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Design and Development of a Test Bench for Robotic Interventions

CERN

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Abstract

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Abstract

The goal of this thesis was to design a test bench for robotic interventions as a part of a collaboration with the CERN Robotics Department. The objective of the project was to develop and design a station at which the functional possibilities of robots could be rigorously tested and demonstrated before being sent on actual missions.

The design process of the proposed product was based on the comparison of the initial concepts, determination of technical specifications and functional possibilities of the future device, the definition of the constituting mechanisms that ensure the tests of robots' capabilities.

The outcome is presented as a 3D assembly uniting various systems, accompanied by a detailed material selection for the test bench framework. The represented documentation provides recommendations and considerations for future studies and the development of the product designed from scratch.

Keywords

CERN, test bench, robots

Contents

1 Introduction

Intelligent robotic systems are becoming essential for industries and productions, being an irreplaceable element in terms of the harsh working environments including the particle accelerator complexes and experiments at CERN, the European Organization for Nuclear Research, in collaboration with which this work has been carried out.

At the home of the world's largest and most powerful particle accelerator, the usage of the robotic equipment is highly required due to many perilous factors concentrated in a confined space, meaning that even routine operations by humans would be difficult and costly (CERN a).

The numerous tasks completed by robots at CERN ensure a completely safe environment preserving human visitors to be hazardously exposed by ionizing radiation, electrical or magnetic fields, protecting from the risk of oxygen efficiency, while providing teleoperated maintenance operations, autonomous inspections, repairs and tuning carried out not only at the LHC (Large Hadron Collider) complex, but at many others facilities and installations.

1.1 Research objectives and motivations

Such multifunctional and compound systems as robots have to be rigorously tested in advance before being sent on an actual mission undergoing real working conditions. The research will be dedicated to the project of design and development of a test bench allowing the preliminary performance of robots operating trials, demonstrating that the robots are capable to work with specific systems and grant necessary manipulations, guaranteeing reliable and safe utilization.

The goal of the current study is to contribute to the solution of minimization of the need for human presence and labour at the zones of health and safety risks by ensuring that the necessary operations in hostile environments can be carried out as a consequence of the usage of robotic equipment. Robotic manipulations help to prevent potential accidents causing a severe threat to life, as well as occasionally completing tasks faster, safer and more reliable, resulting in better quality outcomes. Such an approach is aimed not only to reduce human involvement but also to improve productivity, efficiency and accomplishment quality of desired interventions depending on the nature and magnitude of the hazards.

The fact that human nature influences the research has a place to be. The objectivity of the study is affected by the motives and material resources of the researcher. The present investigation is conditioned by the personal conviction that idea matters and there is a possibility to make a difference. This work is an opportunity to inquire and create, communicating the findings while learning more about how the world works, desiring to be of service to society.

This fundamental interest is described by the desire to face the challenges in solving current practical problems of the proposed topic and get the intellectual joy of doing some creative work.

The conceived system might be successfully utilized not only in terms of the surroundings of CERN where many unique challenges are presented at the same time but also can be relevant to many other harsh fields where the minimization of human work is essential, e.g. nuclear power plants, space and aviation industries, railways, mining, petrochemical sector, oil and gas industries, pharmaceuticals and other fine chemical productions.

The correlation between several spheres confirms the relevance of the suggested research which will be dedicated to the study which may become at least a small step towards the contribution to the scientific world.

1.2 Scope

The section defines what the study is going to cover and what it focuses on simultaneously with establishing what the study is not going to cover, setting the limitations.

The robots used in terms of CERN infrastructure will be a reference point of the study, their structure will be investigated to flag the working principle and define the essential operations. This knowledge will be a base for future considerations and design suggestions, reflecting the working system. This investigation will cover the mechanical comparability of CERN robots to the bench potential design, definition of individual constituting systems for each function and their creation, material selection, consequently uniting the obtained results in an output of one design of the test bench, forecasting its probability of being integrated and providing recommendations.

Several crucial aspects are highlighted and will be gone through during this study:

- Robots types, chief constructions and the principle of work
- Auxiliary components and tools
- Design of constituting mechanisms

With regard to what is going to stay abroad of this research, it is the electrical filling by which the test bench will be run. In addition to this, the programming and coding of particular components included in the working structure will not be described. Any conclusion and decision in terms of these aspects should be reinforced with a full-fledged own research on the topic. The research is going to cover the design and construction of the subject being studied showing the mechanical dependencies and connections.

The conceived outcome of the study will be represented in a form of a test bench 3D-model including divers constituting mechanisms separately designed for specific testing purposes. The output of a concept level model will demonstrate the external styling of the device and correlations between the composing mechanical arrangements. Whereas the emphasis is placed on the development of devices that make up the entire test bench, they will be designed depending on the preliminary definition of the desired functional requirements, as well as based on the dimensional relationships with regards to the utilized robots and between the projected devices themselves.

The product will be done with a perspective that it can be easily modified and advanced by other designers proceeding with this CERN project in terms of which the current development is held. The outcome of the current study will not be a fully designed product with 2D drawings as far as the elaboration has just started and the evolution of the product will be hereinafter carried out by the Robotics department.

All the listed aspects will build insight on what frames to adhere and what to concentrate on. Establishing these parameters is crucial especially when working on such a complex and time-dependent project uniting many specialists, as in the case of the present work.

1.3 Thesis organization

The thesis is built in the way of first providing theoretical basics needed for an acquaintance with the subject being studied and the environment for which it is planned to be built. General knowledge of CERN and its structure will be described as well as the reason why the test bench for robotic interventions should be created in terms of CERN's medium.

In addition to this, the theoretical section is going to cover the representation of the available robots that are planned to be tested with the test bench, their functional possibilities and requirements, tasks and contexts of use.

Onwards, based on the analysis of the theoretical data, initial concepts are represented, consequently selecting the optimal one and proceeding with the practical part, implying the design itself.

The main unit of the thesis illustrates the process of the creation of 3D models, the practical comparability and integration of the highlighted technologies with the general design of the test bench while comparing the options and forecasting each one's efficiency in terms of the overall structure.

The concluding section provides a summary of the completed study, presents the obtained results with all the assumptions and estimations, gives recommendations and discusses the future potential tendencies. Furthermore, the possible utilization of the gotten product for different industry field applications is depicted, proving the demand for such a device.

2 Background

2.1 Introduction to CERN

CERN, which stands for the European Organization for Nuclear Research, is one of the largest and the most respected laboratories for scientific research on Earth, based in a northwest suburb of Geneva on the Franco-Swiss border (Wikipedia 2020). Established in 1954, it currently has 23 member states that contribute to the capital and operating costs of CERN’s programs and are responsible for all important decisions about the Organization and its activities (CERN b).

Science brings nations together towards a common goal and thousands of scientists from all over the world are welcomed to CERN annually, resulting in one of the most multicultural and diverse environments in the scientific world (CERN c).

Specializing in high-energy physics research, CERN seeks to find answers to the most fundamental questions, especially concerning the Standard Model, studying the basal constituents of matter and forces acting between them.

2.1.1 CERN’s accelerators complex

CERN complex is a succession of machines at which numerous experiments are held to study nature’s tiniest building blocks. Operating a network of seven main accelerators creating a chain, each element of which increases the energy of the particle beams running almost at a speed of light before delivering them to the necessary experiments or to the next more powerful accelerator, featuring the most expensive and advanced scientific experiment and laboratory in history as the final stage – the Large Hadron Collider (LHC). It is built in a circular 27 kilometres underground tunnel along which powerful superconductive magnets and four major detectors are situated. Through this machine, beams of particles (e.g. protons) are accelerated and consequently smashed together at high energies to reproduce conditions similar to the first instants of the universe. These collisions create great disturbances in quantum fields and lead to the spontaneous birth of new particles that are obtained as decay products. The four huge detectors help to observe these new species that might be invisible otherwise. (CERN d; CERN e)

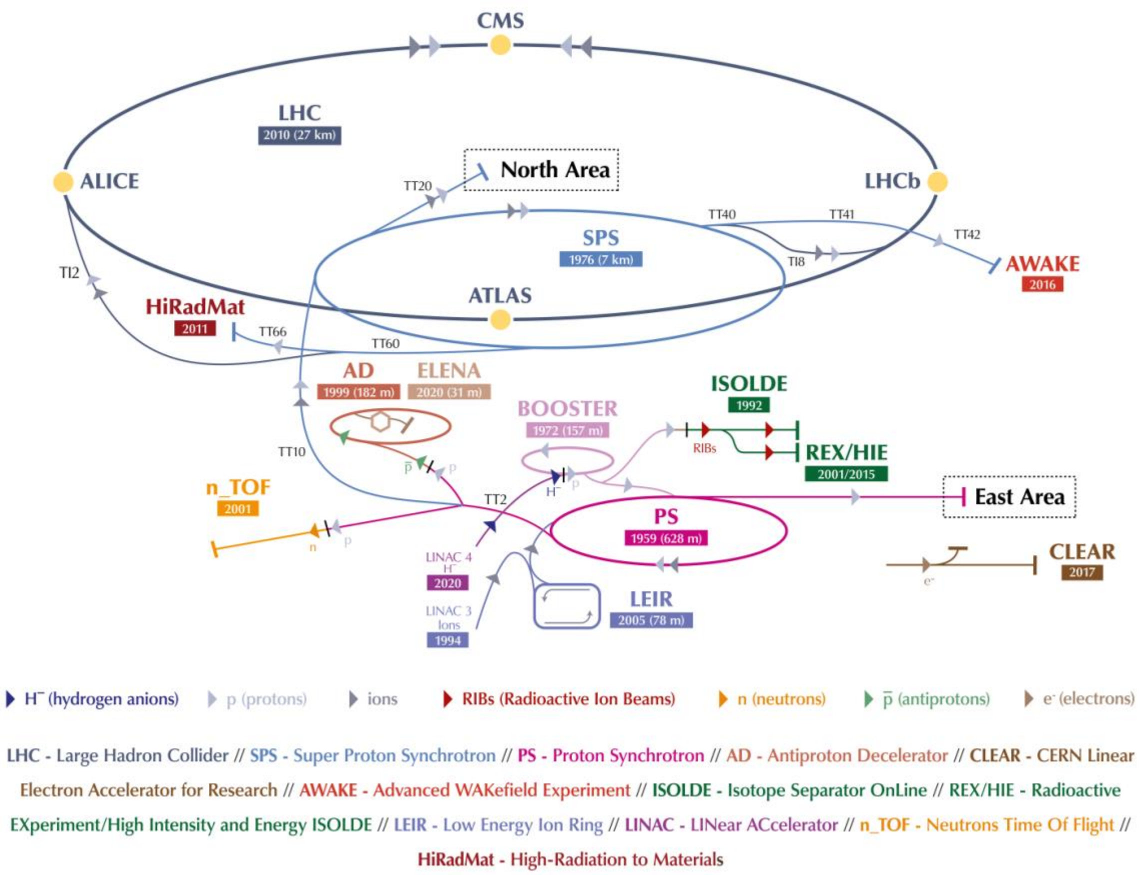


Figure 1. The CERN accelerator complex (Mobs 2019)

The enormous sizes of the facilities are conditioned by the fact that the heavier the desired particles are, the more energy is needed to produce it as the well-known formula (1) says. A lot of energy is needed to make particles that are assumingly nothing, but then the massive detectors are needed to see all of the debris that comes out and the particles that the initial ones decay into.

$$E = mc^2 \quad (1)$$

The monumental discoveries of CERN include the invention of the World Wide Web (WWW), the successful creation of a form of antimatter called antihydrogen, detection of the Higgs Boson, the tip of the iceberg when it comes to fundamental particles that make up everything in the universe (CERN 2003; Lewis 2014). These are not all crowning achievements that have been done at CERN, however, they all led to the development of many global fields such as medical and biomedical technologies, aerospace applications, safety and environment industries.

2.2 Robotic systems usage purpose in hazardous environments

Many industries that play essential roles in the development of the modern world have hazardous environments in which working personnel might regularly be exposed by potentially fatal hazards, that may include radiological, chemical, biological, thermal, electrical and other hazards. Such mediums require the highest levels of competency, innovation and most importantly - safe working methods, restricting access by humans and necessitating the use of robots to complete many jobs, replacing humans in undertaking hazardous activities in demanding or dangerous environments. The range of such sectors is described by the petrochemical sector, nuclear, onshore oil and gas, energy production, explosive industries, bulk chemical storage, pharmaceuticals and other areas.

The LHC tunnel and other experimental zones at CERN are not an exception. The main hazards of ionizing radiation, high electro-magnetic fields and oxygen deficiency are the reasons for the underground location of the facility in order to provide a natural barrier. In addition to this, remote inspection and maintenance offer the possibility of reducing human interventions aiming to increase safety and productivity. The purpose of the robotic projects at CERN is to develop the autonomous and teleoperated manipulations for machine maintenance, visual and audio detection of anomalies, measurements, inspections, mappings and performance of various mechanical operations.

2.3 Overview of CERN’s robots

A brief description of the robots that are likely to be tested with the help of the potential outcome in a form of the test bench is represented in Appendix 1, including the functions, technical specifications and general illustrations. This section introduces the robotic systems teleoperated by the working group in order to have a theoretical fundament, a reference point of the study, based on which the design will be discussed. The mentioned functionality aspects define the structure of the possible design in terms of the operations that have to be demonstrated using the test bench.

3 Product specifications development

3.1 Spatial requirements

The proportions of the future design are regulated by the dimensions of the space the test bench will be installed at. A certain area has been defined specifically for the installation of the device, therefore, the available space had to be studied beforehand to set the spatial capacity. The following scheme (Figure 2, Figure 3) illustrates the construction of the allocated zone, where the dimensions are mentioned in meters.

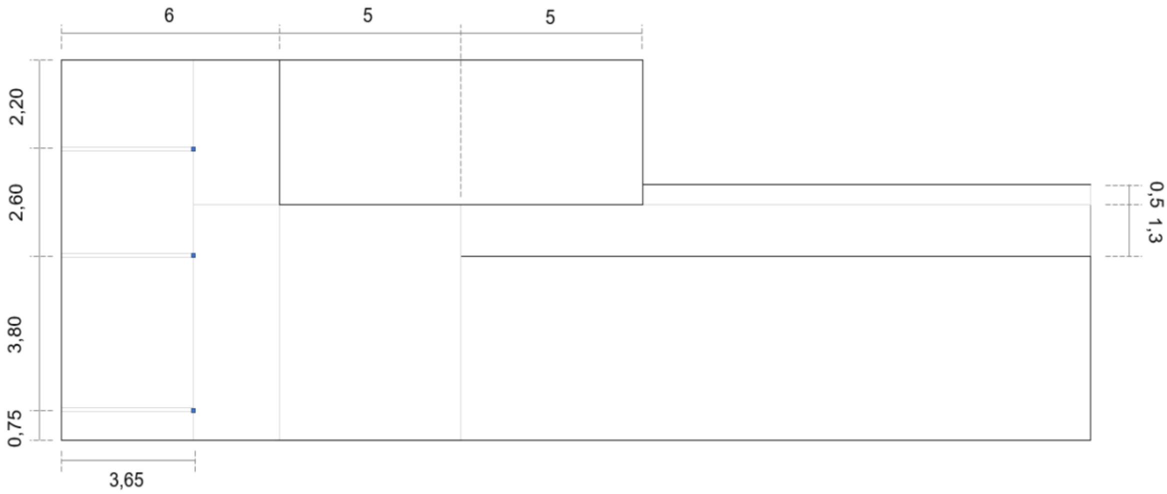


Figure 2. Available space dimensions

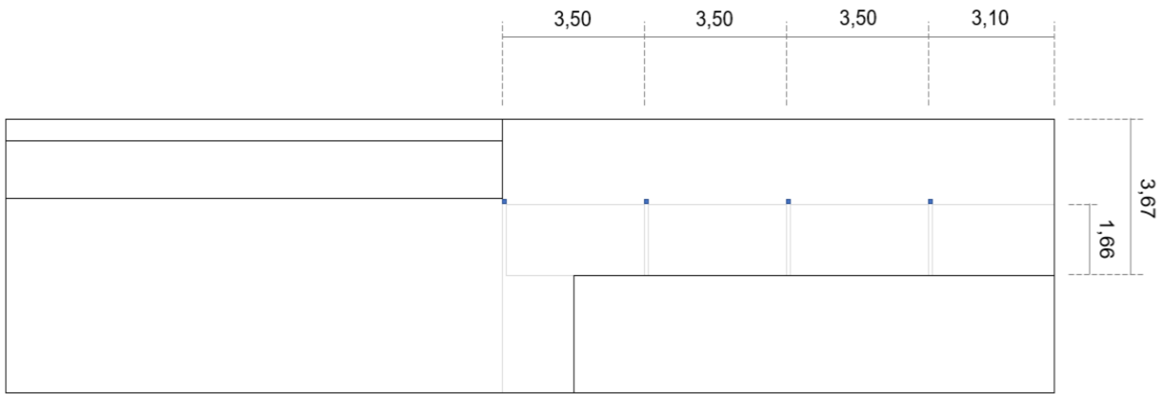


Figure 3. Available space dimensions

The top view is divided into two parts where the first figure is the left part of the entire place, while the second figure is the continuation of the facility. The test bench itself is planned to be placed at the right end of the corridor, behind the beam construction marked with blue squares. Therefore, as the plan shows, the maximum length and width dimensions of the test bench should not exceed 3,50 m x 1,66 m since the bench might be located within one slot area, whereas the maximum allowed height of the construction is 3 m.

These actions assisted in the initial definition of the shape and size of the future mock-up. Not only the dimensions of the special area for the test bench positioning were considered, but also the surroundings as far as the test bench should be first delivered across them, so its dimensions have to fit the entire place.

3.2 Functional possibilities

The list of functions that the robots should be capable to demonstrate with the help of the test bench should be developed based on the knowledge of the current functional possibilities that are described in the “Overview of CERN’s robots” section to create the requirements for the design.

3.2.1 Modules definition

It was decided to use modularity in the design, an approach of subdivision of a system into smaller parts called modules in such a way that they can be independently created, modified, replaced or exchanged between different systems.

This method allows the modification of specific modules for a new requirement without influencing the main infrastructure so that the complex problems can be decomposed into several small ones. It can be especially employed in the current research since some of the constituting components of the test bench are presented in a form of assembly of several smaller parts (e.g. gear, electric circuit).

The reason why this approach was selected is its advantages of design flexibility, augmentation and cost reduction. The modularized components make con-current engineering and flexible manufacturing possible.

In addition to this, modular design reduces the overall number of components or parts consequently reducing the associated indirect costs (administrative and logistical), reduces redesign or test cost by using existing modules rather than new parts.

The idea is to design a testing bench with the opportunity of having several sections of modules intended for different operating and maintaining purposes. Based on the listed operations, three major functional modules were defined that are presented below together with the functions included in each module.

Module	**Function**
Inspection	Visual inspection
	Audio inspection
	Radiation mapping
	Oxygen percentage
	Temperature mapping
	Cell phone reception
	Wiping test
Maintenance, tests	Transporting and positioning
	Extraction, removal
	Insertion
	Vacuum leak test (helium spray system)
	Providing access to closed spaces
	Disposing of dangerous (radioactive) items
	Epoxy resin or oil filling or emptying
	Providing and placing foam
Mechanical operations	Drilling
	Laser welding
	Screwing/unscrewing

	Cutting different materials
	Use of electrical and mechanical tools
	Delivering high torque output

Table 1. The defined operating modules

These modules are the first step in developing construction ideas of the test bench appearance that will also guide the internal structure of the device.

3.3 Constituting systems and devices

Onwards, knowing the available robots' functional and constructional arsenal, crucial constituting and auxiliary tools that are involved in the performance of the operations were defined. It was done with an eye to designating what kind of mechanisms have to be designed to correspond to the existing robot's instruments.

The list of the tools the robots might be equipped with includes:

- Electrical and universal screwdrivers
- Helium spray system for vacuum leak detection
- Nibbler
- Scissors
- Liquid pump and injector
- Peristaltic pump (Epoxy resin pump)
- Impact and torque wrench
- Foam pistol
- RP (Radio-Protection) sensor
- Pipe and cable cutter
- Saw
- Hook

Based on such a layout, various auxiliary components that might be involved in the tests are concluded. These details affect the choice and design of the constituting mechanisms the test bench will have, as they define what operational possibilities should be performed.

- Screws
- Bolts
- Nuts
- Flanges
- Washers
- Rivets
- Pins
- Rings
- Clamps
- Cables
- Valves
- Pipes
- Testing plates (for cutting, drilling, welding, etc.)
- Wires
- Hooks

Uniting this information, a catalogue of the devices for tests to be designed and included in the test bench’s structure was developed. It has to be noted that some of the mentioned systems were specifically asked to be implemented by the supervising side of the project, some of the devices have already existed and needed to be included in the bench's constituting construction.

System	**Testing purpose**
Physical objects with different levels of visibility and reachability	Ability of visual inspection, testing of the installed camera
Sound source	Audio inspection

Controlled radiation source	Radiation measurements and mapping
Device with a controllable imitation of the leak and its rate (helium)	Vacuum leak test, oxygen percentage
Heating element with the possibility of adjustable temperature rate	Temperature measuring and mapping
Sections, zones for placing and storing auxiliary elements	Transporting and positioning
System of apertures of different diameters, depths, reachability levels, inside which various auxiliary components might be positioned	Extraction, insertion of the auxiliary components (e.g. screws, bolts, pins, etc.)
Doors to be opened/closed, obstacles to be gone over	Providing access to closed spaces
Specialized space where a potential radiation source might be stored, as well as a case/box for its disposal	Disposing of dangerous (radioactive) items
Container with all the appropriate constituting elements for oil or other liquids	Oil or other liquids filling or emptying
Specimen of a pipe or similar object to imitate the water leak	Water leak repair with the help of epoxy resin filling or foam throwing
Plates samples of different materials for mechanical works	Drilling, cutting, welding, etc.
Fixation tools	Drilling, cutting, welding, etc.
Installed fasteners (screws, nuts, bolts, etc.)	Delivering high torque output, (un)screwing

Electrical connectors	(Un)plugging connectors
Water connector	Changing the copper gaskets

Table 2. Testing systems and devices

Complementary general requirements that have to be followed in the design of the test bench are listed below based on the analysis of the previously derived aspects.

- Possibility of pulling the test-bench up/down
- A power supply integrated for powering future systems
- Easy access to the test bench's inner components for maintenance
- Possibility of opening the faces to reach the internal equipment and to make the installation of the new testing components easy

3.4 Engineering specifications

Notwithstanding there are no many quantitative, measurable criteria besides the spatial dimensions that the product is designed to satisfy and there were no detailed records of technical requirements claimed from the supervising side, some crucial and evident limitations were tried to be defined to be the targets that can be followed later on. Nevertheless, some individual mechanisms might have certain strict specifications that will be highlighted in the chapters specifically allotted for their designs.

Despite the fact that most of the requirements cannot be described as metric ones, there are other parameters affecting the total effectiveness of the machine. These aspects are a crucial fundamental part in order to define the basis for material selection and future design enhancement.

- **Materials**

The coating material of the bench's frame does not have any special electrical requirements, however, the electrical conductivity of the motor-shaft system has to be good in order to make the machine work. The limitations of used materials are set by the environmental specifications in which wide temperature and relative humidity range are required. Because of the environmental requirements, materials should have good corrosion and oxidation resistance.

- **Environment**

The conceived test bench is planned to be located at a surface facility of CERN, where room temperatures are maintained, the overall required environmental characteristics are the following:

- Operating temperature: from –30°C to +125°C
- Operating humidity: from 0% to 100%

- **Ergonomics and safety**

Since the test bench is going to be supplied with electricity, the user has to be sure certain safety aspects are followed. The work zone should be clean and well lit. The device should not be used in explosive atmospheres in the presence of flammable liquids, gases or dust. Electrical safety is a crucial point. The tool plug must fit into a power outlet. The user has to avoid any physical contact with grounded surfaces such as pipes, radiators, stoves, and refrigerators.

The instrument has to be protected from rain and moisture. Water entering the instrument increases the risk of electric shock. The wire has to be handled and protected carefully as well.

The operation and maintenance of the tool should be also followed. The power tool should not be overloaded.

4 Mechanical design

The procedure of the mechanical design of the subject being studied has started with proposing the initial options of the structure appearance. The approach describes the general characteristics of each solution, consequently comparing, eliciting advantages and disadvantages of each variant, eventually determining the optimal one.

