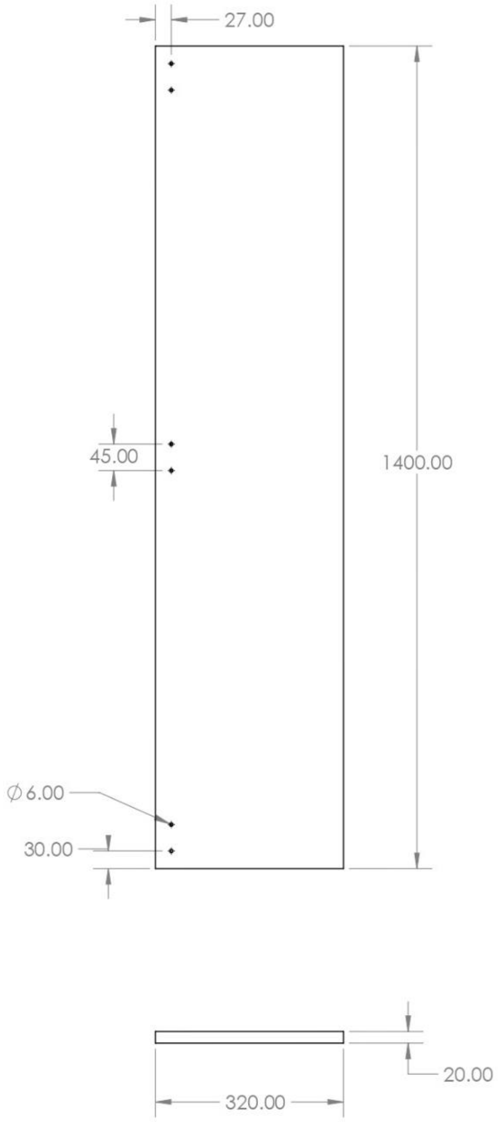

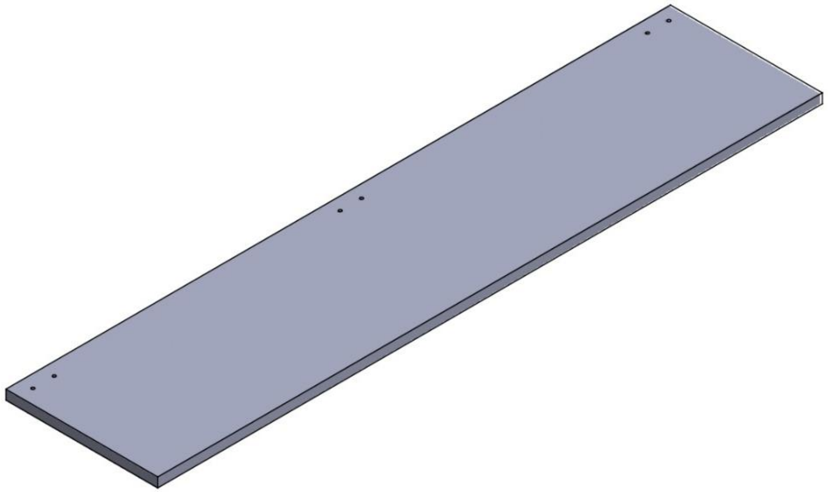

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