4.1 Concepts

Several potential initial designs of the future device are represented. The illustrations include just the overall appearance of the proposals, not taking into account dimensions and the exact locations of all the auxiliary systems. The sketches were performed considering the amount of the functional modules that were previously defined.

The test bench is planned to be designed as a stationary station the walls of which will be equipped with different auxiliary devices by manipulation which the test of robots and their functionals will be held. The test bench itself, as a carcass is conceived to have a possibility of being lifted up/down with the legs (potentially hydraulic ones) placed on both sides of the frame, the shapes of which are generally picturized in the concepts below. Such a shenanigan will provide easy accessibility for the robots that will be able to work with different plains superficies of the bench even from under the test bench.

In addition, a motor-shaft system can be installed with the purpose of providing an ability of rotation of the frame at the desired angle, which would ensure great reachability for the robots depending on at what side of the test bench the robot is supposed to stand.

4.1.1 Sketching

It has to be noted that the vertical pillars illustrated in the sketches represent the proposed moving legs, while the figures on the right side are the cross-section areas options of the frame on the sides of which the devices will be located.

1. Triangular base

The major disadvantage of such an option is its small cross-section area, meaning that there would be the complexity of installing the inner constituting components and all the connections between them. The closed space would significantly reduce the number of possible configurations and would cause difficulties in the maintenance. In addition to this, the intersecting angles of such a form would be an issue from the constructional point of view and would also make it difficult to place all the needed elements in an appropriate way.

However, this option has an advantage of the surfaces titled at different angles what would bring more testing opportunities.

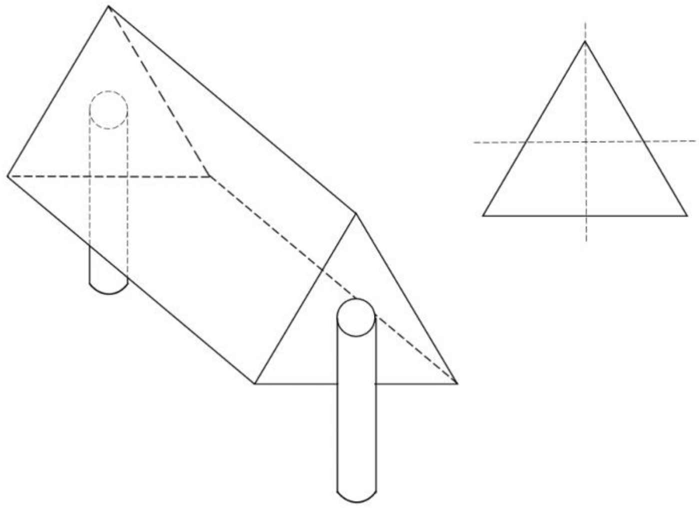


Figure 4. Triangular base concept

2. Circular base

This variant, in its turn, has similar characteristics. Its curved surface would become a challenging point when installing all the necessary devices and systems, it would be an obvious alternative to have a straight surface with an eye to having a working modular system. Having just one circular surface would also cause a problem with the internal structure and disposition of the components. In general, such an option has the same disadvantages as the previous one.

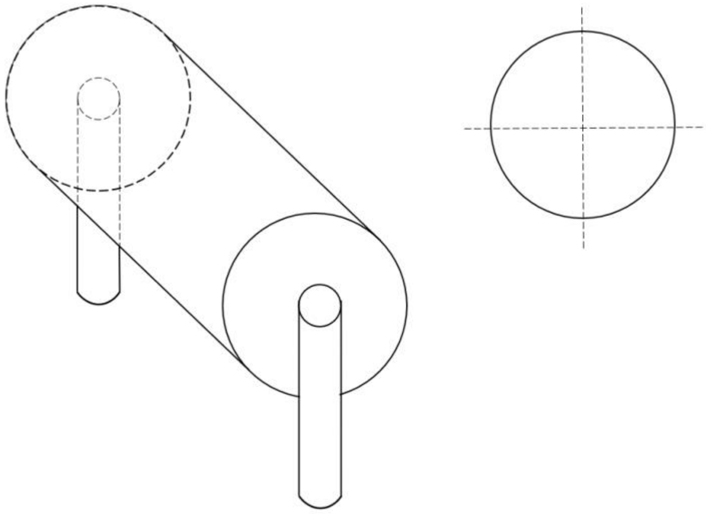


Figure 5. Circular base concept

3. Square/Rectangular base

This option seems to be an optimal one since it has many useful surfaces that can be divided into various modules to have the ability of simultaneous operations at different functional modules. With having a motor installed so that the platform can be controllably rotated, the configuration will allow accessibility and reachability at various angles. The cross-section area might be designed to be either square or rectangular, depending on the modules' configurations and mechanisms dimensions.

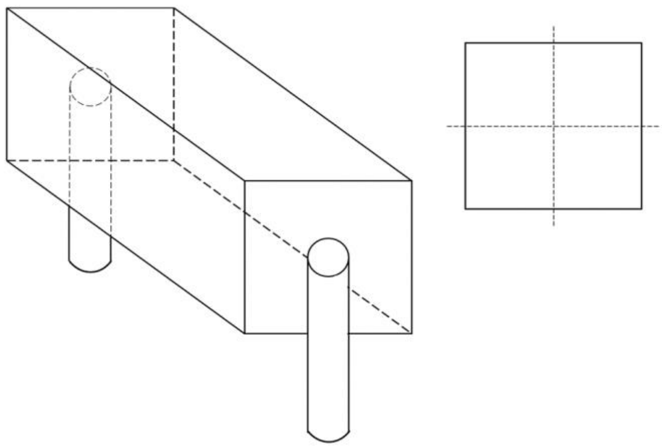


Figure 6. Square/Rectangular base concept

3.1. Square/Rectangular base - Curved configuration

Taking a square or rectangular shape as a base one, the following configuration can be designed (Figure 7). Having one or more surfaces in a curved state would be an advantage that would simulate the real form of the collider to directly perform the test in conditions similar to the actual ones. This manipulation can be performed immediately as a default face or an auxiliary adapter that can be installed anytime when needed.

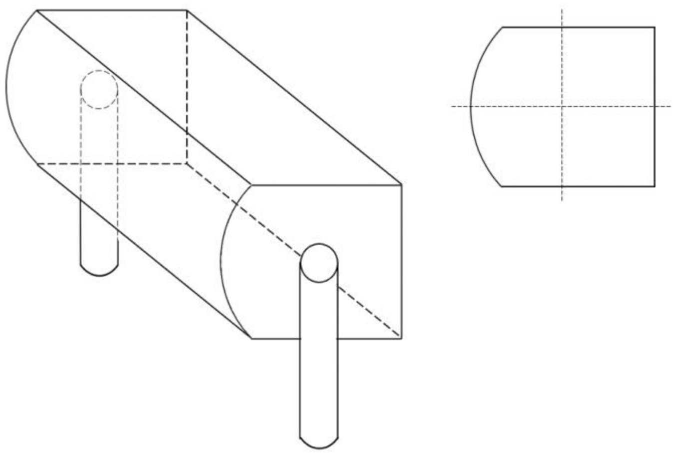


Figure 7. Square/Rectangular base - Curved configuration concept

4.1.2 SWOT analysis

A strategic planning technique of comprehensive SWOT analysis was settled to be employed in order to evaluate the advantages and disadvantages of each concept, eventually coming up with the optimal project.

SWOT stands for Strengths, Weaknesses, Opportunities, and Threats and is aimed to reduce the chances of choice failure and estimate feasible hazards. Four highlighted factors represent key insights to be paid with attention and considered in the selection process. This simple but powerful methodology helps to develop the best possible strategy justifying the choice with a clear comparison representation.

Concept	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Triangular base	Surfaces tilted at different angles	Small cross-section area Intersecting angles inside the construction	More testing opportunities due to the tilted surfaces	Inner and outer mechanisms installations issues Reduced number of constructional configuration due to the closed space
Circular base	Entirely circular cross-section area	One uniform circular surface	Opportunities for testing in the conditions as close to reality as possible	Inner structure and disposition of the components problems
Square/Rectangular base	Many useful surfaces Configurations possibilities	A more bulky and onerous construction	Accessibility and reachability at various angles	The complexity of designing in case of adapting a

			Simulation of the real collider form with the auxiliary configuration/adapter	complimentary pickup

Table 3. SWOT analysis of the proposed concepts

4.1.3 Finalization of idea

Eventually, it was decided to proceed with the strategy of the square or rectangular base implementing the curved configuration. The comparative approach has demonstrated that this approach would blossom forth in providing more practical opportunities ensuring the conditions close to the real working ones. The curved surface will imitate the radius of the collider's curvature which provides the possibility of accelerating particles, steering them to collide at the end. At once, the flat planes of the test bench will reliably host the necessary pieces of machinery and arrangements via which the testing purposes will be fulfilled.

As it was mentioned before, the test bench is presumably planned to have a possibility of being rotated in case of necessity to resolve the issues of robots' reachability, providing convenience and easement of operations being performed. For this purpose, a rotation transmitting system should be installed, potentially an electric motor and a rotor shaft that will transmit the electrically induced torque via a corresponding positive connection in the aggregate, making the test bench revolving at a certain angle.

The mechanical system might be set up in the core of the test bench, while the electrical energy for powering would be transferred by an electric circuit inside the legs supports.

Onwards, the designing process of the device is gradually described principally focusing on developing the constituting components eventually uniting them into one system. The dimensions of the future design chiefly depend on the mechanisms' sizes and the available space that was previously shown.

5 Modeling

A computer-aided software of Autodesk Inventor was used for 3D design, visualization, simulation and subsequent documentation during the project. This application was a working platform as far as it was the one provided from the supervising side of the project.

The modeling process of the project was divided into three stages with respect to which the present chapter is sectioned. The consistent implementation led to the eventual realization of all the constituting devices in one generic construction with modular possibilities demonstrated as a model in Figure 8, the creation process of which is described onwards.

The procedure of design development and modeling usually was carried out starting with handmade sketches of the potential device options, consequently discussing the best ones by negotiating with the supervising side and team members of the Robotics department who knew what exactly was needed and what would fit the requirements better.

Onwards, when the alternative was chosen, the 3D modeling would be started with estimating the dimensions and gradual building of the future device.

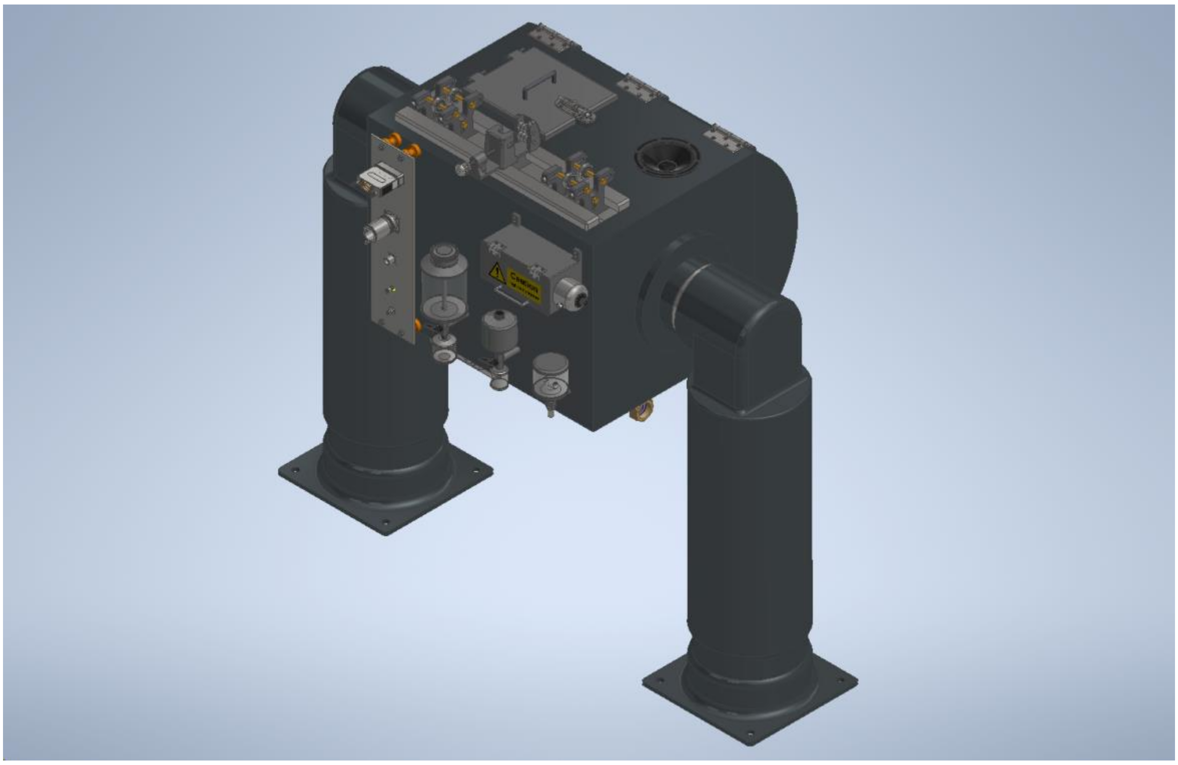


Figure 8. The final assembly

5.1 Test bench framework

As it was mentioned, the external structure of the test bench majorly consists of the following parts: the body and two vertical legs that are supposed to provide the lifting movements of the construction.

The modeling process started with designing the body, that, in its turn, includes a main cavity and a curved wall that is fastened to the base and serves as an opening for maintenance and support operations.

The models are first provided in generic material to grant a better visualization, detailedly displaying the structural peculiar properties of the parts.

The main cavity that is presented in the figures (Figure 9, Figure 10) below, is developed with various apertures and chambers for fastening and placing the complementary mechanisms. The model has a size of 700 x 500 x 500 mm (length x height x width).

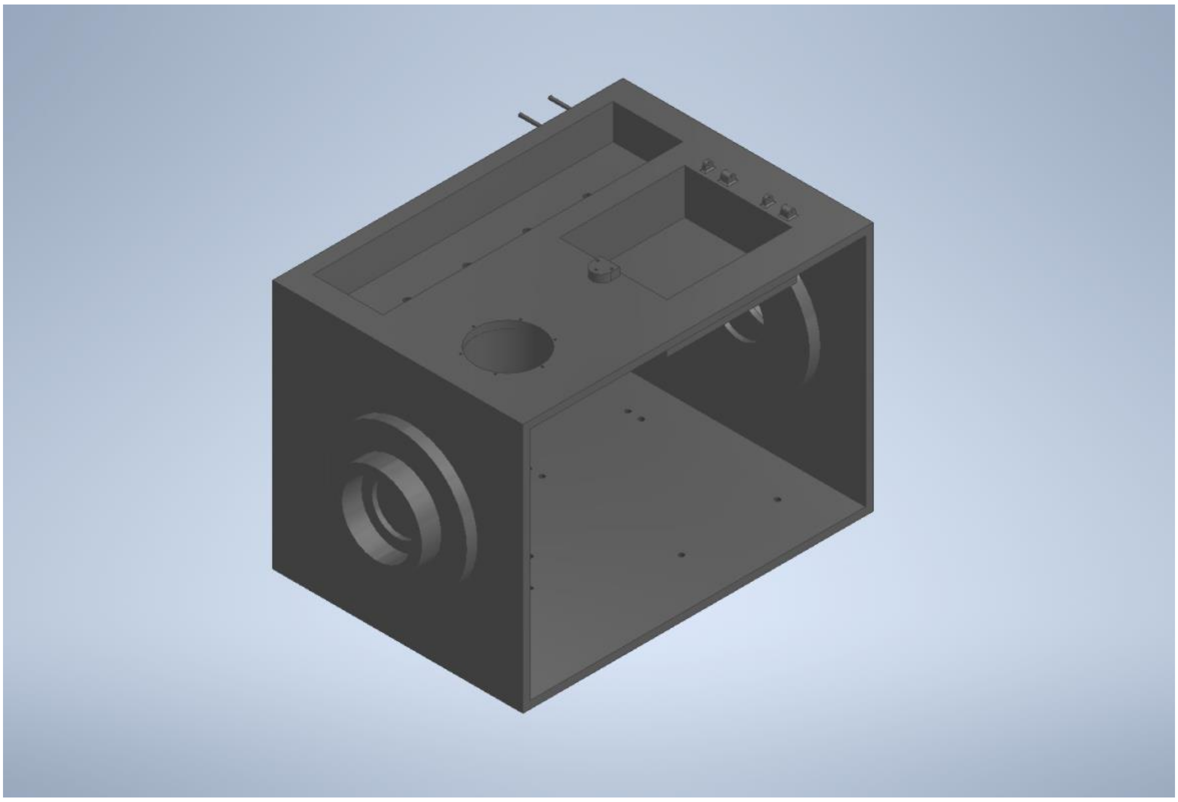


Figure 9. The body's main cavity - Front view

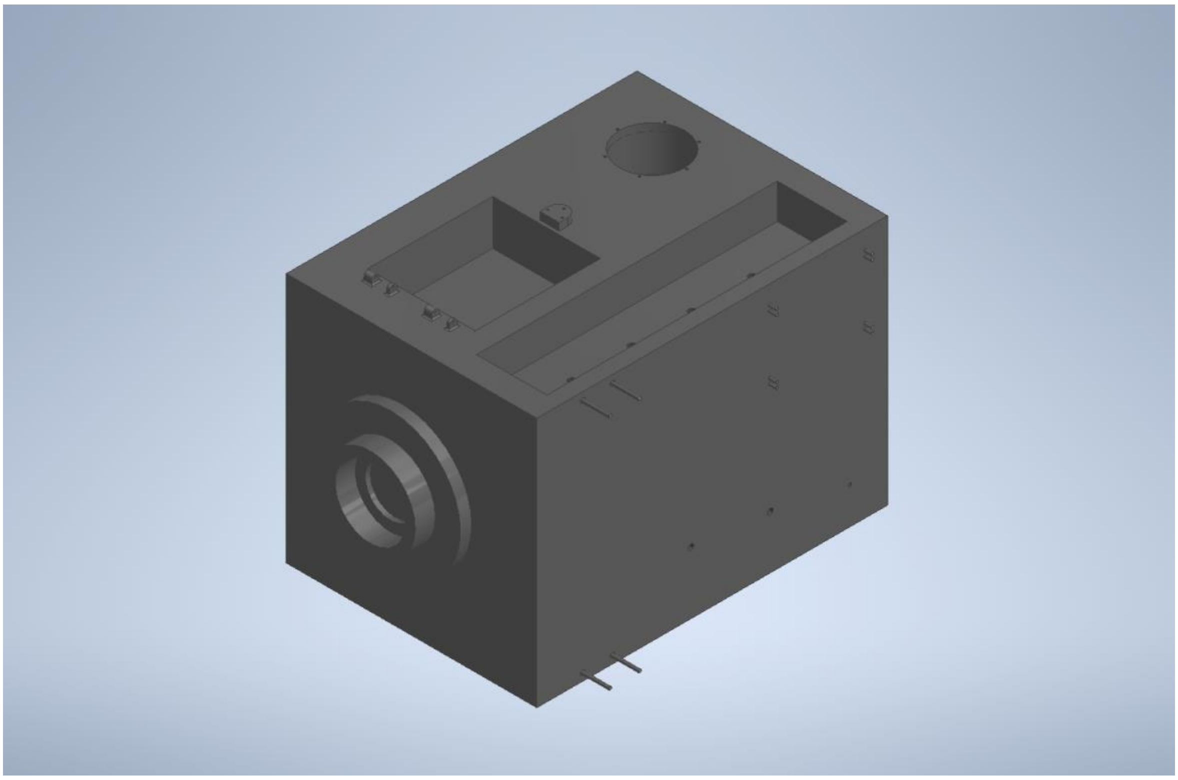


Figure 10. The body's main cavity - Back view

The walls are designed not only with the holes for fastening but also screws and bolts already protruding from the body at the spots where the internal structure does not allow the devices to be screwed inside.

The sidewalls of the body are planned with holes for placing a shaft that is considered to ensure the rotating movement of the construction. In addition to this, specialized hollows for bearings to reduce friction between moving parts, are foreseen as well.

Hereafter, the mentioned curved wall is presented (Figure 11). The wall has the following dimensions: 700 x 500 x 132,5 mm (length x height x width). It is planned to be fastened to the top wall of the main cavity making use of common hinges.

The wall is equipped with a handle to simplify the opening and a special extra mechanism that will ensure the reliable fastening with the main cavity to avoid opening while rotation.

Half of this mechanism is a small part of the curved wall that is designed in a form of a simple pin with a particular aperture in it as shown in Figure 12. While the second part is performed as a separate box (Figure 13) that should be welded to the main cavity's bottom wall. This wall is appointed with a spring and a crooked clip that fits the pin's hole and is moved when the external side of the clip is pressed so that the pin is released, and the body's cavity can be opened.