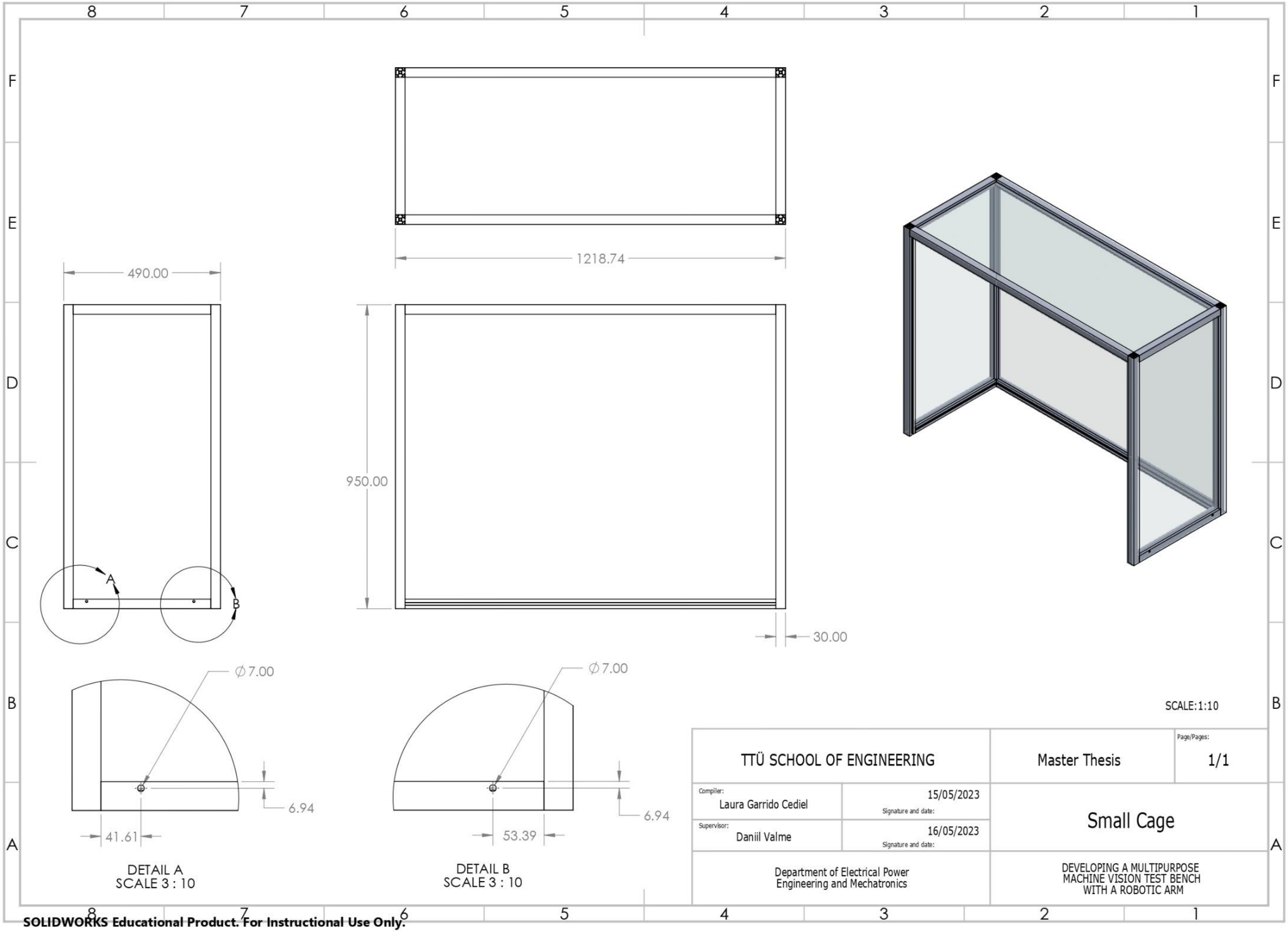

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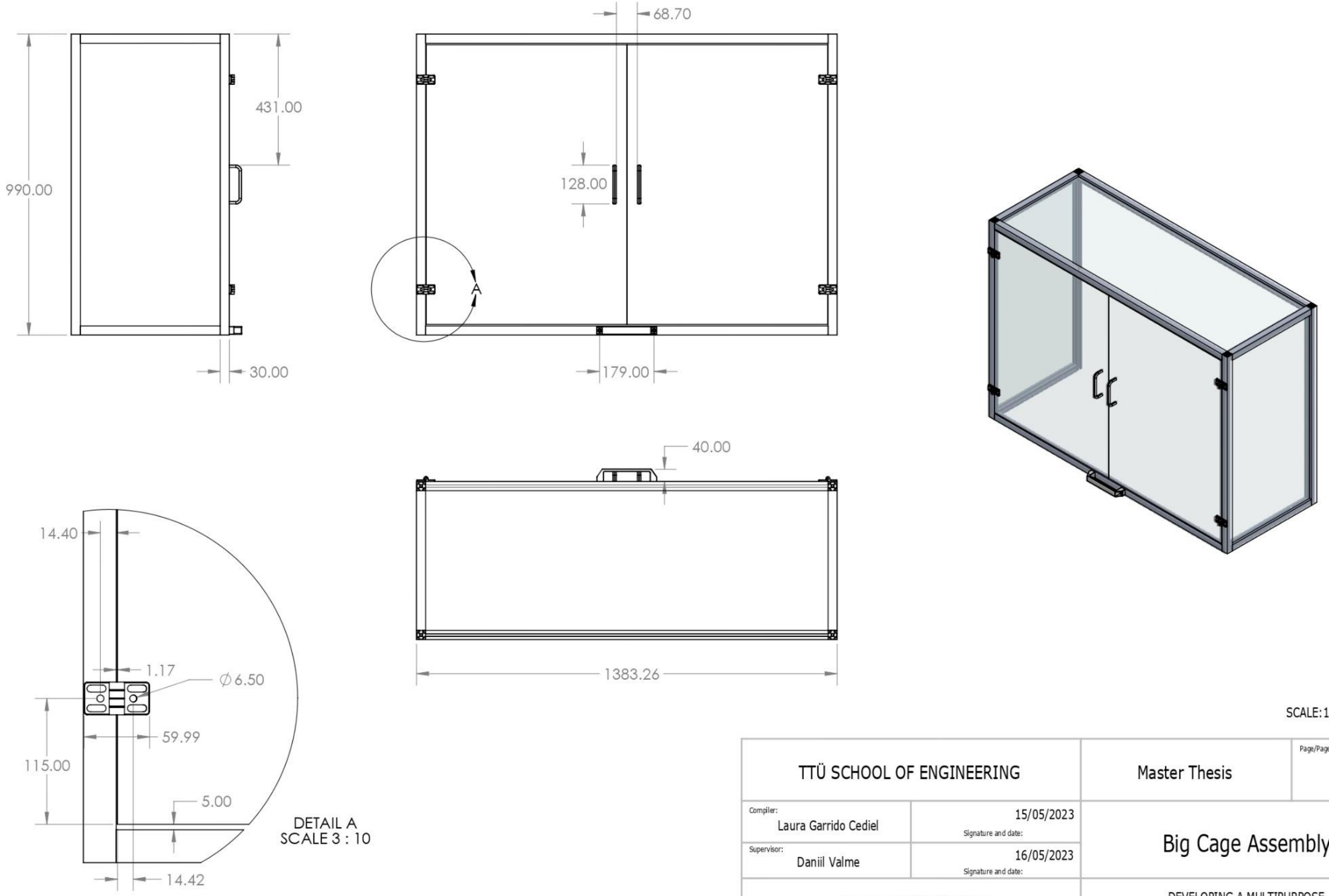

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Big Cage Assembly

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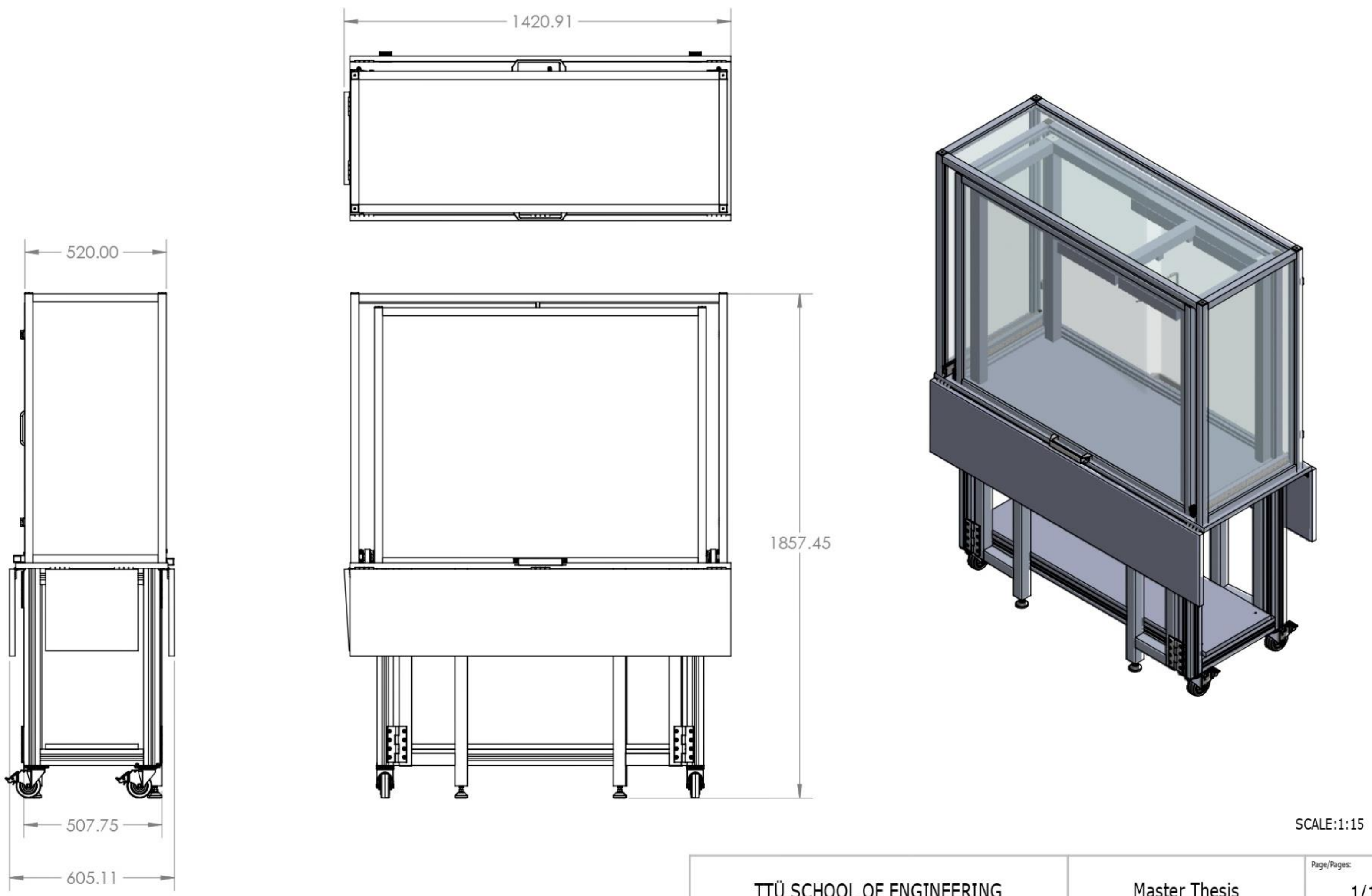