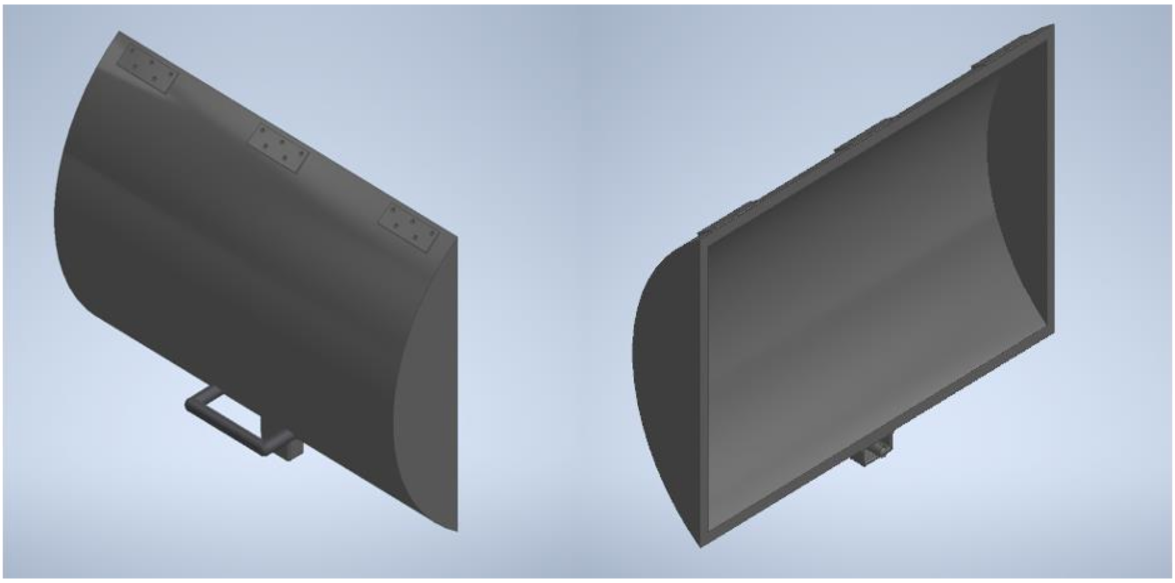


Figure 11. The curved wall

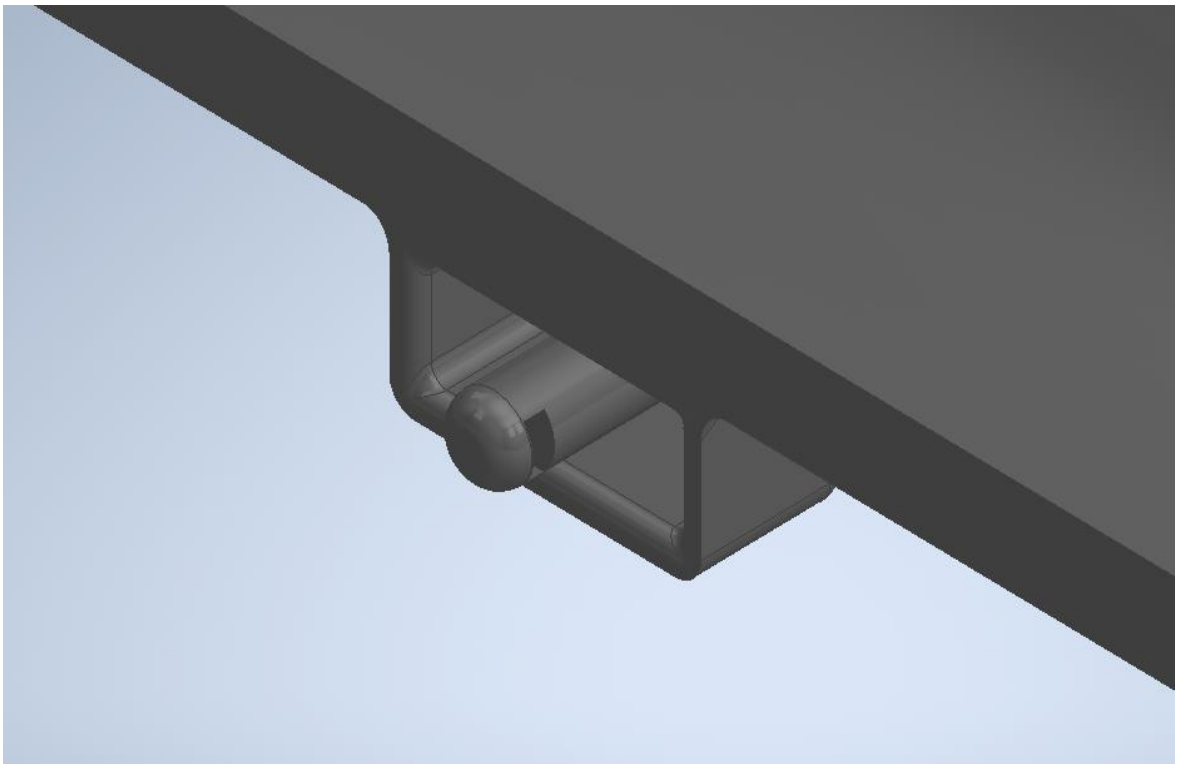


Figure 12. The fastening pin

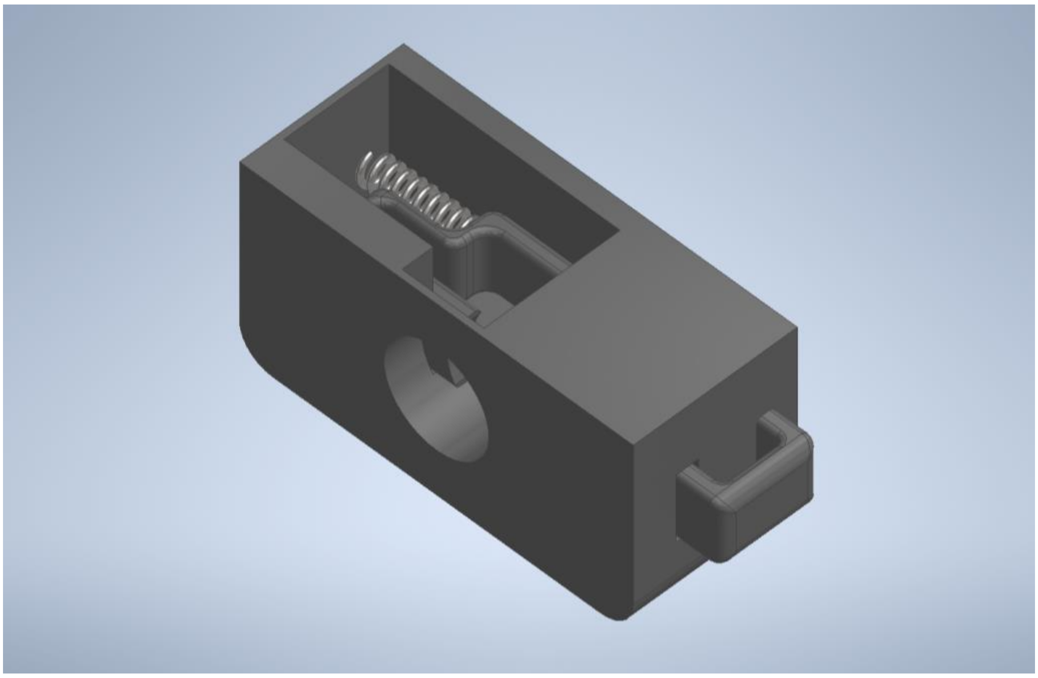


Figure 13. The fastening box

The next phase was the projection of the legs that provide a mainstay and ensure the possibility of regulating the height of the test bench that expands the list of testing conditions. The upper parts of the legs host the shaft, while the chief portions hold the system allowing the lifting movements. The bases of the legs are designed so that they can be screwed to the floor to guarantee stability. The leg is 275 mm in diameter and 1055 mm in height.

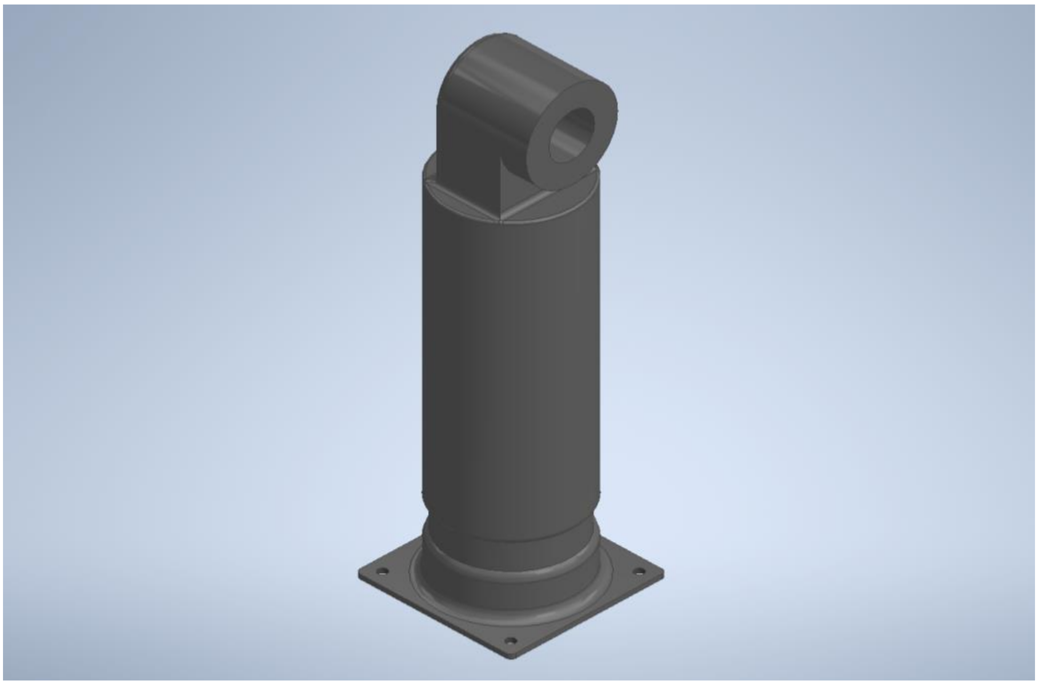


Figure 14. The test bench’s leg

In addition to this, a demonstrative shaft (Figure 15) with the main diameter of 100 mm and length of 1065 mm was designed that is assumed to be connected with a motor to make the rotational manipulation of the test bench possible.

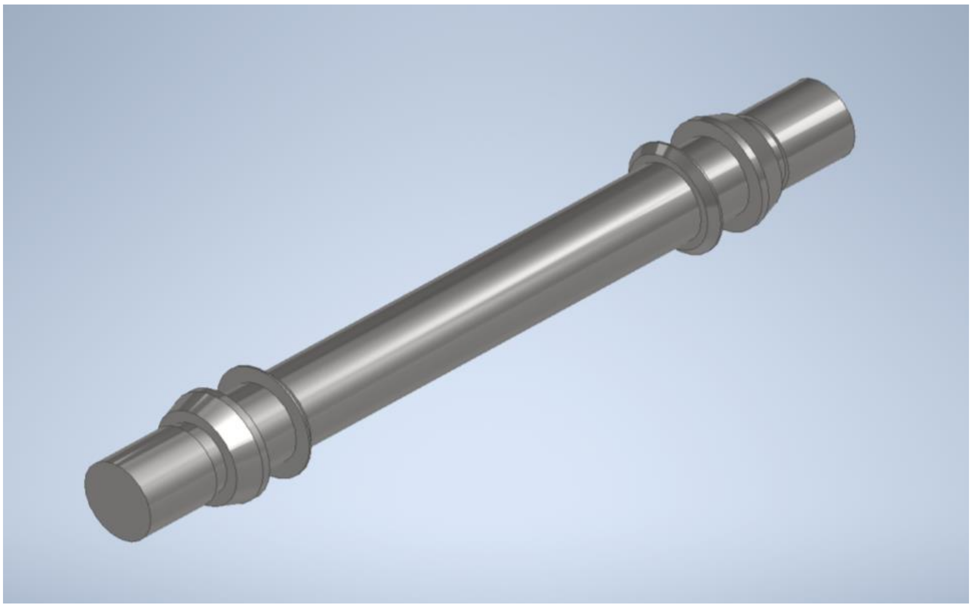


Figure 15. The shaft

Eventually, an assembly was performed having all the major components done. The final framework demonstrates the fastenings and matings of the elements and is presented as a mock-up.

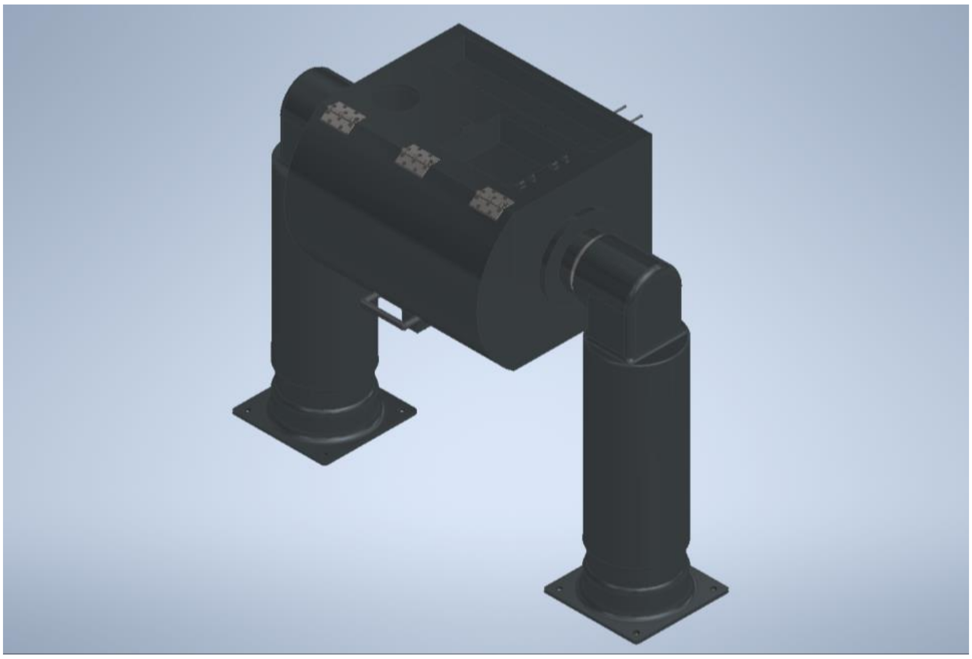


Figure 16. The test bench framework assembly

The shaft was joined to the corresponding orifice and the bearings, that were designed singly, were mated to the appropriate cavities. Figure 18 demonstrates the internal appearance of the structure, where the described parts and their positions are seen.

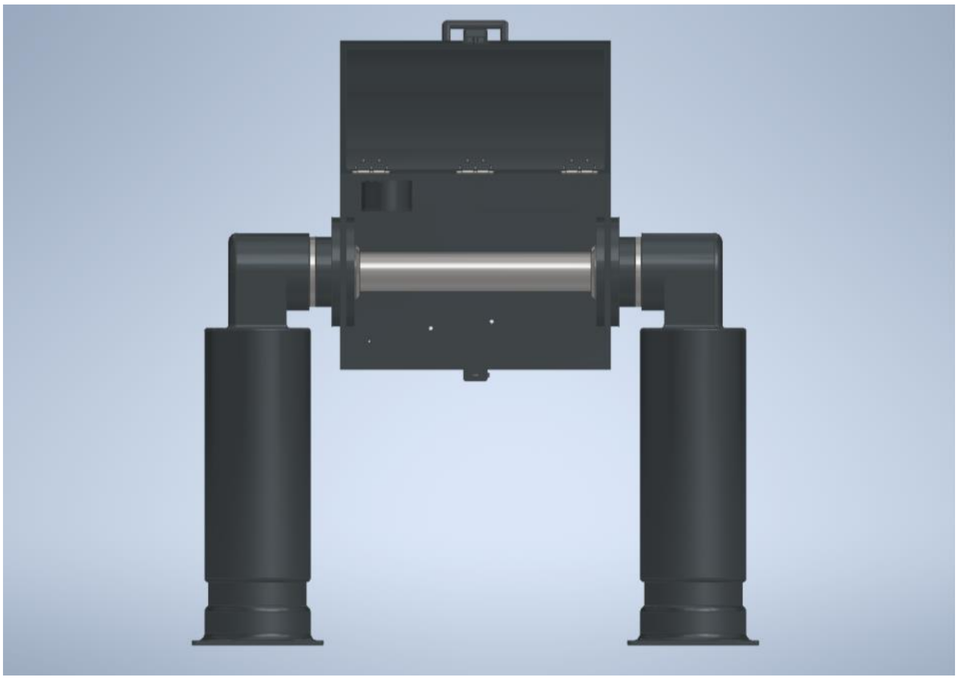


Figure 17. The test bench framework assembly with an open wall

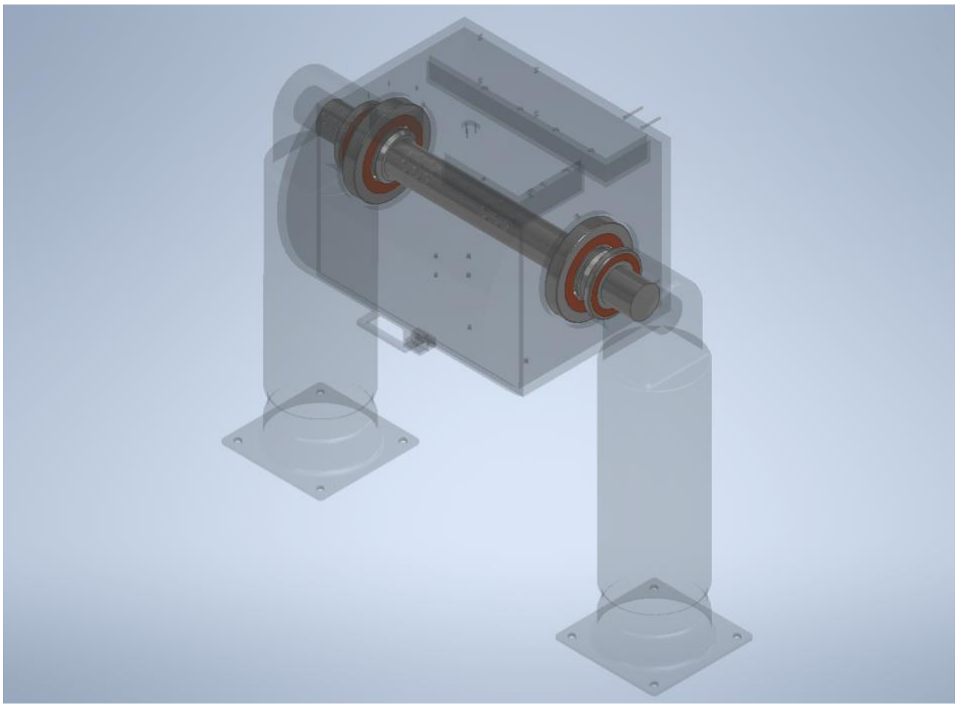


Figure 18. The internal structure of the test bench

5.2 Composing mechanisms

Based on the "Testing systems and devices" table that was presented earlier, various constituting mechanisms for different purposes were invented and designed. They all are represented below with the help of illustrations and descriptive paragraphs. The processes and functions that were used in the design are also depicted.

5.2.1 Liquid container

One of the devices that had to be designed and included in the testing features was a container for oil with the help of which an operation of filling and emptying the space with the liquid should be demonstrated.

In practice, a line of these glass tanks is installed at an underground arrangement as it is shown in Figure 19, concretely at its part called an injection kicker, a special type of magnet used for abrupt deflection of the particle beam off its previous trajectory for its extraction to a different line. (Ducimetière et al. 2003; Barnes et al. 2018; Barnes 2017; Kramer et al. 2014; Salvant 2010.)

Figure 19. Oil containers

Such a glass container has already been in practical usage by the department and was physically provided for taking the necessary measurements in order to complete an appropriate 3D model to be subsequently included in the test bench with the purpose of performing the needed manipulations by the robots.

The container was first scrupulously studied with an eye to defining the constituting elements and the working principle. The chief construction of the object included a glass frame, two metal fastening hats (top and bottom), a cap closure which would be taken off by the robot to reach the internal cavity to bring the liquid in, a pipe installed inside for the following injection of the oil to the kicker's components through the valve attached to the bottom hat and connected to the pipe.

All the parts were designed with respect to the real dimensions measured using a digital caliper beforehand. The shapes of certain parts required the usage of specific features to achieve the desired forms, appearances and compatibilities. For instance, the thread was needed for the pipe-valve connection and therefore both parts are threaded by selecting appropriate input geometries and desired behaviour (depths, offset values).

Onwards, the components were assembled together into one common product so that all the elements suit each other and do not collide, destroying the functional requirements. For this purpose, the cross-section view is also provided (Figure 20), where the matings are clearly seen.

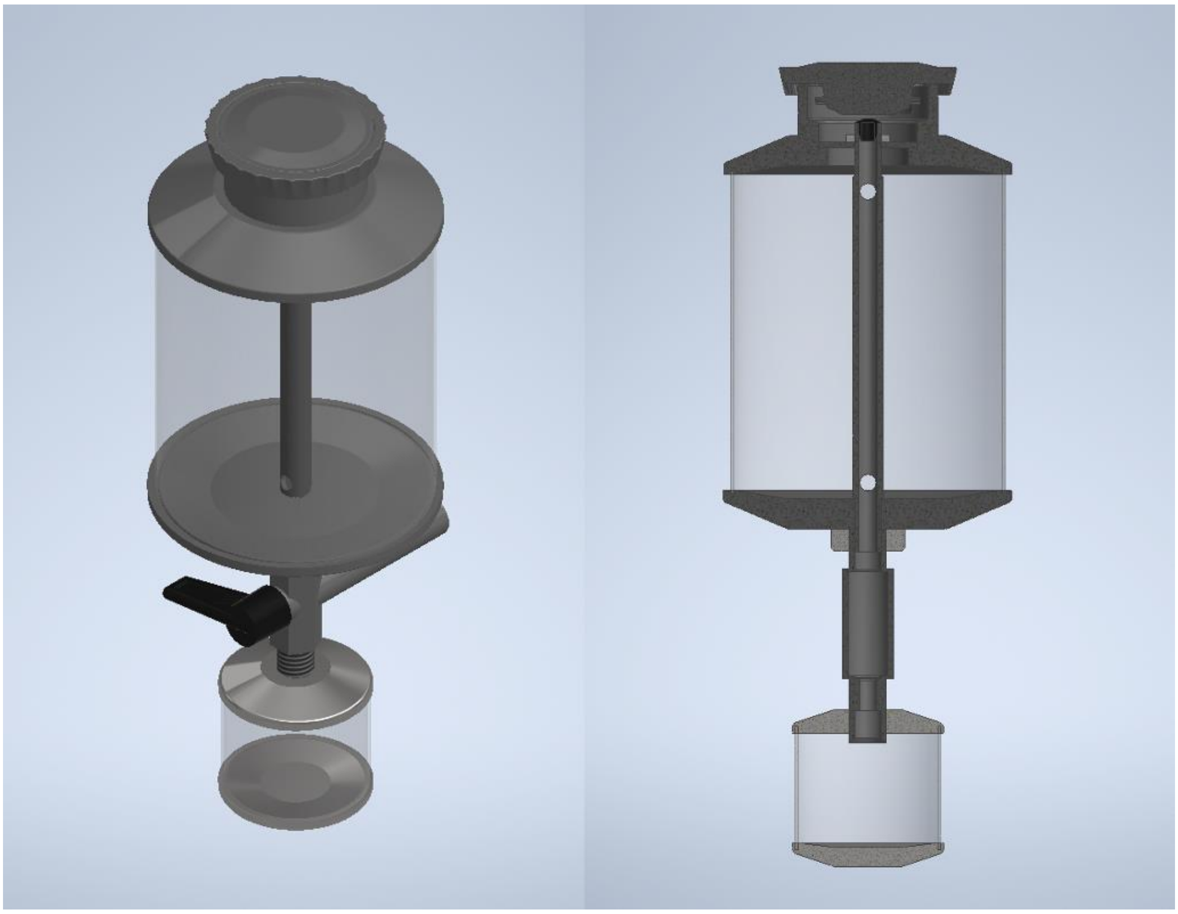


Figure 20. Oil container assembly

The final size of the obtained part can be described as a cylinder with a diameter and height of 105 mm and 292,5 mm respectfully, taking the maximum dimensions of reference edges, where height is the distance between the cap peak and a small glass tank's bottom surface, and the diameter is the dimension of the hats diameters. These values were initially taken based on the done measurements of the actual container.

5.2.2 Sound source

The list of the testing systems that have to be considered also includes a device for an audio inspection, implying detection and recognition of varied types of sounds at different volume amplitudes. For such a purpose, a basic speaker might be successfully utilized.

It can be mounted directly to the bench's surface, as it is usually done with ceiling speakers. A great option would be a wireless Bluetooth flush mount in-wall speaker that could be regulated remotely by selecting the required sound type while controlling the volume in parallel with tracking the data obtained by the robot.

The design of such a speaker consists of four main parts that together with an electrical system inside make it possible to reproduce sound. Since such a device does not have to be manufactured by CERN services but can be simply purchased from a wide market of available options, the dimensions of the future system were defined based on the knowledge of the usual size of such a device. The reference values were decided to be 150 mm for diameter (of a part which is mounted to the wall) and 75 mm as maximum for the depth.

The assembling elements of the speaker do not include many parts, the major ones are a frame or basket that consists of a gasket, a cone diaphragm and a dust cap, a magnet, a terminal, a plate and a yoke that are connected into one part that is further mentioned just as the yoke. The 3D model consists of just four general parts that are the basket, the magnet, the terminal and the yoke.

The eventual device assembled from all the parts satisfied the initially set dimensions with the obtained diameter of exactly 150 mm and the total depth of 71 mm.

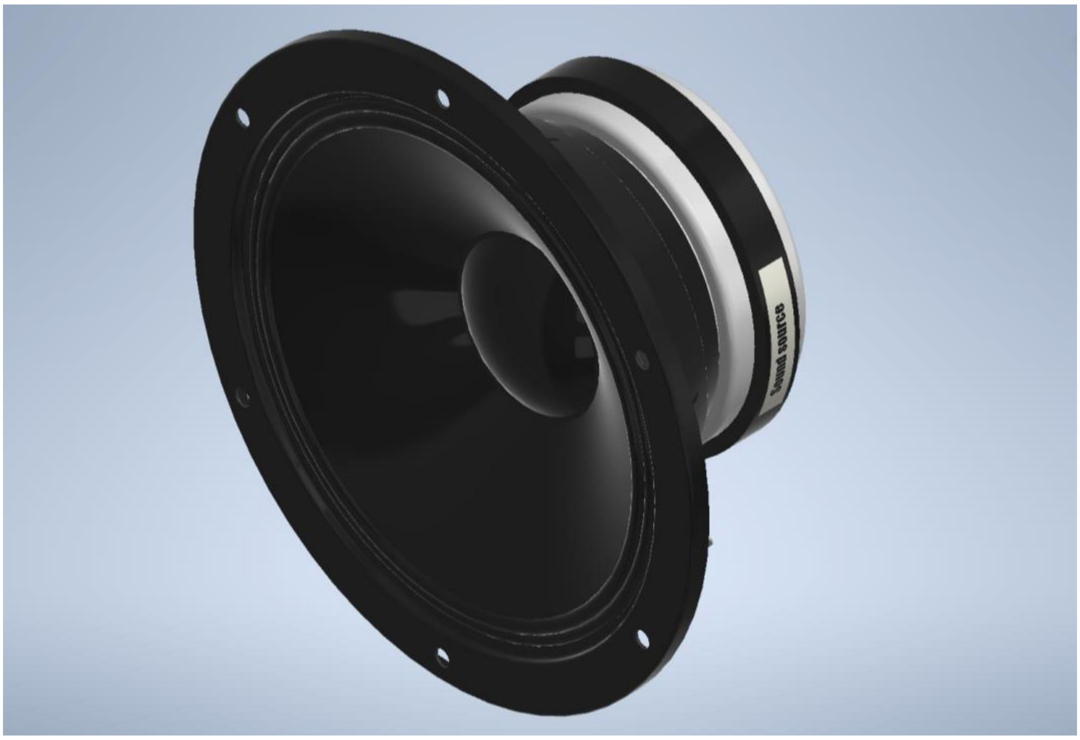


Figure 21. Sound source 3D model

Figure 22. Sound source - side and cross-section view

One peculiarity of this model was a curved funnel shape of the diaphragm that was managed by first sketching the needed form (Figure 23) and then revolving it as a cut. In addition, a hollow cavity of the basket, in its turn, was achieved using the Shell function.

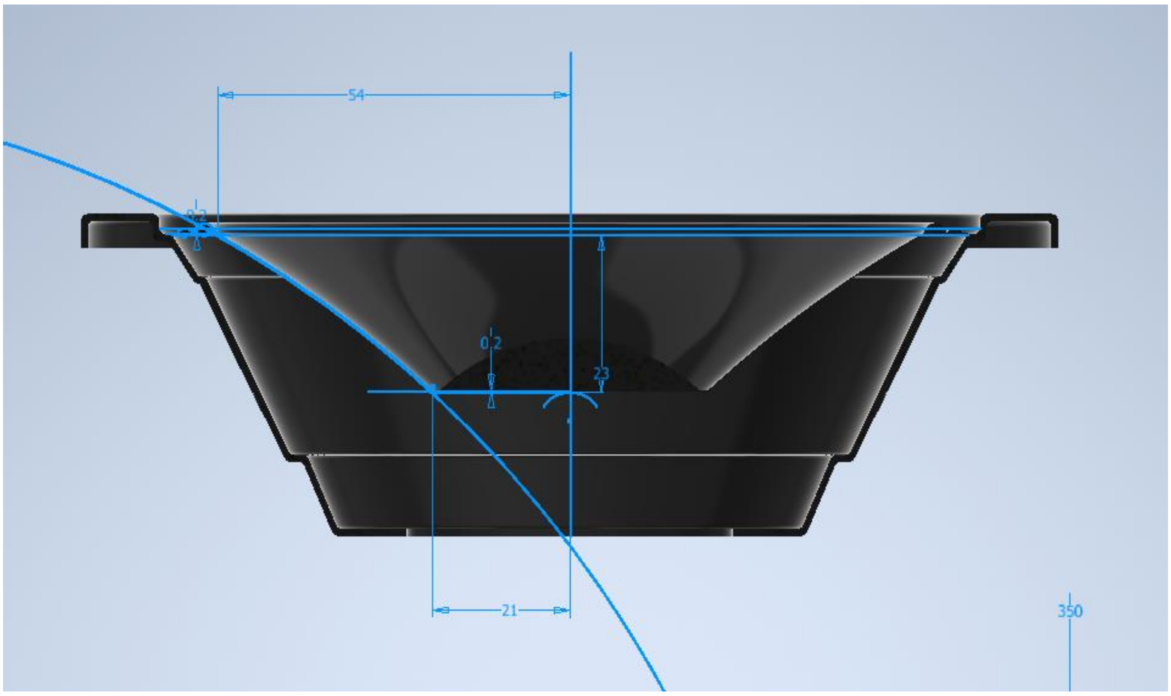


Figure 23. Sketch of the curved funnel shape

5.2.3 Electrical connectors plate

It was required to design a space that could be utilized to test if the robots are capable of handling the connection and disconnection of the cables that might be used for various purposes such as transferring data, signals, power, fiber optics, fluidic/pneumatic or thermocouple media.

For such various assignments, different types of connectors are used and were provided by the department for familiarization and consideration in terms of the projects. Most of the connectors were so-called push-pull connectors that lock and require only an axial force to be put in and out, ensuring a secure mating which is essential for such mission-critical applications.

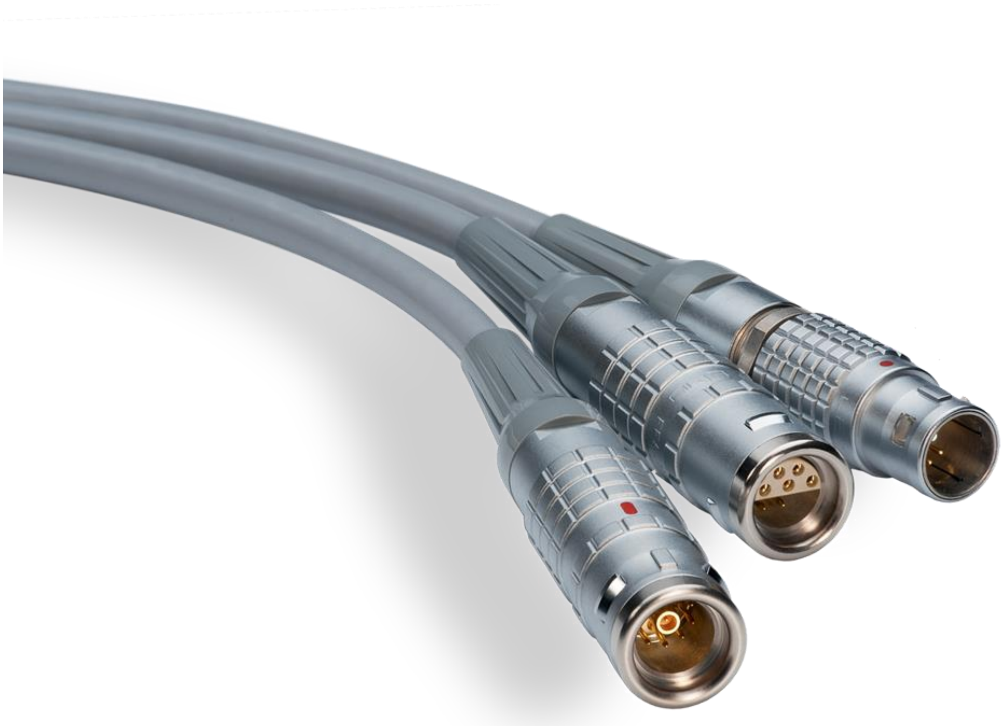


Figure 24. Push-pull connectors

It was decided to create a plate with several joints based on the provided selection that included three different models of push-pull connectors, as well as two other connectors types. Not only the plate and connectors had to be created, but the female sockets to which these connectors are plugged as pins.

Primarily, all the gotten connectors were measured and the gotten dimensions led to the decision on the overall size of the plate. The connectors had to be placed at safe distances between each other, so the robot's gripper has enough space to interact with them without interfering with others. Considering the connectors' sizes and the defined in-between distances, the plate dimensions were set to be the following: 132,5 x 500 x 4,5 mm (length x height x width).

Such a plate was then easily designed with the appropriate apertures for the future plugs (Figure 25) which were narrowly measured, so the needed sizes were defined beforehand. The apertures are numbered from 1 to 5 from the bottom to the top for clear designations. Safe and reliable positions of these connections were also determined by knowing the scales of the devices.

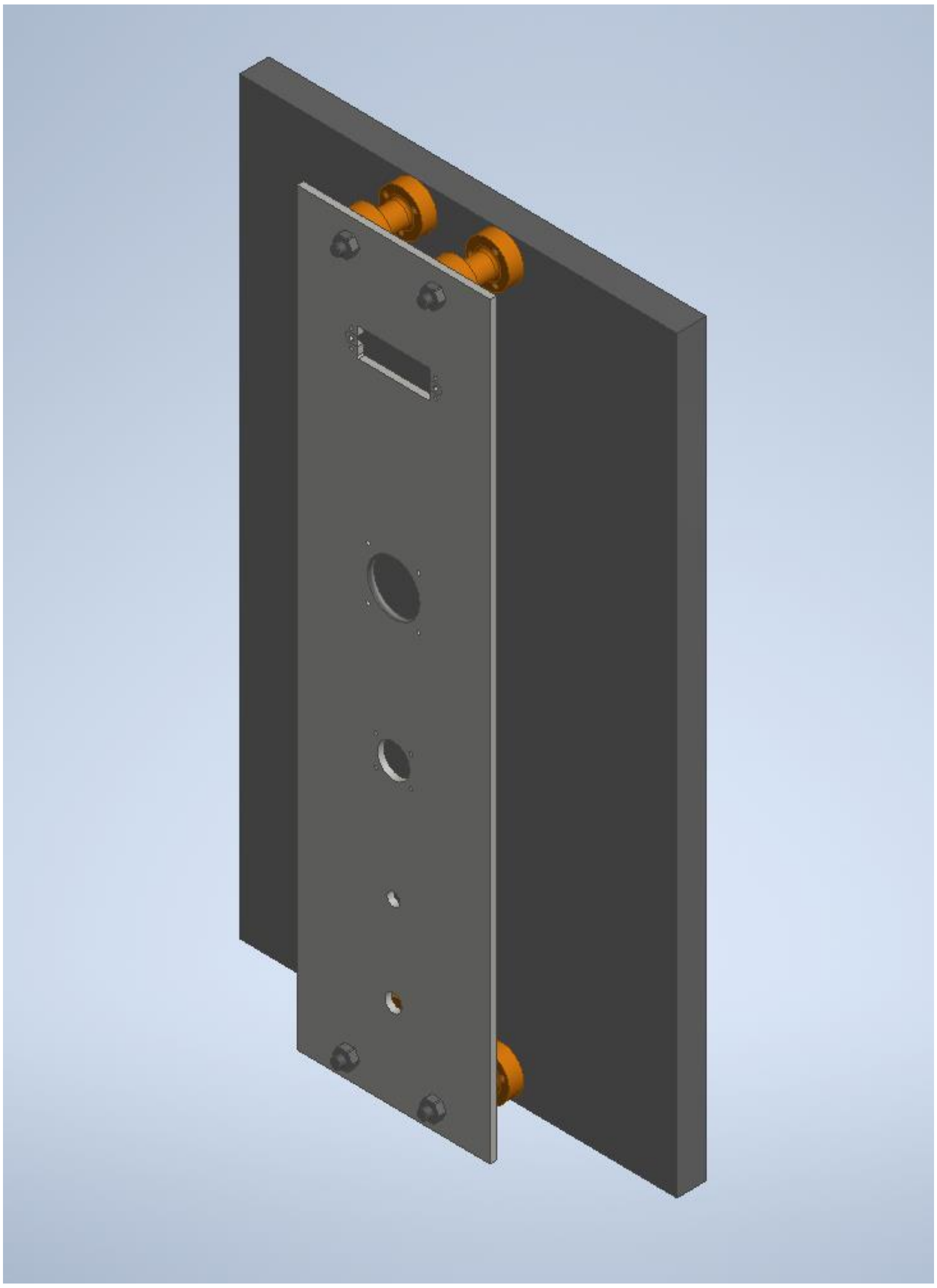


Figure 25. The plate for the electrical connectors

The plate had to be placed at a certain distance from the test bench wall as far as there should be enough space for the plugged connectors' tips. For this purpose, special supporting separators (Figure 26) were designed, through which the plate is screwed to the main wall.

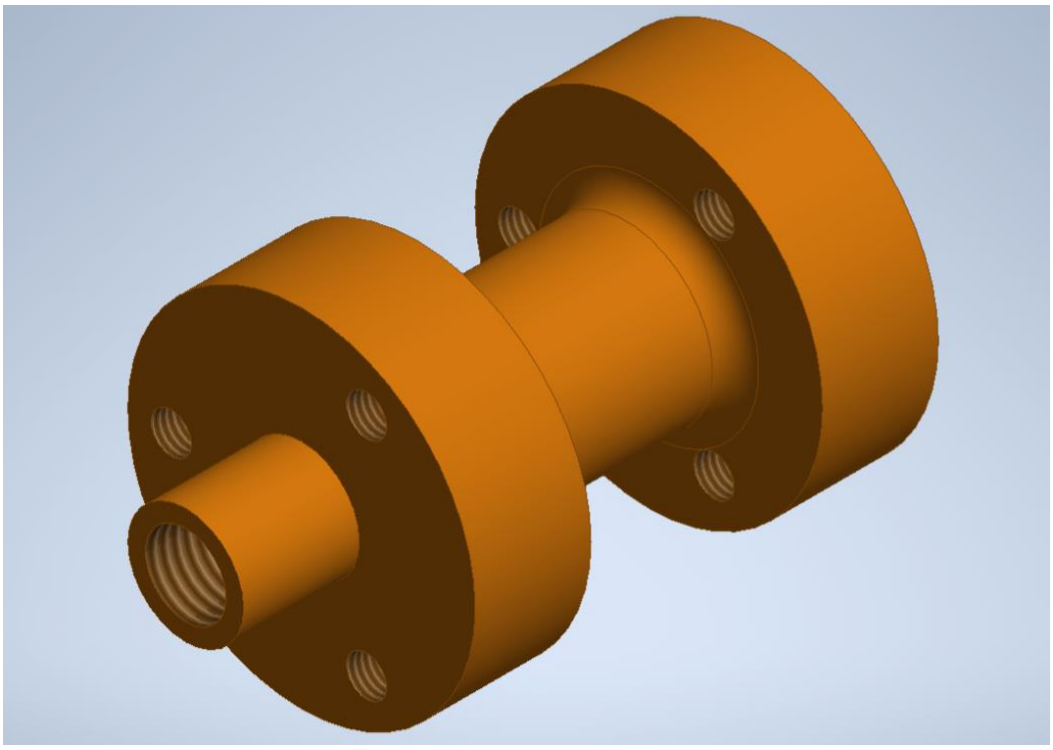


Figure 26. The supporting separator

As Figure 27 shows, the fastening method implies the presence of wall screws to which the separators are firstly attached, and then the plate itself. The procedure is finalized by attaching the nuts to provide a clamping force and prevent axial movement. All the fastening holes were threaded.

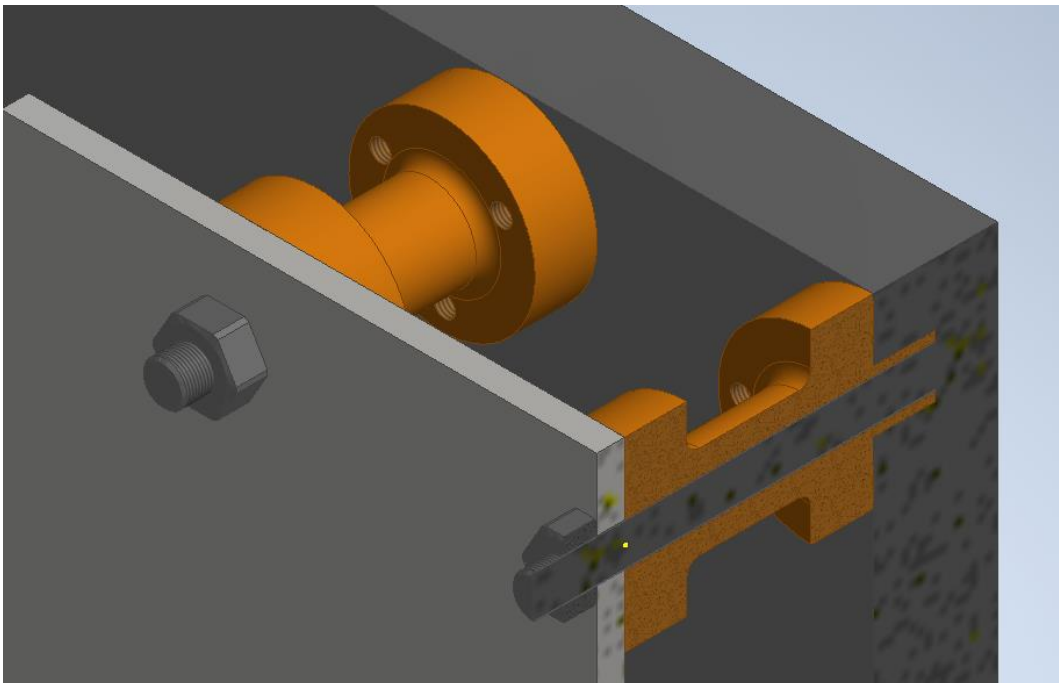
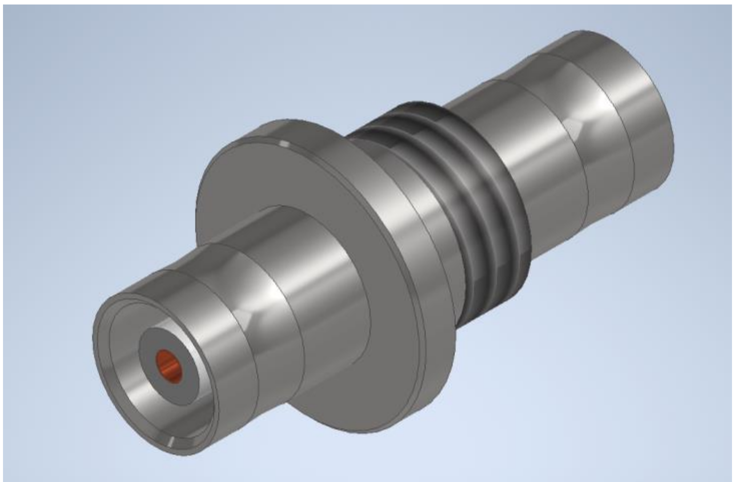
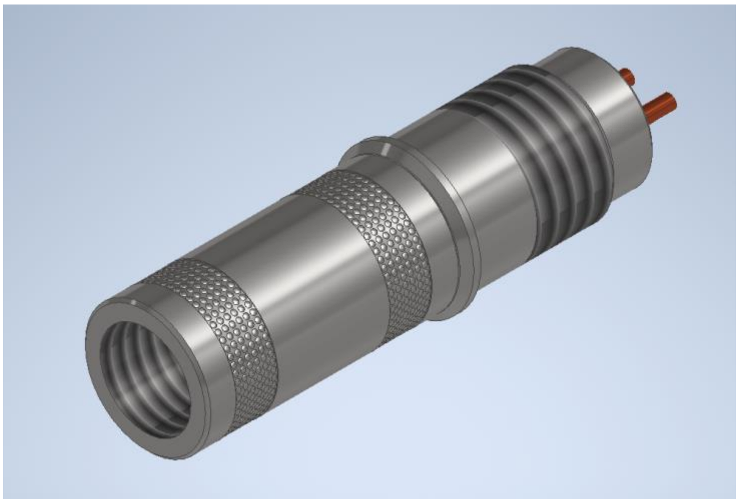


Figure 27. Plate fastening method

As the next phase, all the connectors were built and are presented in Table 4 below. The first three ones are the noted push-pull connectors and do not need any auxiliary fastening hardware (e.g. screws, bolts) to be mounted. However, for the last two connectors, such additional devices were designed and included in the final system.

The push-pull connectors did not require several constituting parts to be assembled and were designed facilely, while the rest plugs were presented in forms of assemblies of individual elements that allowed to complete fastening/unfastening process and manipulation.

Connector	Illustration
1	
2	

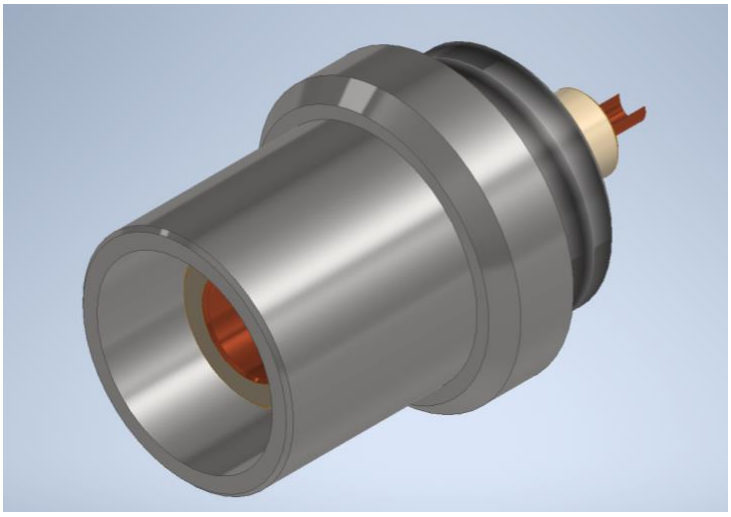
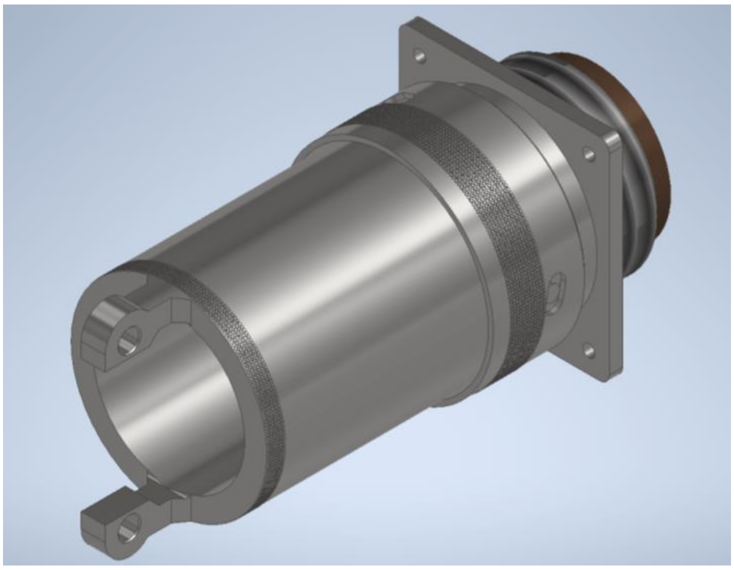
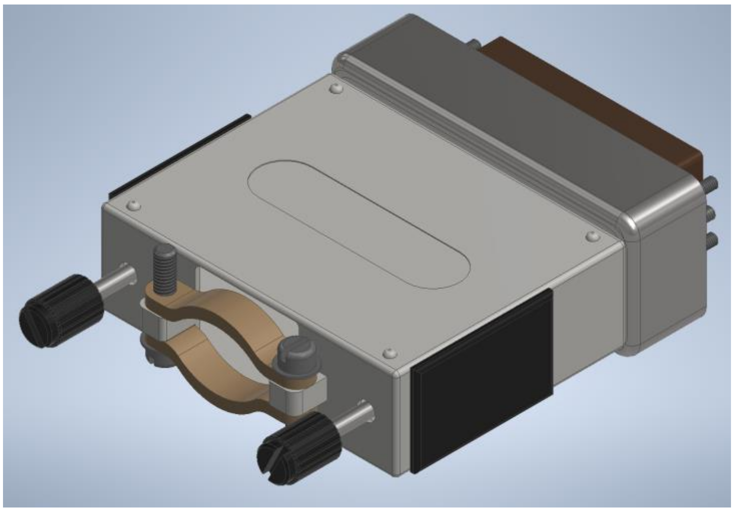
3	
4	
5	

Table 4. Designed connectors

Thereon, all the connectors were mated to the appropriate plugins, either using nuts, screws or combinations of them. For connections number 1 and number 2, washers were also used to prevent or reduce damage and friction between the joined components and nuts, ensuring screws securing and preventing corrosion.