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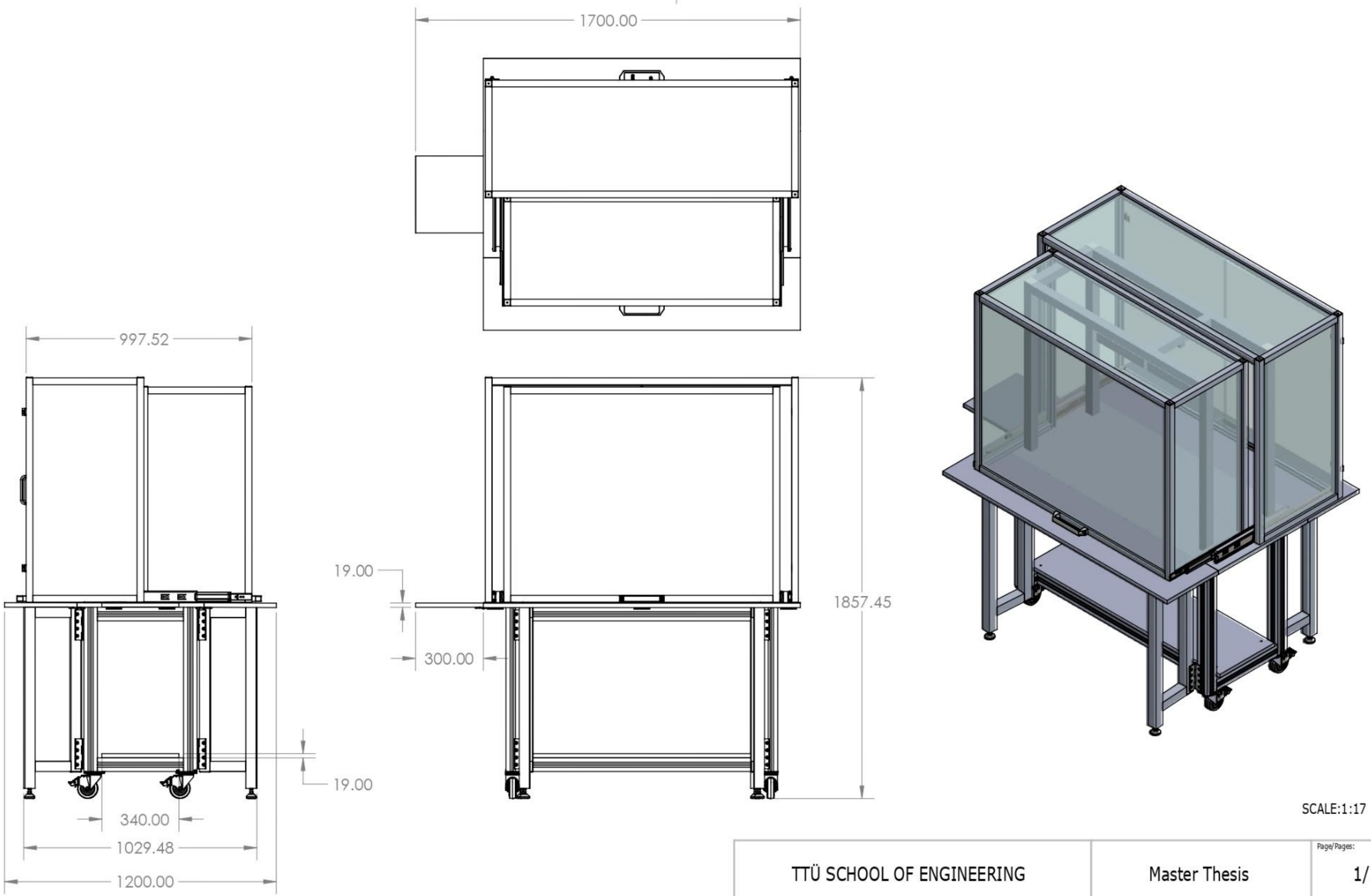

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