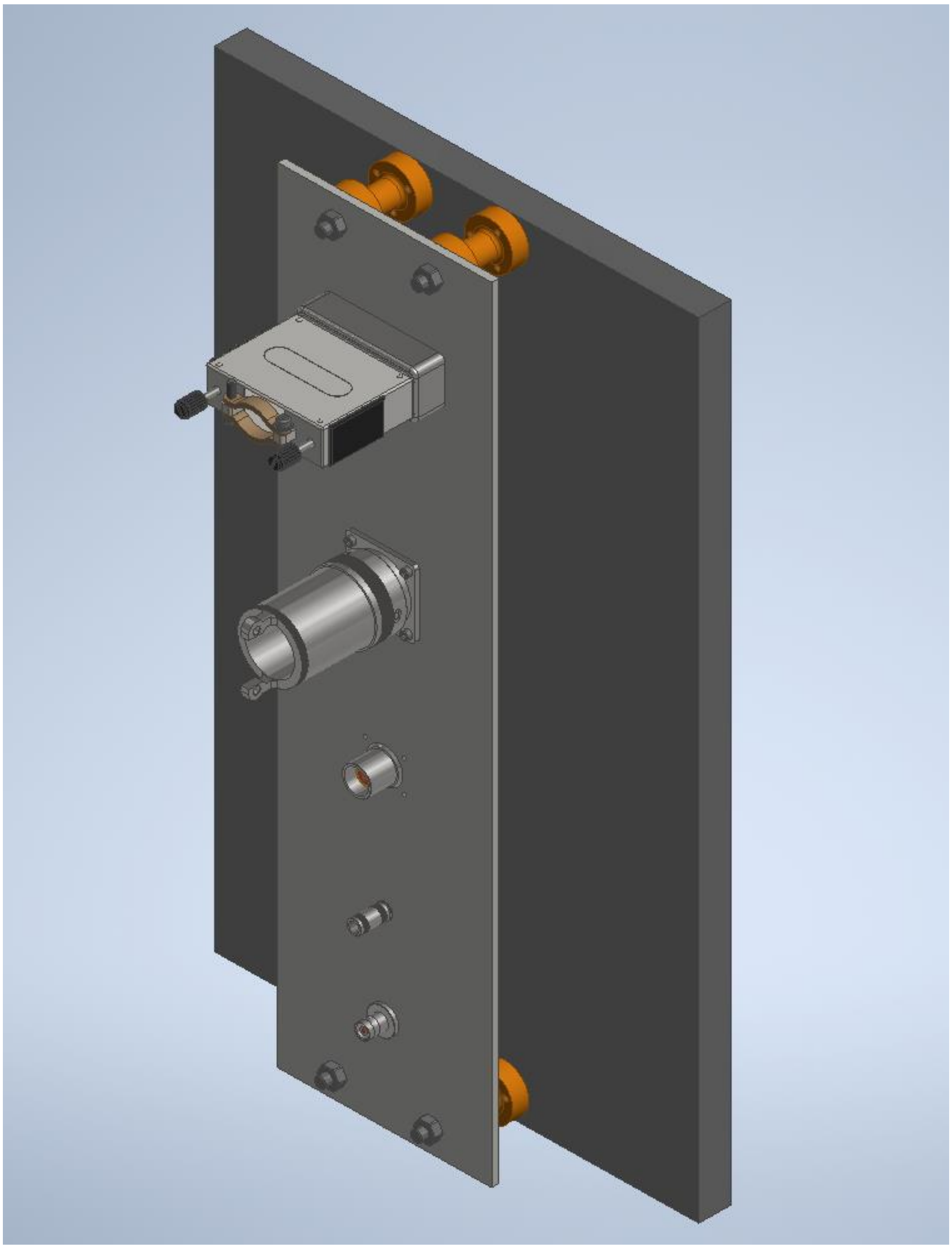


Figure 28. Electrical connectors plate assembly

The illustration below (Figure 29) demonstrates the matings and the cross-section area of the designed system. The picture is presented in a horizontal view for convenience, however, the system is planned to be installed vertically in real conditions.

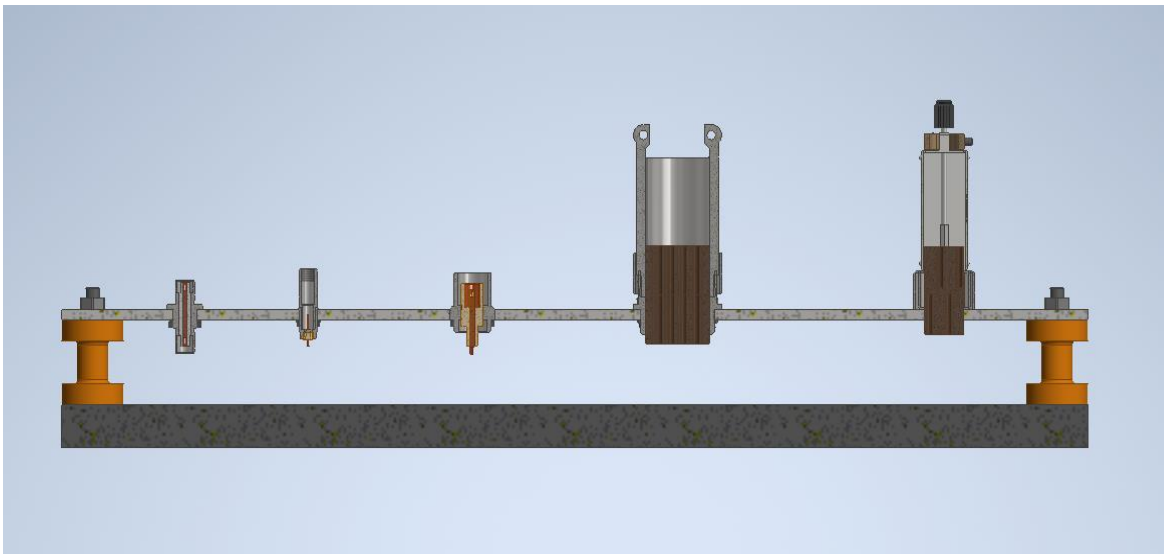


Figure 29. Electrical connectors plate assembly - Cross-section view

5.2.4 Water leak imitation device

At CERN, a circulating water system is used for cooling processes of various installations including cryogenics, electronics, ventilation and others (Schaeffer 2019). The water-cooling systems have to be constantly monitored with an eye to identifying and solve potential water leakages. In many cases, this is done by robots that are capable of repairing the water leak spots with the help of epoxy resin filling or foam throwing.

For the purpose of testing these proficiencies of the robotic equipment, a device similar to the previously described oil container was designed. The result (Figure 30) consists of six chief components: a water reservoir, a scale, a valve, a small glass receptacle and two caps.

The working principle of this appliance implies the presence of water in the reservoir that is injected there by unscrewing the upper cap. Then the water enters the valve’s pipe, the valve itself should preferably be a ball one with a small-diameter hole so as the output, the water incoming as drops.

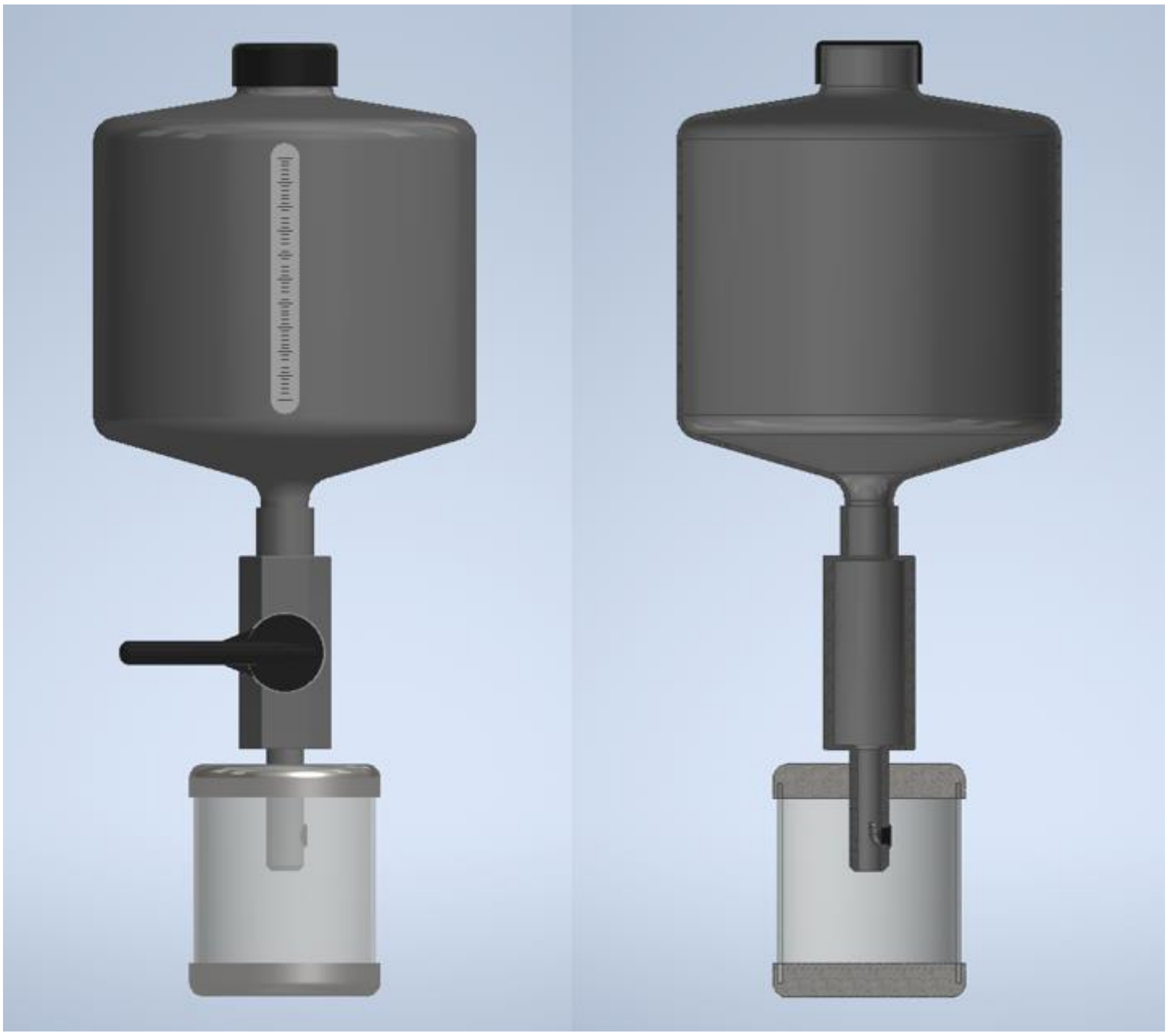


Figure 30. Water leak imitation device - Front and cross-section views

The bottom pipe of the valve, to which the glass receptacle is screwed, possesses a special notch for separating and accumulating the water drops (Figure 31). The form of the notch would guide the flow to the side aperture that imitates a crack through which the leakage is performed. The hole is plugged with a little cap when it has to be ensured that the water flows in the right direction - vertically falling to the glass receptacle through the hole at the bottom of the valve’s pipe. When the side hole is opened, simulating the crack, a part of the water will be also coming from the pipe side, forming two dropping flows.

Eventually, the final assembly has a diameter of 80 mm and a height of 196,992 mm, and the device is presented in the figure below (Figure 32).

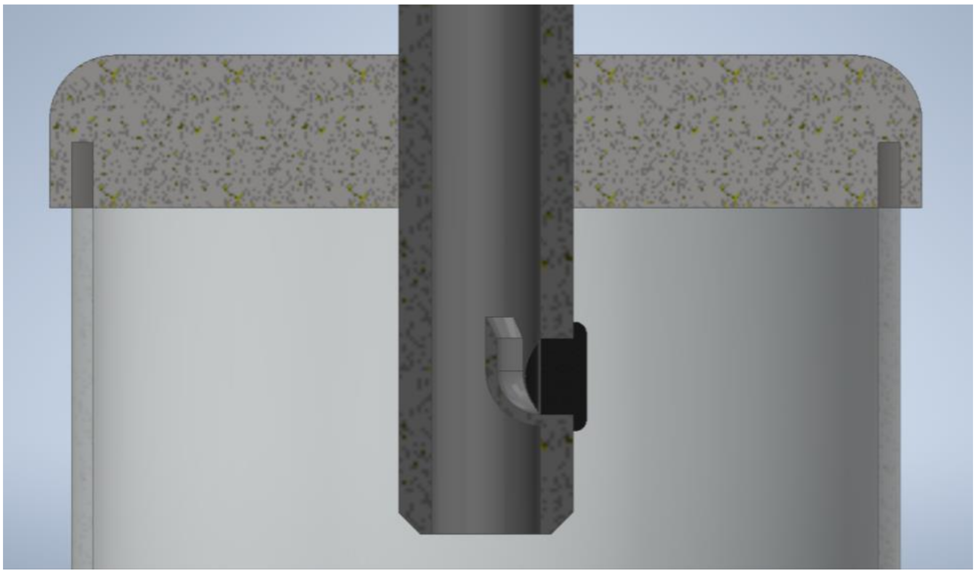


Figure 31. Water leak imitation device's notch - Cross-section view

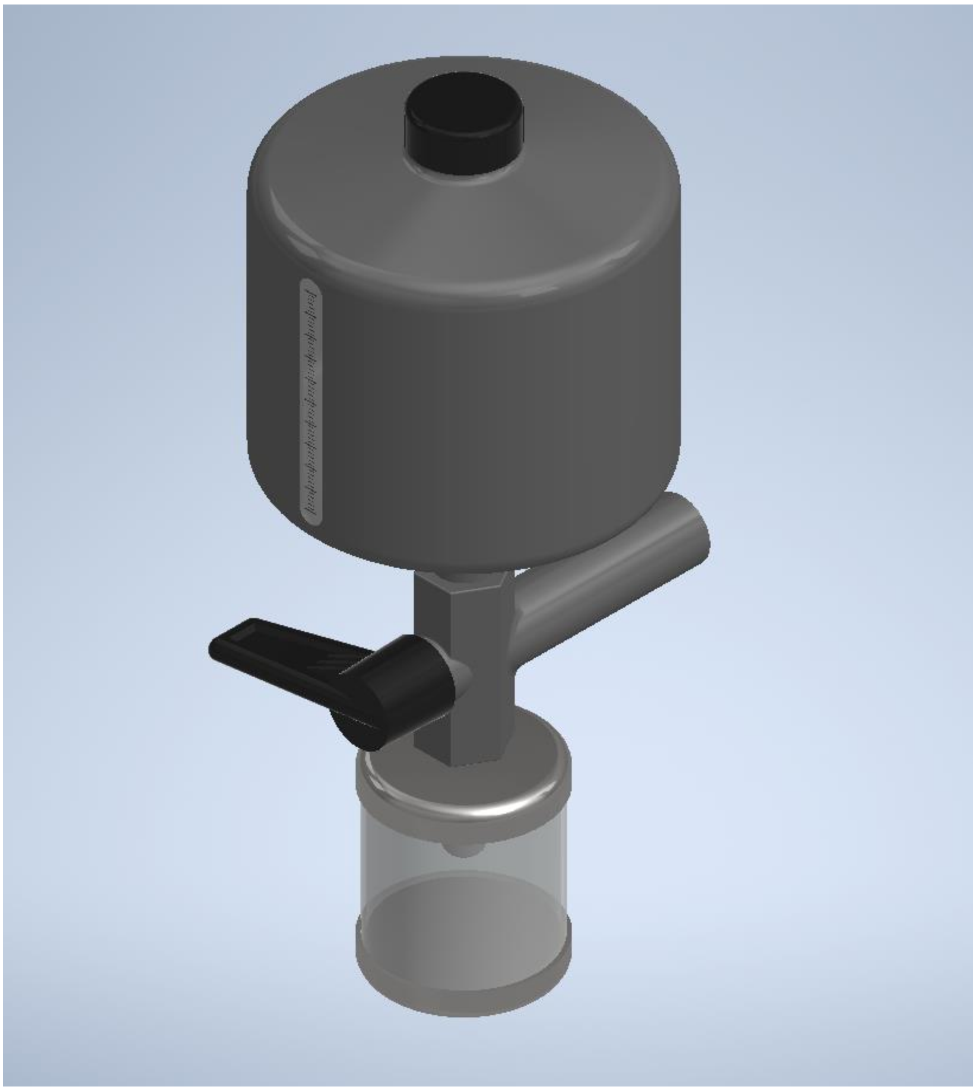


Figure 32. Water leak imitation device assembly

5.2.5 Water connector

Another device that was provided by the department and was asked to be included in the future design was a water valve or a water connector, a manipulation with a part of which should have been ensured. This part was a copper gasket that has a certain work/lifetime and has to be replaced with a new one with the lapse of time. The 3D model has already been created by the department and was provided for the project (Figure 33).

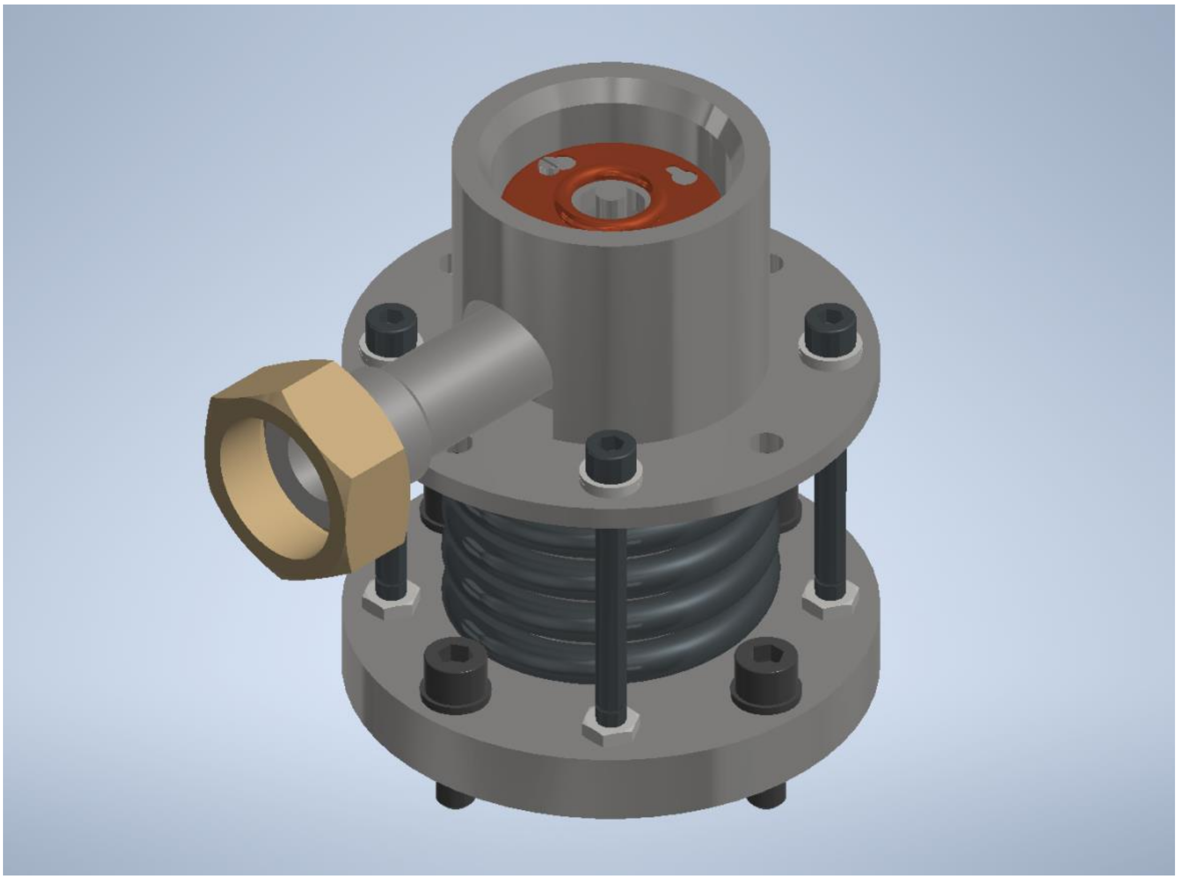


Figure 33. Water connector

The given arrangement occupies an area of 135 mm, a diameter of the largest section, and a height of 156 mm. The device can be attached via the holes by screwing it to the bench's wall.

5.2.6 Heating element

Since the presented robots are able to measure and map the temperature values, an appropriate device should have been added. It was decided to design a heating element that gives off heat when an electric current flows through it, by converting the electrical energy into heat that it radiates out in all directions. It was desired to have a possibility of temperature control to adjust the values based on the requirement, so a thermostat had to be created.

For safety reasons, the element should be installed in a shielding box, so the nearby components are not damaged by the emitted heat. Thereby, the general parts of such a device should be the following: a heating element itself, a case, a thermostat, flanges. The case should have an opening possibility to be able to place the heating element inside and connect the thermostat to it.

Based on this knowledge, all the constituting elements were designed and are presented below (Figure 34). Furthermore, several fastening parts were created, for example, screws and nuts to mount the flanges to the case's walls, as well as to connect the heating element to the thermostat body.

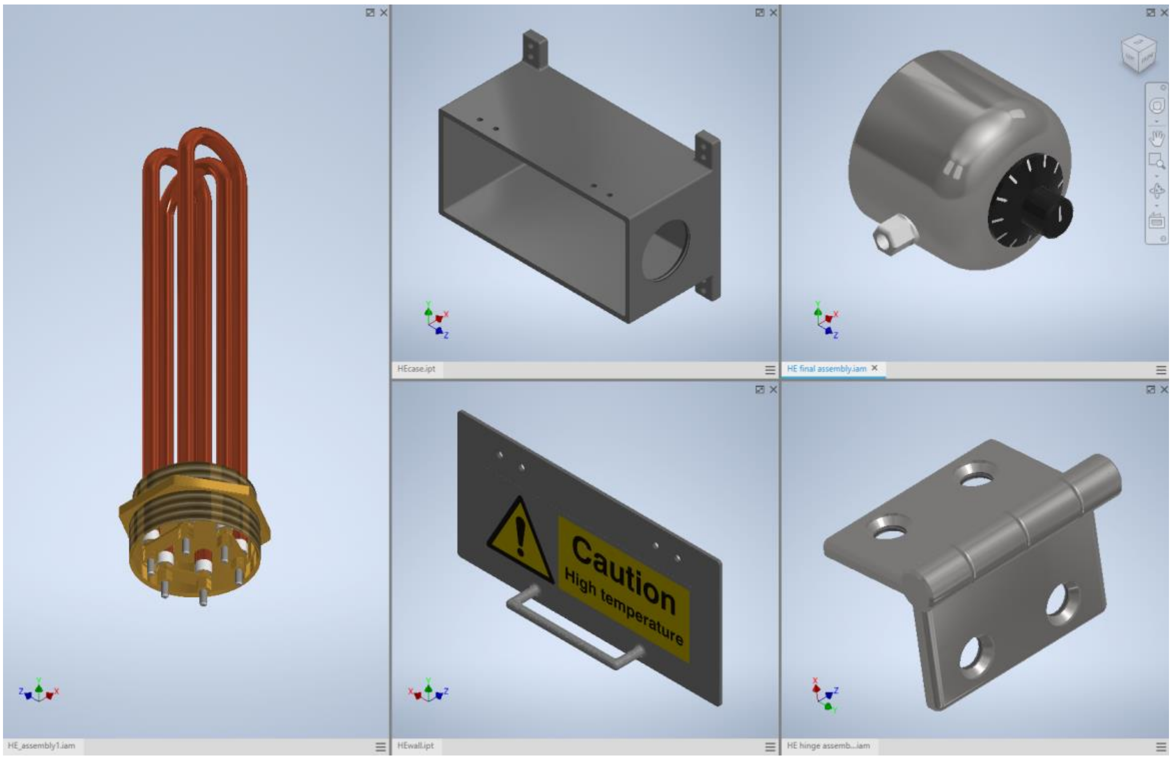


Figure 34. Heating device constituting parts

It has to be noted, that the case wall that is fastened to the case using the flanges, has to be made from a different material with good thermal conductivity, unlike the rest walls of the case, so only one, the front wall is majorly heated, thus the robot is able to trace the temperature change. The wall, in its turn, was designated with a sticker warning about the potential danger of high temperatures, so incompetent individuals are apprised.

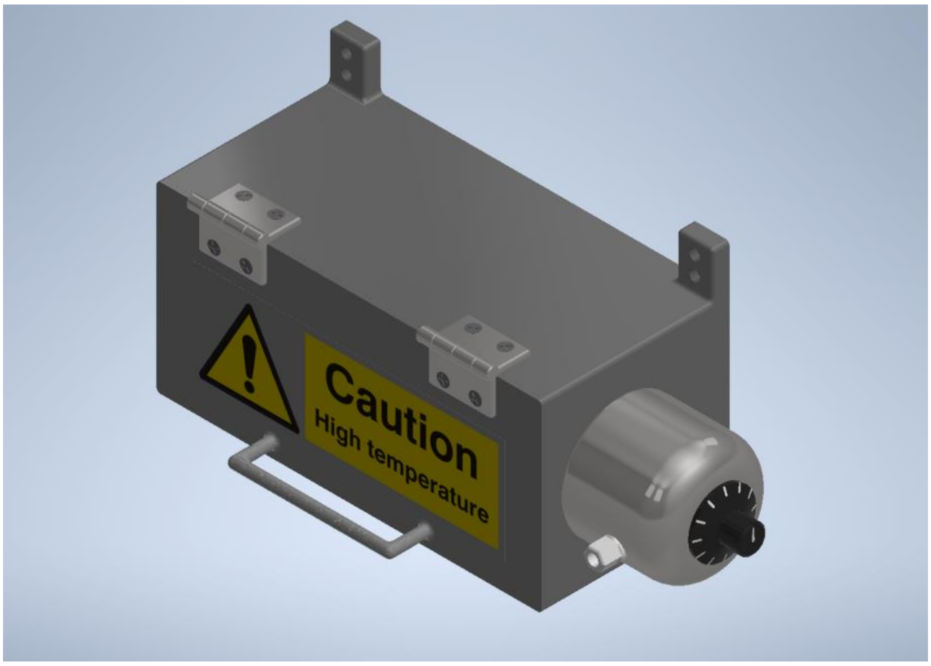


Figure 35. Heating element assembly

The components were then assembled into one system that has an external appearance of a box (Figure 35) with the dimensions of 210 x 100 x 102,35 mm (length x height x width) that will be attached to the test bench's wall. The hinges allow a vertical opening (Figure 36) of the device, inside which the heating element is located and attached to the thermostat. The side location of the thermostat requires the entire device to be placed preferably at the right-hand side of the test bench's wall, maximally close to the power socket. A white plug of the thermostat is a power connection housing to which a cord is inserted.

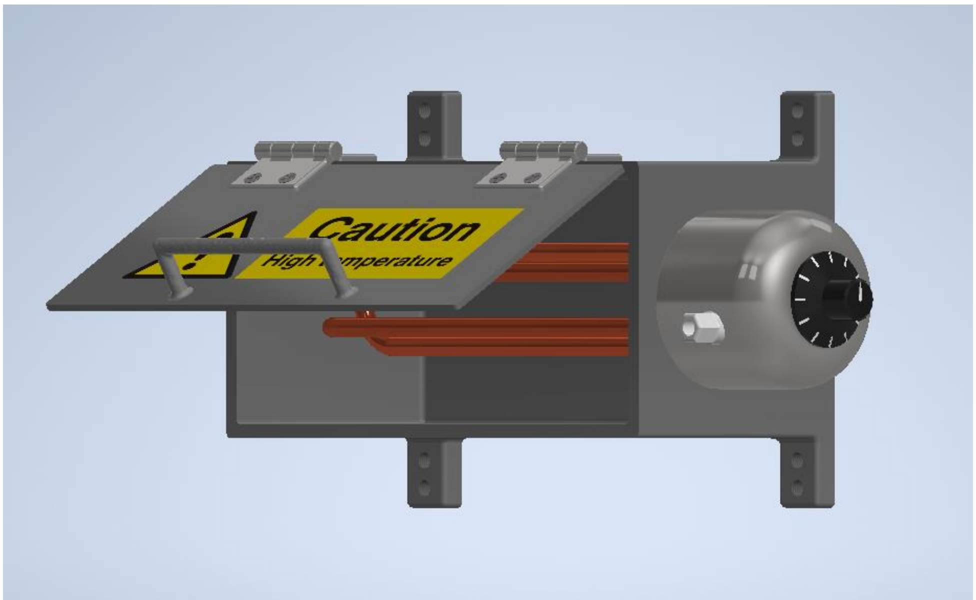
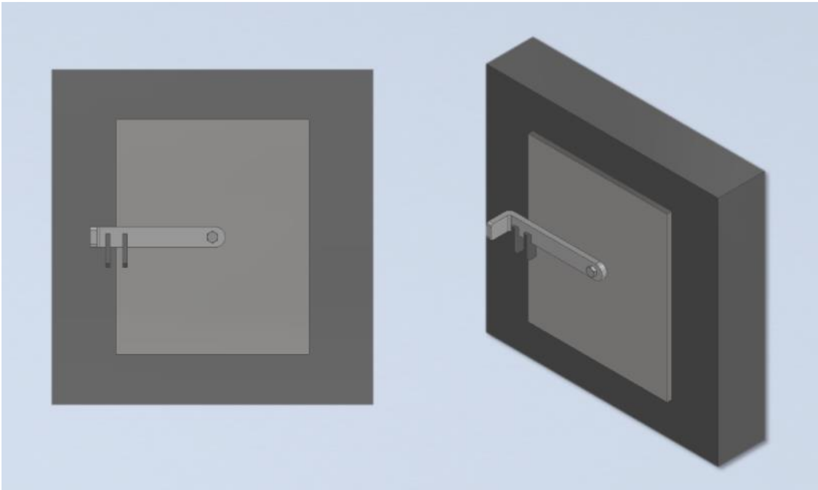
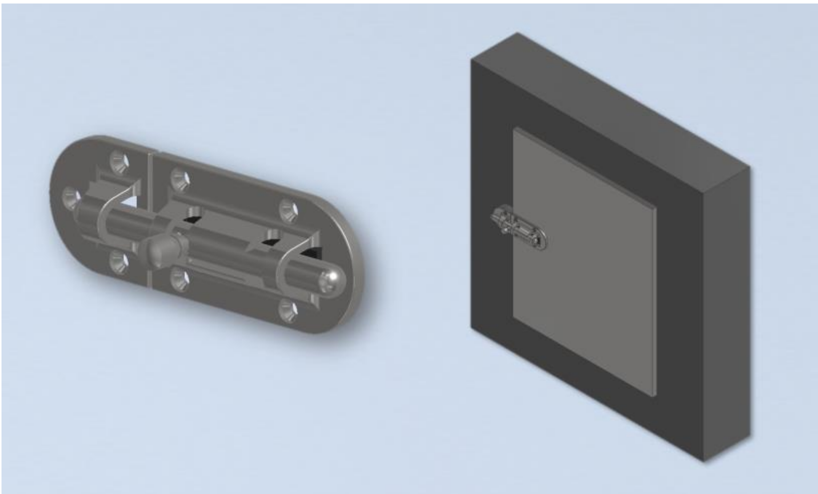


Figure 36. The vertical opening of the device

5.2.7 Obstacles

Some obstacles were needed to be designed to show that robots are capable of providing access to closed spaces. For this purpose, simple doors that had to be opened and closed with the robot arm were built. For these components, the major focusing points were the creation of the fastening, handles and hinging mechanisms of the doors as far as they had to fit the robots' structure. The following table (Table 5) demonstrates the options for both handle and fastening.

Part		**Illustration**
Locking handle		
	Normal handle	
	Sliding lock	
Fastening		

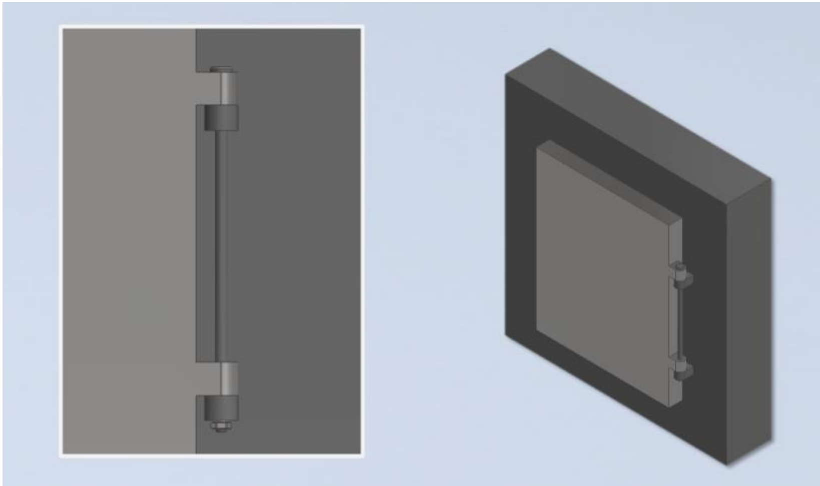
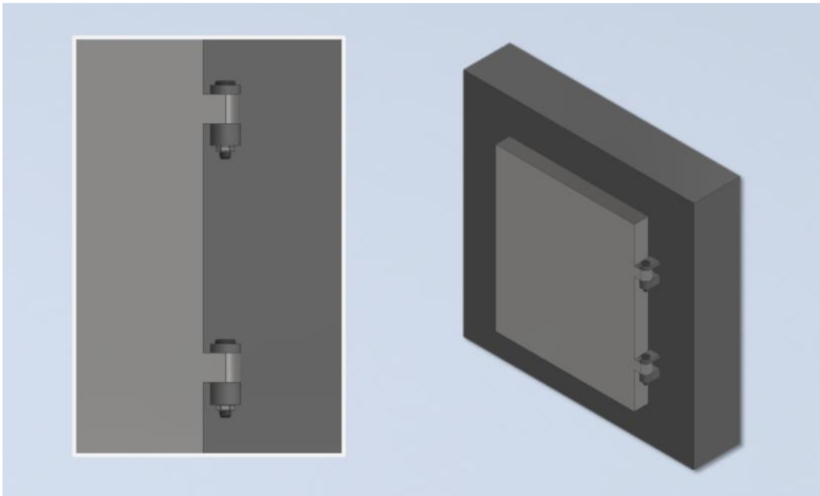
	One pin	
	Two pins	

Table 5. Doors configurations

Both options might be successfully implemented in the final structure since they all ensure reliable efficiency and provide the necessary functions. However, the combination of the sliding lock and the two pins fastening can grant a more reliable performance in case of potential rotation of the frame, while the normal handle would slide away from the allotted slot, the sliding lock would stay still. The two pins option would, in its turn, provide more secure fixation in case of failure compared to the one pin version.

Therefore, exactly the alliance of the sliding lock and the two pins fastening will be realized in the final structure.

5.2.8 Fixation tools

Since the robots' functional arsenals include the performance of various mechanical works, a system for testing these possibilities was also designed. It is proposed to use a press vise

(Figure 37) commonly included in the structure of any bench drilling machine to fasten the specimen. This device should be provided with a slotted base for easy installation and positioning, the same has to be done with the base wall so that the press vise can be reliably fixed. The gripper in its turn has to be designed so that there are no issues for the robot to grab it and fix the plate. Whether used for cutting, screwing, drilling, planning, sanding, or just holding, it is a perfect tool.

For the tool's fixation to the test bench's wall, additional supporting surfaces were added, through the apertures in which the tool can be screwed and unscrewed whenever it is needed.

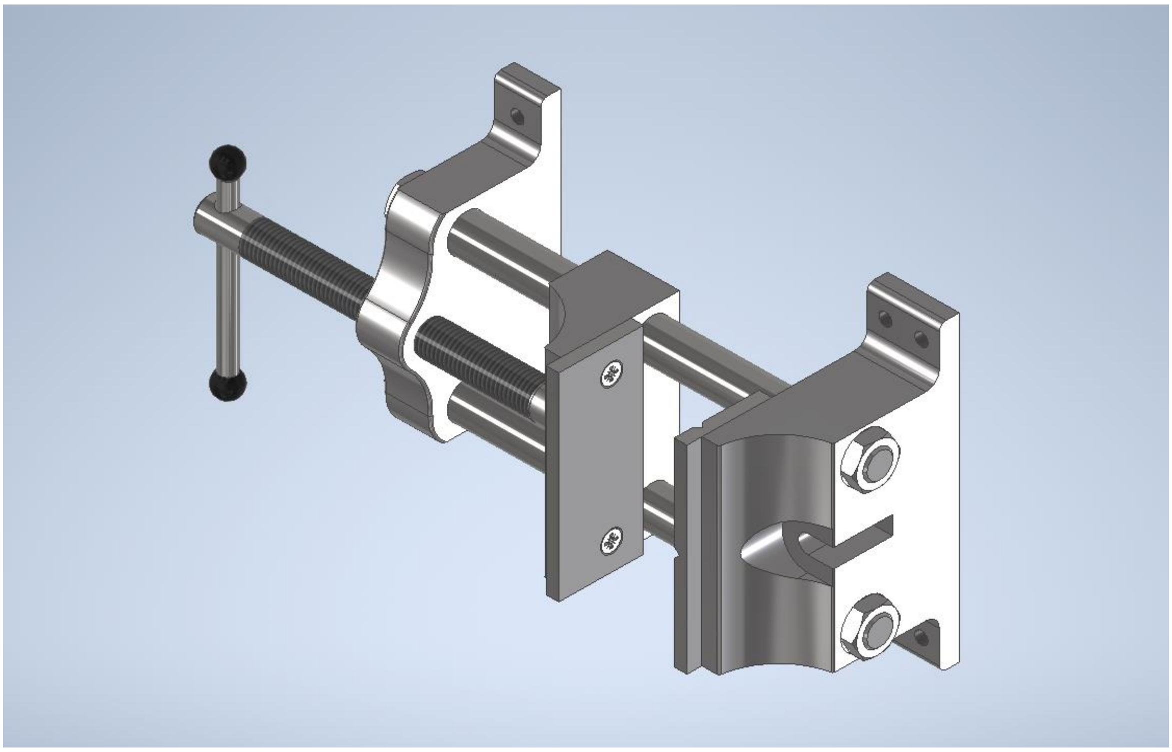


Figure 37. The press vise

The test plate is fixated between the jaws of the device and the necessary operation can be carried out reliably. The maximum distance between the jaws and respectively the maximum length of the plate is 171,45 mm. However, in theory, it can be regulated depending on how close the stationary jaws are located, what, in its turn, is limited by the length of the guiding bars.

The dimensions of the device itself are 333,4 x 152,4 x 150 mm (length x height x width).

5.2.9 Radiation source

Radiation is one of the major reasons why robots are being highly demanded at CERN. They first have to show that they are capable of detecting, measuring and mapping the radiation. For this purpose, a symbiosis of both the radiation source's holder and a box for its future storing and disposal was designed.

The radiation source itself is an object that has been contaminated or irradiated and emits a certain rate of radiation. For the testing purposes, only sources of small radiation rates are allowed and provided by the appropriate departments.

In the case of the present needs, a simple beam, pipe or another compact part is planned to be fixated with the help of the designed holder (Figure 38), which, in its turn, will be attached to the test bench's wall.

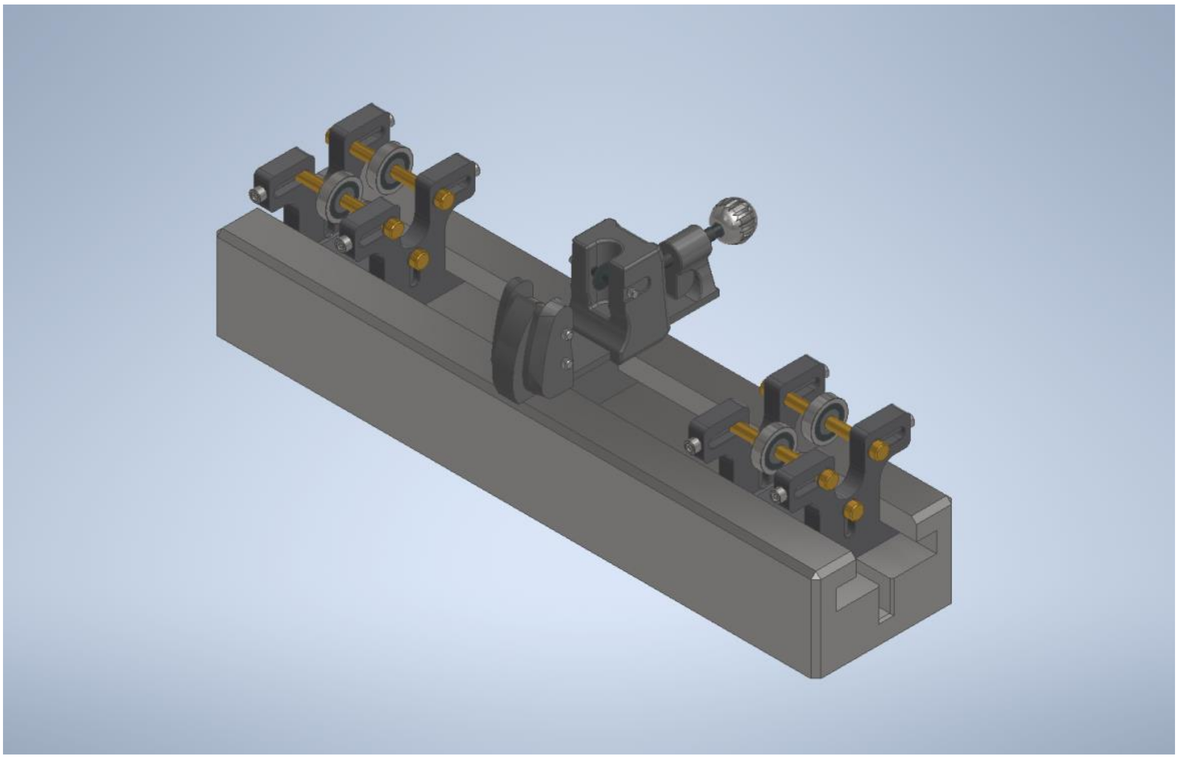


Figure 38. Radiation source's holder

The holder is done as an assembly consisting of a static base that is screwed to the wall, two movable supports between the jaws of which the source is fixed with the help of bearings and the third support that is installed in the middle to provide stability. The third support has another working principle that allows having a larger dimension in the center in case of a more complex part being inspected.

The final size of the assembly is 600 x 170,5 x 140 mm (length x height x width).

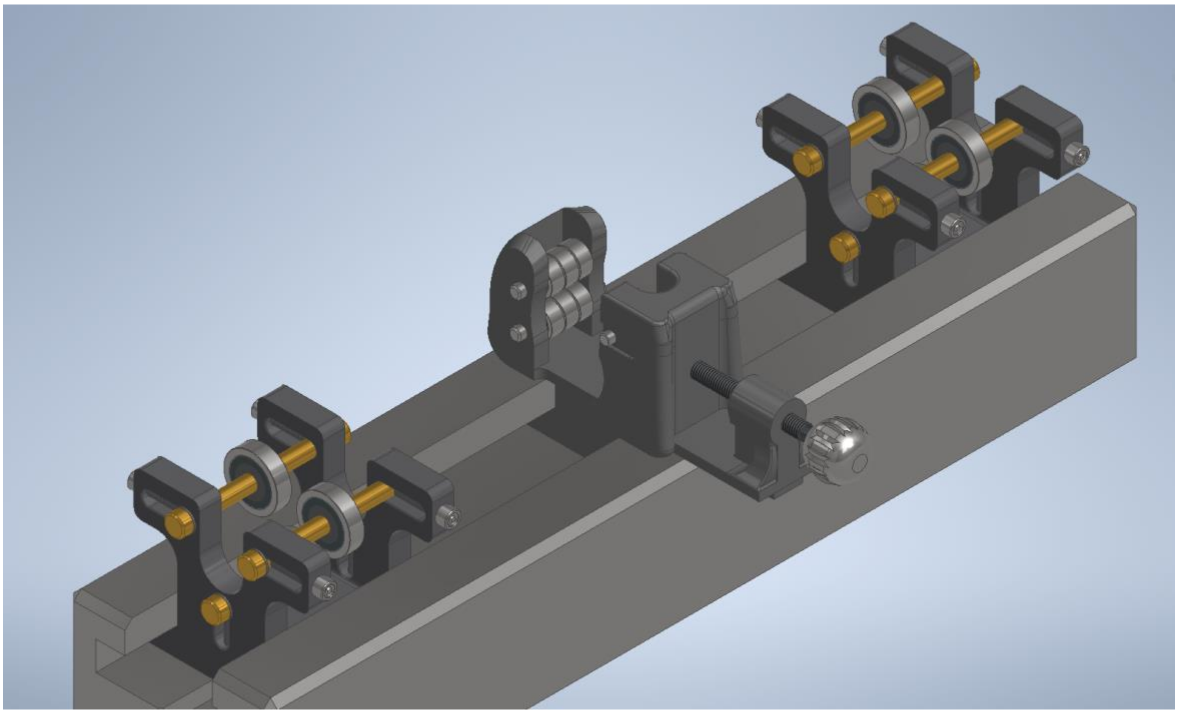


Figure 39. Radiation source's holder

The distance between the bearings of two supports on sides can be regulated by the screws so the device can be adapted to the width and the thickness of the part. The appliance itself is attached to the test bench by screwing via the holes in the holder as Figure 40 shows.

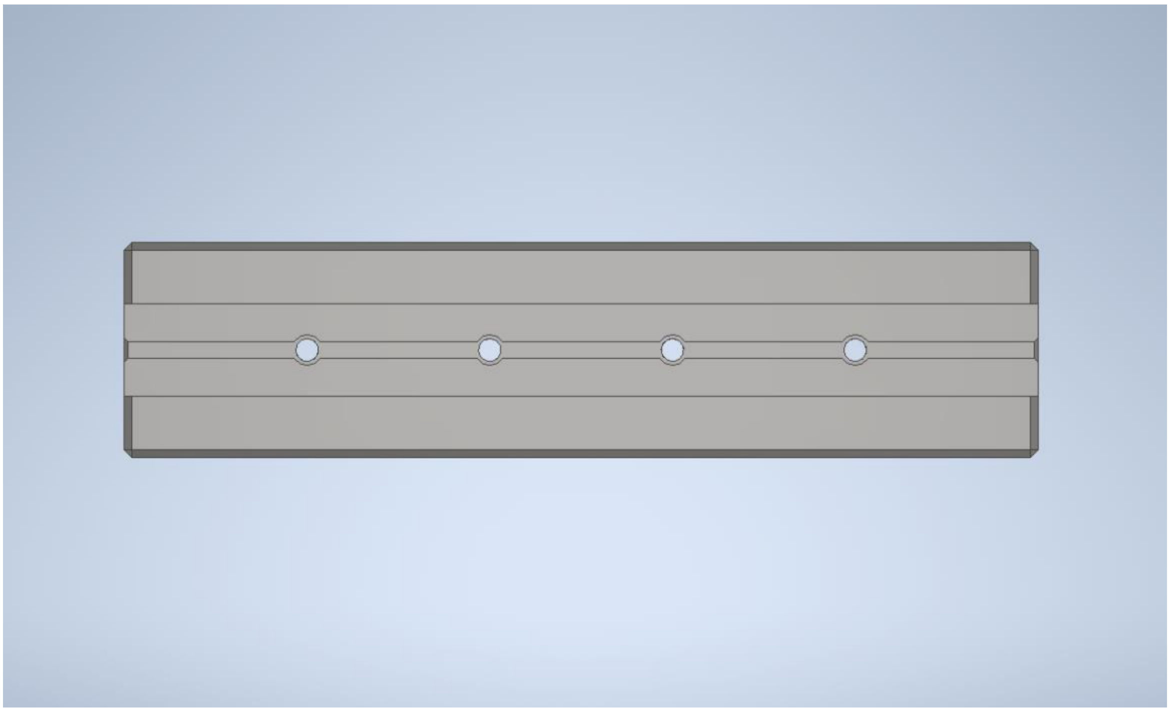


Figure 40. Radiation source's holder - Top view

The radiation test sample should not be left held at the test bench after the operation, so a specialized box for its storage with the dimensions of 600 x 650 x 350 mm (length x height x width) was created (Figure 41). Internal storage is equipped with shielding walls made from an absorbing material and special warning signs message about the hazard.

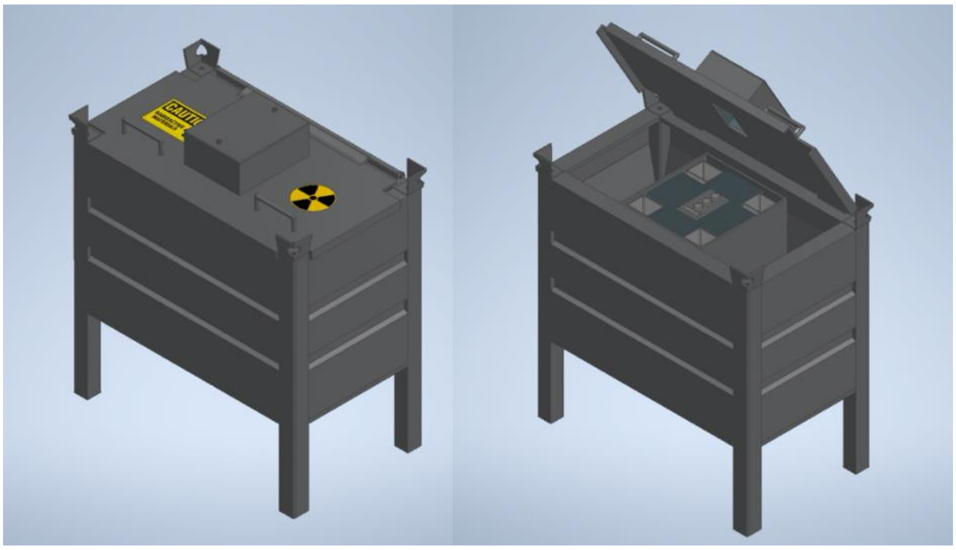


Figure 41. Radiation source’s storage

The radioactive objects are proposed to be placed in the appropriate slots that are placed between the lead blocks, protecting from the radiation. An eye-catching block at the top of the box is also equipped with the lead blocks to ensure additional protection as it is shown in Figure 42 where the block's cap is removed.

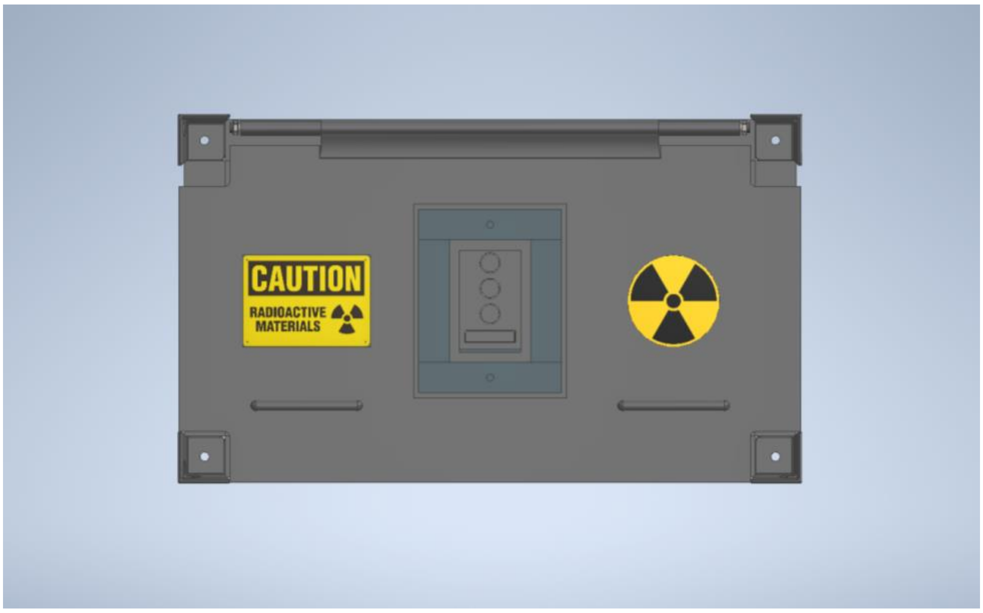


Figure 42. Radiation source’s storage with the opened cap - Top view

5.2.10 Helium leak device

Helium is a natural choice of coolant of many systems at CERN, particularly the electromagnets since the properties of this chemical element allow components to be kept cool over long distances (CERN f). However, the sequence of various elements is not insured from potential helium leakages and the underground tunnel has to be constantly monitored on the helium content percentage as it can act as a simple asphyxiant in excessive amounts that can lead to severe consequences (University of Florida). Such inspection and repairs are done by robots that are planned to be first tested with the following device (Figure 43).

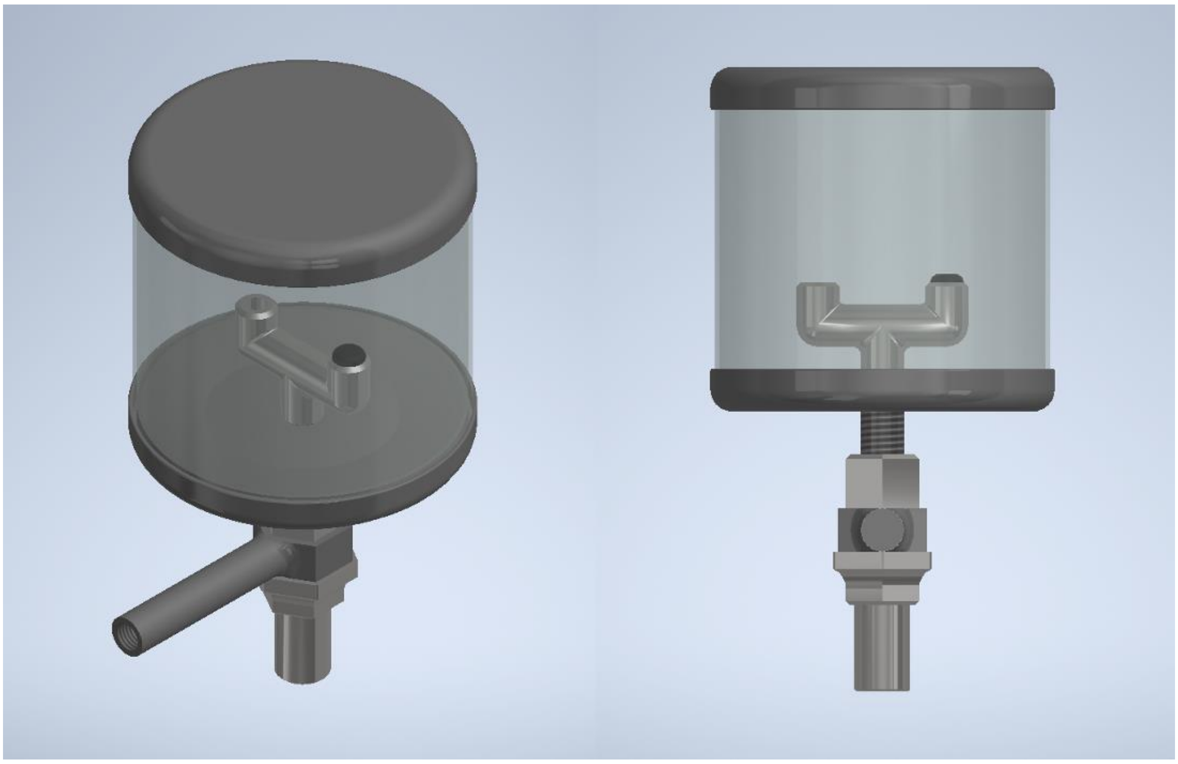


Figure 43. Helium leak device

The appliance consists of a piping system through which the helium is applied, a distributing system of two outputs and a glass tank that prevents the helium from propagating to the surrounding air. In addition, a handle for screwing the device to the test bench is fastened.

This mechanism works by a similar principle as the water leak device does. When only one aperture is open and the helium stream flows only from one of the holes, it implies a normal operation, however, if the second aperture is open as well and the robot detects the flow going through both ports, it should signalize the leakage.

The device takes a space of 80 mm in diameter and 145 mm in height.

The helium itself is pumped from a helium tank that should be located nearby and connected to the bottom of the device's pipe with the help of an appropriate transfer tube. A demonstrative helium tank was designed as well (Figure 44). The size of the tank is described as 230 x 380 mm (diameter x height).

Figure 44. Helium tank

5.3 System assembly architecture

All the designed constituting mechanisms were positioned and safely mated to the appropriate zones that were allocated depending on the defined modules and dimensions. It was assured that all the parts are located at safe distances from each other, so the absence of collision potential is guaranteed.

The elements are fastened so that they can be easily removed in case of necessity and be changed to any other system. Since they all are connected to the test bench by screwing approach, the robots themselves can also be tested to unfasten and install the mechanisms back

Figure 45, demonstrating the final assembly, also shows that the curved wall is freed from any surplus apparatuses with an eye to avoiding any obstacles while opening the system and performing the inner works. However, it can be adapted to any complementary adjustments in case of need.

The final assembly has dimensions of 1470,8 x 1285 x 777 mm (length x height x width).

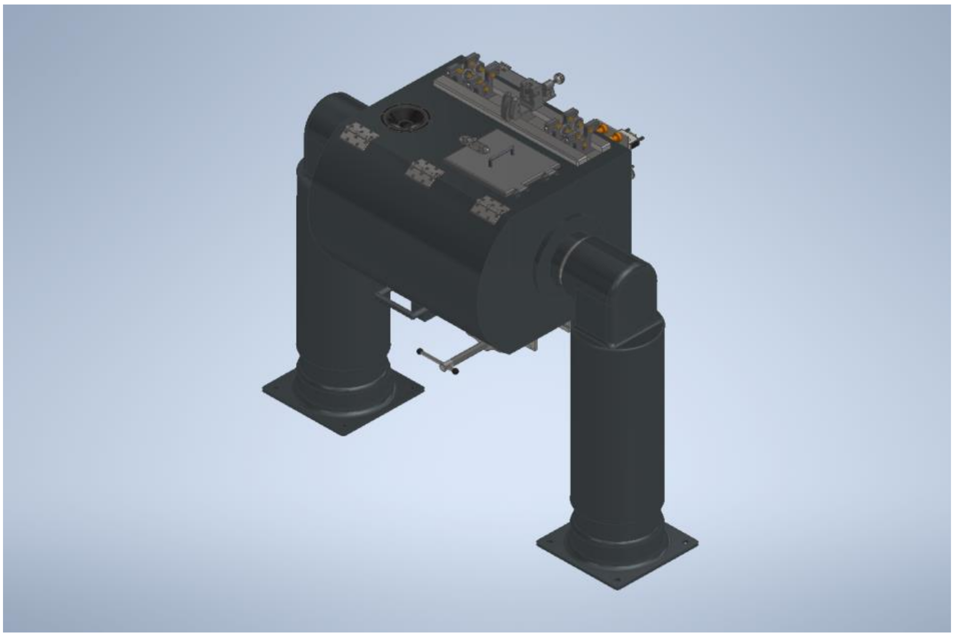


Figure 45. The final product

The top surface of the test bench is intended to host the radiation source holder, the sound source and the door behind which a small storing space is designed. The fastenings of these components imply the presence of inner placing slots in the body's structure, therefore all these mechanisms are located on the same wall.

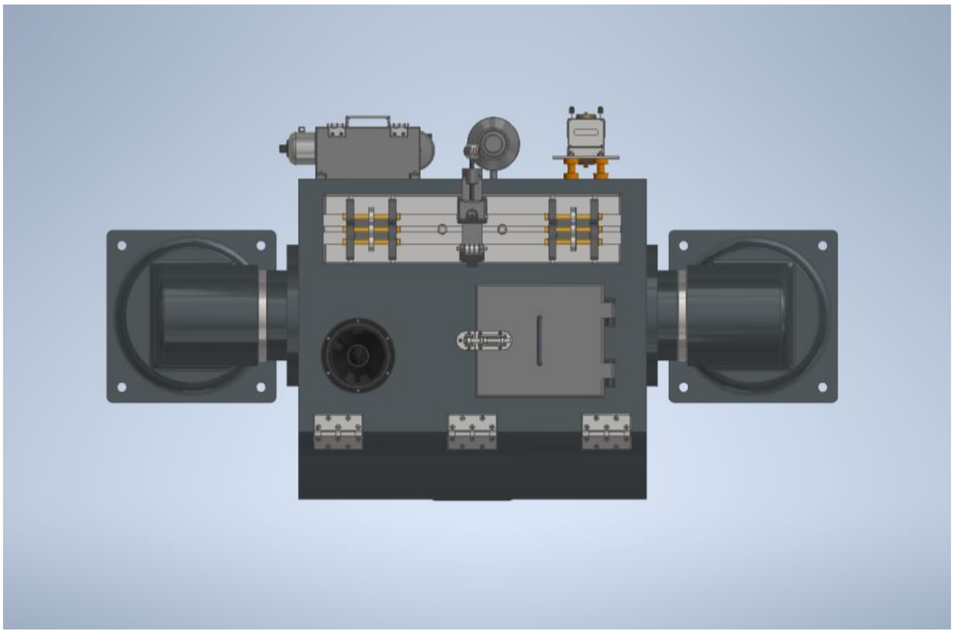


Figure 46. The final product - Top view

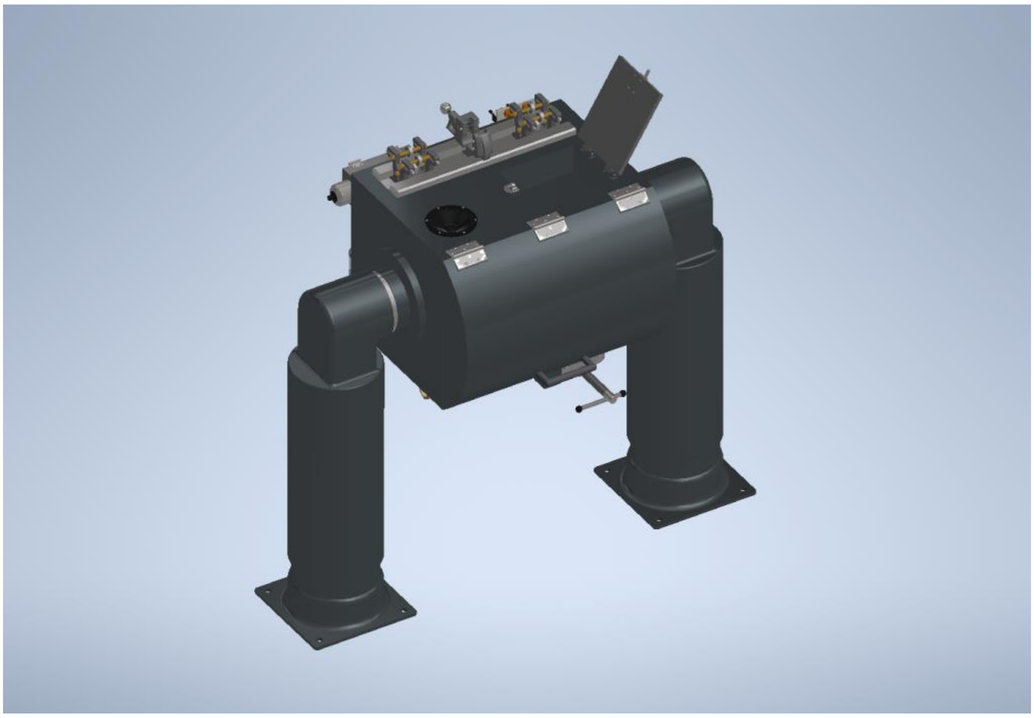


Figure 47. The opened door with the storing space

The oil container, devices for the water and helium detections, the heating element and the plate of the electrical connectors are arranged at the back wall so that the glass containers do not touch the wall, as Figure 49 illustrates, and each other, thus the robots' grippers have enough room to manipulate a certain device without colliding another one.

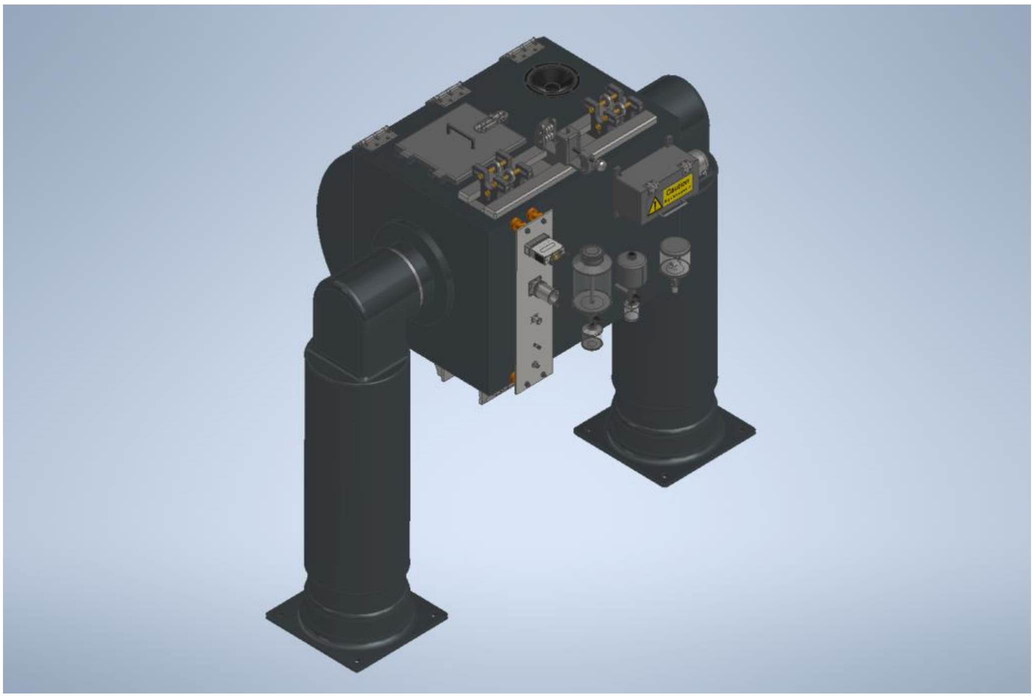


Figure 48. The final product - Back view

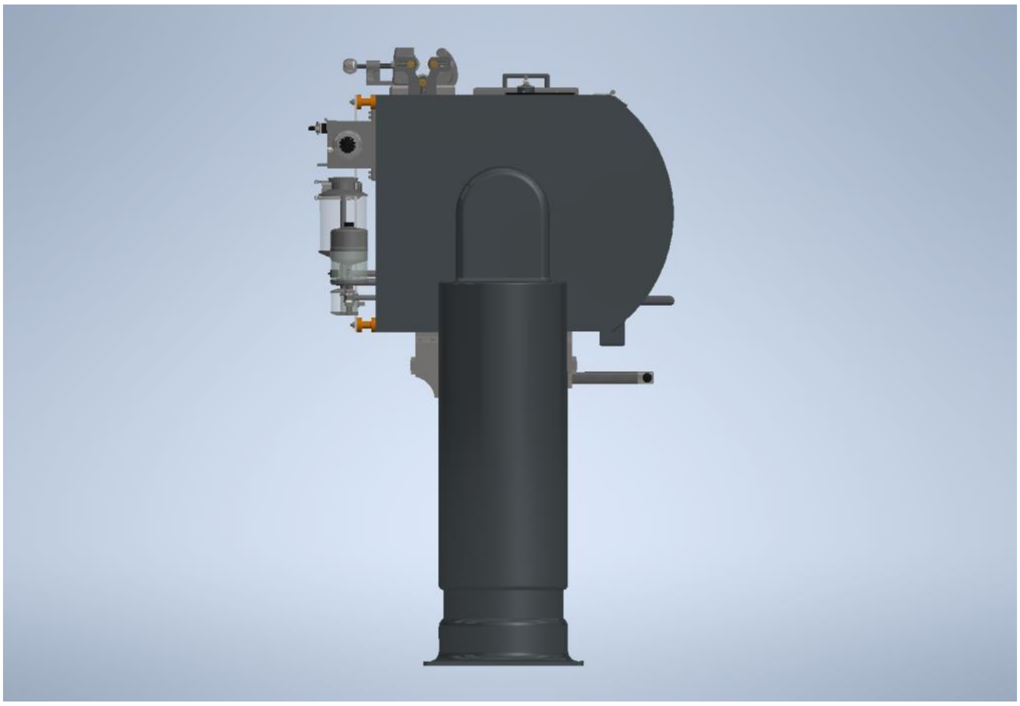


Figure 49. The final product - Side view

The bottom part, in its turn, hosts only two devices - the water connector and the press vise for fixing the plate samples and performing various operations. This is done to prevent the possible damage of glass parts caused by the mechanical works.

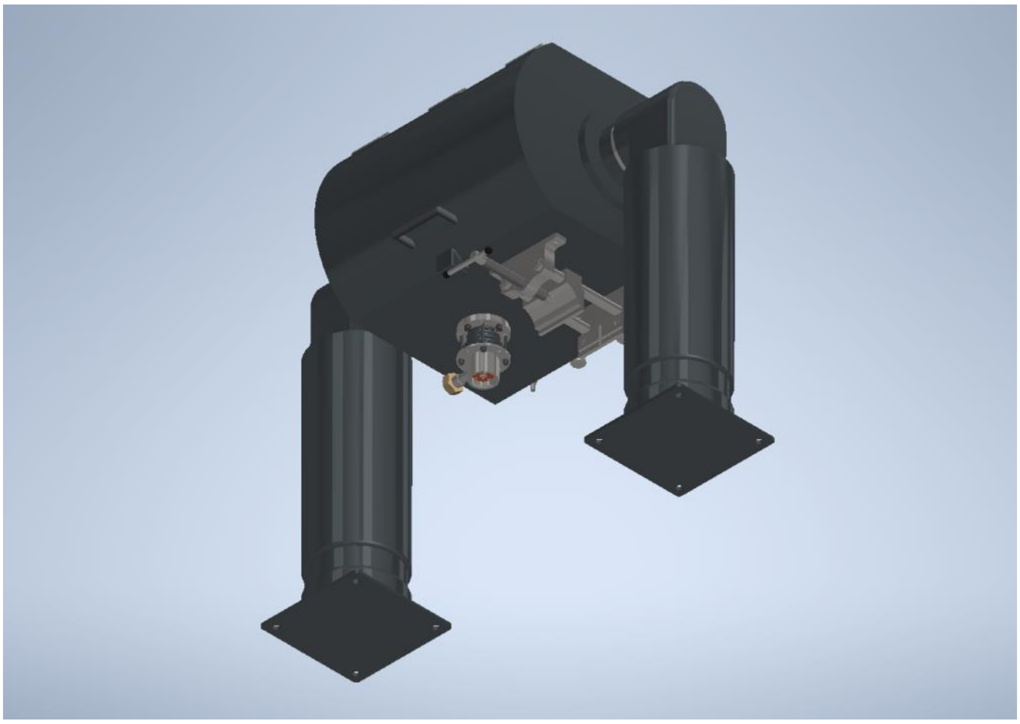


Figure 50. The final product - Bottom view

All the devices were securely fixed to the test bench body and the following illustration (Figure 51) shows that there is much internal space left that can be utilized for the electrical system of the construction that will ensure the normal work of the devices the operations of which depend on the presence of current.

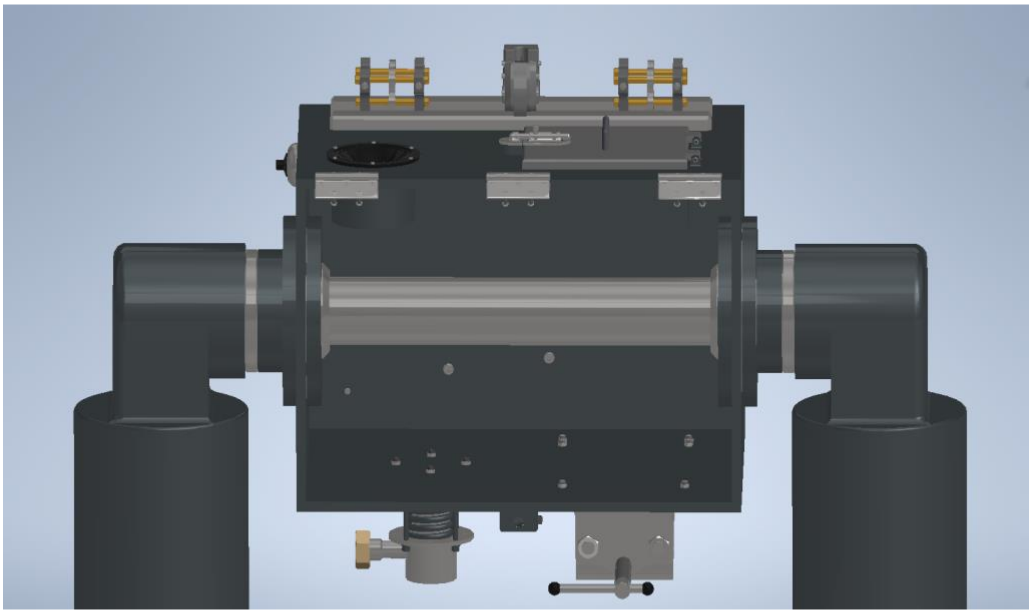


Figure 51. The internal space of the final product

As a final phase, the accessory devices, specifically the storing box for the radiation source and the helium tank, were added next to the final installation to create an exemplification of how the setup is planned to look in total.

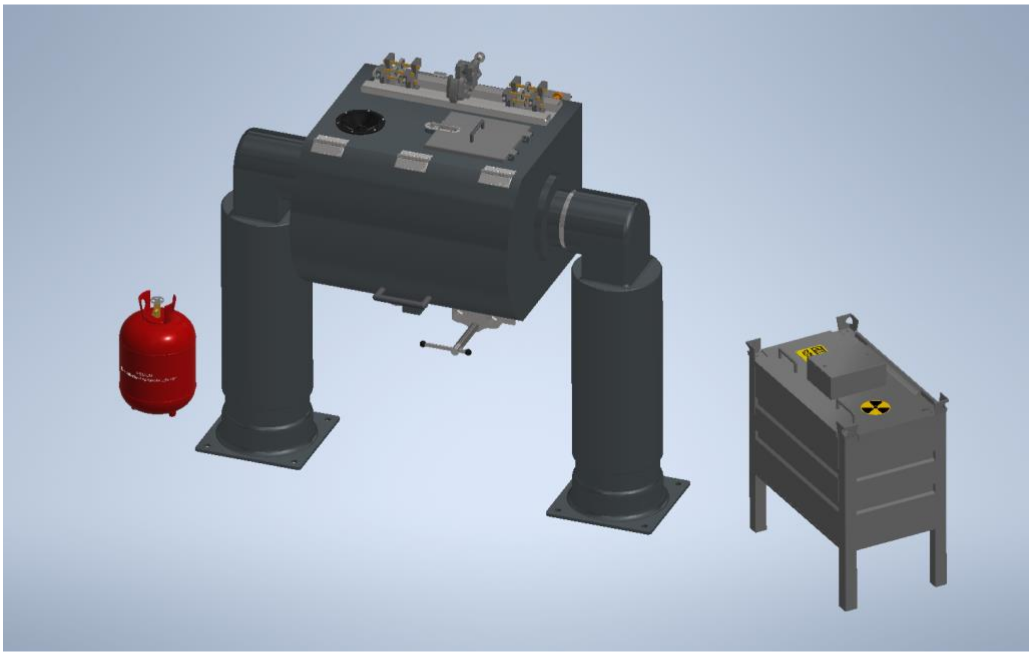


Figure 52. The conclusive system of devices

6 Material selection

The approach that has been followed during the project implementation was based on the principles of the systematic material selection process in order to choose the materials best suited to achieve the requirements of a given application.

The material selection of the present study covers the analysis of the test bench framework, the base, not including all constituting auxiliary devices that are also being designed in terms of this research since the material selection process for each of them requires an individual full-fledged investigation.

The carcass of the bench, in its turn, acts as the core component of the entire construction, to which all other supporting mechanisms are attached.

Many various factors go into determining the selection requirements, such as mechanical, chemical, physical and electrical properties of the product, as well as cost. These are the aspects that have been weighed during the material selection process.

6.1 Selection criteria

Detailing the listed above, it was decided to focus on the following chief viewpoints:

- Wear resistance
- Corrosion resistance
- Strength properties
- Manufacturability
- Reliability
- Environmental and sustainability aspects
- Cost-effectiveness

The procedure of systematic material selection is a crucial element in the production. If it is absent, it impacts the product's design by making it highly susceptible to failure and leads to many difficulties in the goal of delivering the desired performance.

Design analysis and its subjection in real working conditions help to recognize flaws, consequently identifying what material properties have to be altered and improved. As the outcome, the optimal material that is able to augment designs durability, performance and output, is defined.

It is an important step with an eye to ensuring the ability of the product not to succumb to extreme conditions still representing great performance in unpredictable conditions. The test bench for robotic interventions might be used exactly in such circumstances, therefore, factors of stable and assured working operation have to be guaranteed.

6.1.1 Base

The base includes the frame and the vertical pillars, or legs.

The frame serves to accommodate all devices and assemblies, as well as to provide the necessary strength and rigidity. The actuator, a movable part placed inside the frame, in its turn, is a set of movably connected parts (shaft, gears and bearings) for which a power source is used. As it was mentioned before, the drive system might be performed as a motor-shaft connection.

The supporting structure in the form of legs is fixed and does not move by itself, but a part inside it can be lifted and down on its axis perpendicular to the floor. The legs refer to rigid beams that hold the frame structure. The bases of the legs should be fixed firmly to the ground, ensuring the stable and safe performance of the work done by movable constituting elements.

It has to be noted that there are two elements of this component: a moving part and the stationary base itself. They are usually constructed using different materials since the moving/rotating part's moment of inertia has to be reduced and the moving/rotating quality has to be improved, while the stationary base does not face these considerations. The selection process is focused on the stationary base as far as the internal mechanism that allows the lifting movement is a fully separate study requiring corresponding computations and considerations. The stationary base is further generally mentioned as legs.

The major possible failure mode of the base is the probability of the rest of the device to fall while rotating. The main issue is how to prevent the shaft that is holding the base from this potential falling, the industrial reliability has to be ensured.

However, this problem is solved mechanically, particularly utilizing the right bearing types, for example:

- Screwing regular ball bearings on the static part of the connection to act like wheels enabling the rotation of the base
- Using a thrust bearing between the static and the rotational plates

Since the working principle of the machine is known, the most probable loading cases can be defined. This allows determining the necessary material properties and requirements based on which it can be proceeded with finding the most suitable material.

Base component	**Loading case**	**Critical material property**
Frame	Static and dynamic loads	Stiffness
	Compression and bending	Stiffness, strength, rigidity
Shaft	Radial, torsion and axial loads	Stiffness
Bearing	Radial and high one-direction thrust (axial) loads	Toughness
Gear	Tangential, radial and axial loads	Toughness
Legs	Shear	Shear strength
	Bending	Stiffness
	Compression	Stiffness, strength, rigidity
	Axial load	Stiffness, toughness

Table 6. Base's most probable loading cases

When a system has many potential ways of failing, it has multiple failure modes. The more complex a system is, the more failure modes there are. The base of the test bench is not related to such a complicated system, however, it has its own factors leading to failures in perspective.

Understanding these factors is key with an eye to improving the final product reliability. When these potential failure modes and their impacts are identified, appropriate corrective actions and plans can be implemented in time.

Base component	**Failure modes**	**Material property**
Frame	Deformation under bending and compression loadings	Increased stiffness High tensile strength High modulus of elasticity
	Corrosion	Excellent corrosion resistance Chemical stability
Shaft	Deformation of cracks under radial, torsion and axial loads	High yield strength High tensile strength
	Corrosion and wear	Excellent wear and corrosion resistance
	Fatigue caused by cyclic stresses	High fatigue strength High fracture toughness Slow crack growth
Bearing	Adhesive wear Abrasive wear	Increased hardness Low surface energy Strength Toughness
	Fatigue wear	High fracture toughness Fatigue strength
Gear	Impact wear and corrosion	Excellent wear and corrosion resistance

	Deformations and cracks	High ductility and elongation
	Vibrations	High damping coefficient
Legs	Deformation under bending and compression loadings	Increased stiffness High tensile strength High modulus of elasticity
	Corrosion and wear	Excellent corrosion and wear resistance Chemical stability
	Deformation or cracks caused by axial loads and shear	High yield strength High tensile strength High shear strength

Table 7. Base’s failure modes

Considering the material for building the base of the test bench, it should be strong and tough enough to withstand the potential loading cases and ensure a reliable fundament for the active movements of the upper part. It has to be easy to machine and work with, providing durability and low cost, while maintaining efficient expenditure. Moreover, the factor of appearance plays an important role, the final product has to have a shiny or attractively coloured surface.

Based on the briefly described criteria, more detailed functional requirements and technical specifications were derived, that serve as a basis for the material selection process.

Requirement type	**Factor**	**Description**
Material property	Toughness	The legs have to have sufficient toughness and stiffness allowing protection of great load strength since
	Stiffness	

		the construction bears the weight of the entire assembly
	Strength	The precision and strength of the bearing structure of the frame and the revolving part should be especially strengthened in the design process as far as it is the rotating joint of the whole system
Constructional requirements	Assembly space	Sufficient assembly space should be provided to ensure the overall reliability and stability of the working process
	Internal space	The base has to provide enough space for the deployment of the drive device and reducer combination, consequently also of speed sensors and brakes
	Disassembling ability	The base structure should be able to facilitate loading, unloading and adjustment
	Reliable limit plane	Great stiffness and a reliable limit plane should be provided to ensure the relative position between the various joints
	Regulation	There should be a possibility of regulation since there are bearings utilized for the wear and tear phenomena caused by the clearance and constant rotation resulting in low-quality machining

Table 8. Base’s requirements

These three tables (Table 6, Table 7, Table 8) represent the most crucial aspects to take into account while selecting the proper material for the base. This systematic approach allowed to consider several constituting elements, subsequently defining the most critical properties the material has to possess.

Based on these results, some possible variants of the material group were derived, they include metals in the majority, as well as polymers and composites. Ceramics is certainly rejected at the very beginning because the brittle behaviour of this material is not able to withstand such high loads as the weight of the test bench provides.

The next step was a comparison process between three highlighted groups by defining and collecting the advantages and disadvantages of each material group in one table, consequently comparing them with the previously determined requirements.

It should be pointed out that another significant factor to be considered besides the leading material properties, is the cost of the material being used. Such a test bench is a product manufactured limited compared to steam irons for example.

Material group	**Advantages**	**Disadvantages**
Metals	High melting point High strength, hardness and durability Versatility, ease of production Cost-effectiveness	Design limitations Low corrosion resistance High weight
Polymers	Chemical resistance Lightweight Good strength and toughness Post-treatment finishing is not required Good thermal and electrical insulating properties	Deformation under load Poor ductility Environmental unfriendliness Low melting point, low heat capacity Cannot withstand very high temperature Low structural rigidity

Composites	Increased strength Low density Light weight Excellent corrosion resistance	High manufacturing and raw material costs Complex fabrication Anisotropic structure High recycling costs Environmental unfriendliness More brittle than metals and thus are more easily damaged

Table 9. Potential material groups comparison

This comparison demonstrates that the most suitable material group for the production of the test bench's aim might be metals. The heat capacity of polymers is very little, they cannot be used in heat applications and in case it is decided to include welding to the testing opportunities by equipping the bench with an appropriate device, this rejects the possibility of this material being used.

The legs are supposed to be heavy as far as it is a foundation of the entire construction that provides stability, heavy structures cannot be made from polymers as the structural rigidity is low. The environmental aspects and low recyclability of the polymers speak for themselves. The project, in its turn, is also focused on finding the most environmentally friendly solutions.

The same concerns composites, in addition, their high cost is not justified and not reasonable in this certain case of using for the base.

Considering the concrete materials among the metals group, the shell of the rotating mechanism of the base might be made of aluminum alloy material in order to reduce the moment of inertia of the rotating part of the manipulator, while the stationary base of cast iron or structural steel. However, since the research mainly concentrates on the stationary base, further selection is focused only on it.

Cast Iron vs. Structural steel

Cast iron and structural steel in particular feature excellent mechanical properties for a wide range of applications. The following table was created in order to provide a general overview of the qualities of each material. While there are many different types of iron and steel to consider, this table focuses on gray iron and carbon structural steel — two of the most common forms of each metal.

Quality	**Cast iron**	**Structural steel**
Castability	✓	
Weldability		✓
Ease of machining	✓	✓
Vibration damping	✓	
Compressive strength	✓	✓
Impact resistance		✓
Corrosion resistance	✓	✓ (with additional measures)
Wear resistance	✓ (depends on the application)	✓
Cost	✓	✓

Table 10. Cast iron and structural steel properties general overview

Machinability

The final application of the base is so that it has to be machined to achieve specific tolerances and to create the desired finish. Structural steel is one of the most common materials for industrial construction comparing to cast iron. Its machinability allows welding or bolting into various shapes.

Compressive strength

It is the material ability to withstand forces that would possibly reduce the object’s size. Compressive strength is especially beneficial in the present mechanical application of the base where pressure and containment are its main decisive factors. Cast iron has better compressive strength than steel.

Impact resistance

This is a significant advantage of structural steel with its good ability to withstand sudden impacts without bending, deforming, or breaking due to its toughness. Cast iron cannot boast of such properties. Since the base might be damaged not only by the great weight of the upper structure but also by a third-party member (e.g. robot arm), this factor is taken into account.

Corrosion resistance

Cast iron has better corrosion resistance than steel. However, if these both materials are left unprotected, metals will oxidize in the presence of moisture, but cast iron will develop a patina to prevent deep corrosion of the metal’s integrity. Eventually, they both will completely decompose. To prevent this, paint or powder coating are recommended.

Wear resistance

Resistance to mechanical wear of the cast iron is better than steel's, particularly in friction-wearing situations. Cast steel wears more readily than iron but may still be resistant to certain types of abrasion. In addition, wear-resistant special structural steels that are quenched and tempered can be utilized.

Cost

Structural steel is the cost leader as it has a higher strength-to-weight ratio comparing to cast iron. Together with a lower material cost, production energy and required labour are less for the structural steel rather than for cast iron, which leads to the cheaper overall cost of the steel.

Summing up the obtained data, it is derived that the **structural steel** has much more attractive and justified properties suited for the case of the test bench than the cast steel.

The good casting properties of cast iron such as good vibration damping, good wear resistance, good machinability and low notch sensitivity, together with the ability to withstand great loads and presence of a certain degree of tightness or corrosion resistance could allow the cast iron to be used in the production of the base in case of a larger production with numerous series with the manufacturing method of casting as the cost of needed molds is considerably big.

However, since the present product is unique and is planned to be manufactured as the only produced piece, the option of casting is not reasonable, unlike welding, where **structural steel** is much more compliant and is the final superior choice.

There are two major grades of this steel: ASTM A36 and ASTM A572 grade 50 (Leeco Steel 2018). However, especially the second one perfectly fits the given application as it can be successfully bent, shaped and easily welded by all commercial methods, having a great value of strength per unit of weight. Machinability, response to heat treat and surface finishes are also good. The following table demonstrates the benefit of selecting a grade ASTM A572.

Property	**ASTM A36, plate**	**ASTM A572-50**
Tensile Strength, min, MPa	400 – 500	450
Yield Strength, min, MPa	250	345
Elongation at Break in 50 mm, min %	23	18
Density, g/cm3	7.8	7.8
Melting Temperature (Degrees C)	1480 - 1526	2740

Table 11. Structural steel grades comparison (MatWeb a; MatWeb b)

Therefore, the selected material for this certain component was assigned to be structural steel, particularly **ASTM A572 grade 50** with **welding** as a manufacturing method.

7 Cost breakdown analysis

The objective of this chapter is to provide economical aspects that affect the final cost value of the project. The budget representation of the expenses associated with the proposed project should be described justifying the costs behind certain items and explaining the use of the funds. The overview given here is for preliminary guidance only to provide a base for further research and estimations, eventually deriving the cost value.

Economical aspects of the test bench and its process can be thought of as four main parts:

- Design costs
- Material costs
- Manufacturing costs
- Cost of an optimized lifetime and maintenance

The procedure of design by brainstorming and selecting the optimal concept for the product are the first steps of the entire project, and this is where the costs first occur. They might include 2D drafting, 3D modeling, CAD (Computer-aided design) conversion, animations and simulations, material testing and FEA (Finite element method). Most of the listed services have already been finalized in terms of the completed study and the phase of designing does not demand further expenses, however, particular tasks might require outside spendings.

Such a parameter is materials cost that turns out to be one of the chief elements of the expenses. This spending is an unavoidable factor and has to be considered as a fixed one. The best approach can be first collecting the best possible materials' properties that are related to the conditions with the least possible costs. Another methodology implies first creating a cheaper and not that qualified material for producing a prototype. Such a lower-grade material before the main manufacturing process can aid to figure out the machining operations needed for the performance of the test bench and to test it in an automated production system. This ideology can help to avoid a significant loss of sums of money.

Since the test bench will not be a part of mass production, proper manufacturing methods have to be selected as certain methods can turn out to be not sensible from the point of view of one-off production. Manufacturing costs will primarily depend on the equipment and tools being used, the possibility of an automated flexible production line, appointed labour, machinery and maintenance.

To provide the optimized lifetime recommendations for the test bench, the decision on the materials being applied has to be done for the entire construction, including the constituting mechanisms. If the selected materials are the base ones, commonly their properties can be advanced when needed. This approach leads to two options: either relatively cheap material with extra maintenance costs or specialized materials with longer lifetime and but therefore, a more expensive product.

The effectiveness of the production cost can be described using the following ratios, where the efficient way of production is used as a guideline and arrows (↑ or ↓) correspond to the increase or decrease of the property.

- Costs [€] [↓] / Properties of the selected materials [%] [↑]
- Costs [€] [↓] / Product lifetime [h] [↑]
- Costs [€] [↓] / Production rate [h] [↑]
- Costs [€] [↓] / Final product accuracy [%] [↑]

All the listed aspects have to be taken into account in terms of further research while specifying the manufacturing methods, materials and inner structure of the device, as far as all these factors have a significant effect on the total cost of the product.

8 Conclusion

The thesis dealt with designing the test bench for robotic equipment and its purpose was to demonstrate the flexibility and modularity of such a station. The objective was followed with particular qualities of CERN conditions and requirements so that the proposed product could successfully serve in strict circumstances.

The device was built from scratch by analysing the initial knowledge and defining the primary dimensions and functional possibilities the future product was supposed to have, accordingly dividing them into modules and determining the appropriate devices with the help of which the tests are planned to be held. Based on the obtained data, concepts drafting was completed, and the optimal design was consequently defined by implementing the SWOT analysis.

3D modeling of the test bench framework and the included elements was accomplished respecting the allowable dimensions and safety requirements. All the models, their functions, working principles and designing procedures were described, recommendations on use were provided with an eye to assisting the prospective work with the project. The finite results unite the created systems in one assembly and reflect the initially set parameters. The obtained outcome successfully met all the derived needs and technical specifications.

Material selection for the test bench's framework allowed to present the potential loading cases and failures of the device that will also be useful documentation for future considerations and decisions related to the test bench optimizations.

The completed thesis represents a documentation of the prepared mechanical design of the proposed device and connections between the created mechanisms. This phase of the project will serve as a detailed base for future studies and development in terms of the Robotics Department at CERN, allowing to continue with the inner structure of the device, projecting the electrical structure and preparing the manufacturing plan and industrial implementation.

The created apparatus's structure and functional confirm the opportunity to embed and root such a system in various industrial fields where it can be relevantly and successfully utilized by setting and equipping it with the necessary devices by virtue of the modular approach of the design. Ensuring the testing of safe and reliable work might be essential in many areas, for which the test bench was designed, as well as to make at least a small contribution to the development of the common goal and business - a technological breakthrough and scientific progress.

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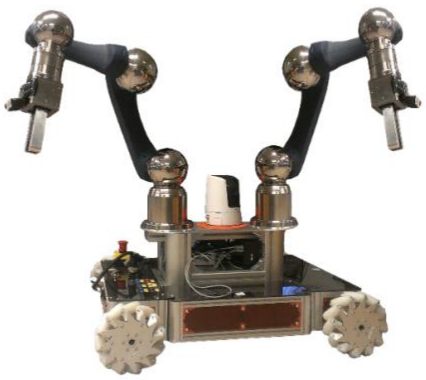
Appendices

Appendix 1. Overview of CERN's robots

Robot	Functions	Dimensions	Construction	Picture	Notes
TIM (Train Inspection Monorail)	- Inspection - Radiation mapping (radioprotection probe) - Monitoring the tunnel structure - Oxygen percentage - Communication bandwidth - Temperature - Visual and infrared imaging of the LHC - Cell phone reception (eyes and ears for the Fire Brigade, operations team)	1 wagon: 30 x 30 x 180 cm 1 wagon weight: 74 – 108 kg (depending on the wagon type) The complete length is 10.2 m	- 5 wagons (control, battery, motor, payload, reconnaissance) - Sensors - Cameras (PTZ and HD) - Electronic components - Safety bumper and laser - Robotic Arm - PC		The mechanical arm is attached to the payload wagon and can be extended to position a sensor at a desired fixed height (beam height). The RP sensor measures radiation every 250 milliseconds. It is possible to install a photo camera for tunnel inspection photogrammetry. RP mission and high-resolution pictures can be taken at the same time. 7 GoPro cameras allow a 360 ° view.
Telemax	- Radiation inspection - General surveys (video and audio inspections) - Small manipulation tasks (Unscrewing and screwing in cables, Cutting wires) - Maintenance operations - Vacuum leak test - Manipulation of dangerous equipment - Use of electrical and mechanical tools - Transporting, positioning, and controlling of measuring equipment - Placing PT100 sensor in AD target	(L x W x H): 80 x 40 x 75 cm Weight: 75 kg	- Tracked wheels for enhanced mobility - 7 degrees of freedom manipulator - 4 colour cameras - PT100 tool		The robot is capable of climbing stairs. It is fitted with a six-axis manipulator. The control station is portable and communication between the control station and the ROV is either by a 3 m cable, optical fibre or via radio. The radiation inspection is done so that a probe must be positioned next to relatively delicate beam-line equipment. Can be used in cooperation with Teodor.

Teodor	- Identification and processing of objects - Providing access to buildings and closed rooms - Disposing of dangerous items using various devices - Monitoring and investigation - Use of electrical and mechanical tools - Transporting, positioning, and controlling of measuring equipment - Cutting cables - Delivering high torque output with minimal exertion by the robot - Precisely applying a specific torque to a fastener, bolt - Placing PT100 sensor in AD target - Cutting surfaces such as metal, aluminium and wood - Securing and moving loads	(L x W x H): 135 x 68.5 x 124 cm Weight: 375 kg	- Chassis - Manipulator - Control station - Control panel - Cutter - Impact wrench - Torque wrench - PT100 tool - Saw - Hook		
CERNbot 1.0	- Autonomous and teleoperated interventions in hostile environments in presence of ionising radiation - Metal cutting - Epoxy resin or oil filling or emptying - Collision detection and object weight and inertia estimation - Torque control capabilities to (un)screw bolts - Helium spray system for vacuum leak detection - Providing and placing foam - Measuring radiation dose - Placing PT100 sensor in AD target - Cutting pipes - Engaging and (un)screwing various types and sizes of screw fastener heads	(L x W x H): 90 x 79 x 92 cm The height depends on the arms quantity and their positions	- 5 cameras - Sensors - Electrical screwdriver - Force torque sensors - Helium spray system for vacuum leak detection - Nibbler - Scissors - Liquid pump - Epoxy resin pump - Foam pistol - RP sensor - PT100 tool - Pipe cut - Universal screwdriver		It can host different robotic arm types. The platform is 100% modular and it runs over Wi-Fi (100 m indoor) /4G (unlimited distance) / Ethernet cable (up to 150 m). Can be equipped with one or two robotic arms, changing their dimensions and reachability. When the second arm is attached, the PTZ-camera is relocated, and the collision avoidance system is switched on.

CERNbot 2.0	- Autonomous and teleoperated interventions in hostile environments in presence of ionising radiation - Metal cutting - Epoxy resin or oil filling or emptying - Collision detection and object weight and inertia estimation - Torque control capabilities to (un)screw bolts - Helium spray system for vacuum leak detection - Providing and placing foam - Measuring radiation dose - Placing PT100 sensor in AD target - Cutting pipes - Engaging and (un)screwing various types and sizes of screw fastener heads	(L x W x H): 90 x 79 x 310 (max) cm The height depends on the arms quantity and their positions	- Electrical screwdriver - Force torque sensors - Helium spray system for vacuum leak detection - Nibbler - Scissors - Liquid pump - Epoxy resin pump - Foam pistol - RP sensor - PT100 tool - Pipe cut - Universal screwdriver		This version is equipped with a lifting stage mechanism allowing to lift the equipment platform up to 1.6 m from the floor. It can host different robotic arm types. The platform is 100% modular and it runs over Wi-Fi (100 m indoor) /4G (unlimited distance) / Ethernet cable (up to 150 m). Can be equipped with one or two robotic arms, changing their dimensions and reachability.
CRANEbot			- Electrical screwdriver - Force torque sensors - Helium spray system for vacuum leak detection - Nibbler - Scissors - Universal screwdriver - Liquid pump - Epoxy resin pump - Foam pistol - RP sensor - PT100 tool - Pipe cut