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MiniCERNBot Educational Platform: Antimatter Factory Mock-up Missions for Problem-Solving STEM Learning

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Abstract: Mechatronics and robotics appeared particularly effective in students' education, allowing them to create non-traditional solutions in STEM disciplines, which have a direct impact and interaction with the world surrounding them. This paper presents the current state of the MiniCERNBot Educational Robotic platform for high-school and university students. The robot provides a comprehensive educative system with tutorials and tasks tuned for different ages on 3D design, mechanical assembly, control, programming, planning, and operation. The system is inspired to existing robotic systems and typical robotic interventions performed at CERN, and includes an education mock-up that follows the example of a previous real operation performed in CERN's Antimatter Factory. The paper describes the learning paths where the MiniCERNBot platform can be used by students, at different ages and disciplines. In addition, it describes the software and hardware architecture, presenting results on modularity and network performance during education exercises. In summary, the objective of the study is improving the way STEM educational and dissemination activities at CERN Robotics Lab are performed, as well as their possible synergies with other education institutions, such as High-Schools and Universities, improving the learning collaborative process and inspiring students interested in technical studies. To this end, a new educational robotic platform has been designed, inspired on real scientific operations, which allows the students practice multidisciplinary STEM skills in a collaborative problem-solving way, while increasing their motivation and comprehension of the research activities.

Keywords: sensors; robotics; mechatronics; physical devices; education; STEM education; interaction; engineering education

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1. Introduction

Mechatronics and robotics play an important role in high-school and University education. They provide the students with real world challenges to be solved using novel solutions and pushing into a deeper understanding and direct application of Science, Technology, Engineering, and Mathematics (STEM) language and systems. STEM education aims to provide the knowledge and tools to the widest number of students for pursuing careers in STEM fields [1]. Mechatronics and robotics provide access to all STEM fields by showing how they work in real life and revealing their impact in the world of tomorrow.

Education is an important mandate for CERN, whose role is to educate Europe's future scientists and engineers and provides a series of educational programmes targeting students of different ages [2,3]. Of the 100,000 visitors who visit CERN each year, the majority are high-school students [4,5]. Opportunities for students in applied physics, engineering, computing, and more are available throughout the whole year, thanks to workshops and internships like high-school internship programme, the Beamline for School challenge, and the S'Cool Lab research facility [6].

The Mechatronics, Robotics and Operations (MRO) section at CERN, part of the Survey, Mechatronics and Measurements (SMM) group of the engineering department is in charge of designing and developing cutting-edge robotics technology to remotely perform real interventions in the accelerator scientific facilities. The CERNBot and Train Inspection Monorail (TIM) platforms are an example of such systems, which are continuously improved and adapted to the CERN necessities, while offering new scientific improvements to the Telerobotics research community [7–11]. The MRO section is part of different CERN's educational programmes and hosts periodically students between the ages of 16 and 19, from diverse background and education. In addition, Bachelor and Master's students take part in longer education activities, related to more specific scientific problems, which need basic training on STEM related skills. Besides this, in collaboration with Universities, CERN offers Doctorate Programs, which might need desktop educational kits for prototyping and preliminary scientific experiments.

STEM is an approach focused on the development of skills in multiple fields during learning. The use of robotics in STEM (Educational Robotics) can increase students' interest and motivation [12], both during the learning process as well as future career decisions [13–15]. Several studies have been done to present the impact of Educational Robotics (ER) even in young students [16–18], thanks to its connection with play and enjoyment is considered to be an important factor that encourages children and enables intrinsic motivation, especially in primary education [19]. Researchers have attempted also to create robotic curricula in high-schools and studying their effect [20,21]. In addition, over the last decade, the interest and engagement of teachers and professor around Educational Robotics and STEM have increased [22]. Different types of educational robots have been presented, adapting to different programs, some more software-centred, others more focused on hardware and mechanical assembly, others on socialisation, interaction and gaming [16]. Overall, Educational Robotics pushes the students at all ages to provide innovative solutions to real-world problems, promoting collaborative skills [23], creativity and problem-based learning [24] and allowing them to learn with technology rather than learning about it [25].

In this paper, the MiniCERNBot Educational Robotic kit is presented. The robotic kit brings the experience obtained during CERN's robotic operation to the educational level. The robotic kit includes different learning paths adapted to different students' ages and different training times, spanning from one day to a couple of months. According to their age and skills, students are required to analyse and understand the requirements of a robotic intervention, inspired by real operations performed in CERN's accelerator complex. They can define the intervention procedures including checklists, failure analysis and recovery scenarios as defined by the CERNTAURO framework for remote interventions [8]. The students can design and manufacture custom tools to simplify the operations' tasks, program a control application for the robot and additional behaviours on the robot control board thanks to the full support of the CERN Robotic Framework [7] and then apply their work to the real robotic intervention. Finally, they can compare their work by controlling the MiniCERNBot educational robot with the same Human–Robot Interface used to control the CERN's robots.

Research Method and Paper Structure

The paper faces the need of a new educational procedure at CERN Robotics Lab, which is centred on solving real related problems, can be adapted to different educational levels (i.e., high-school, Bachelor's and Master's), is flexible in terms of duration of the activity (i.e., from one day to three months), allowing collaborative multidisciplinary teams, and greatly helping students to clarify their vocations in STEM carriers.

In order to walk in this direction, the research has focused on three main aspects: (1) The design of a multidisciplinary and adaptable learning path oriented on solving missions of increasing difficulty, (2) the design of a mechatronic educational kit (i.e., MINICERNBot twins and antimatter factory panel) in order to be used as learning scenario and validation tool, and (3) assessment of the performance, in terms of both mechatronics, and final motivation of the students. The education experiments that provided results on students motivation have been performed with high-school, fourth year Computer Science Engineering, and first year Robotics&AI Master's students.

With the aim of helping on the repeatability of the experiments, the paper proposes a multidisciplinary education path, providing a model to combine STEM practices in the same learning process, identifying free tools that can help enormously in this process. The learning path can be adapted to other education STEM scenarios as required. Besides this, the robotic kit is explained in detail, focusing specially on the used electronics and computer science tools, as well as evaluating their performance by using standard benchmarks (i.e., Android and PC).

To this aim, the paper presents first the proposed learning paths, highlighting the differences and possible customisation according to the student's age and internship duration. Afterwards, the technical details of the educational kit, both from the mechanical and software point of view, are explained in detail. Finally, the results and video demonstration are shown, including a resume of the experience of various student groups.

2. Learning Paths

The education activity presented in this paper follows a collaborative problem-solving learning strategy [26], where the students are introduced to the problem by on-site experts' (e.g., recovering a radioactive source), study the available tools (e.g., robotic platforms, 3D printers, programming), and develop a solution, which has to be designed, implemented, tested, and applied in a simplified and safe mock-up of the radioactive scenario.

The different teams can solve the problem in a synchronised or decoupled way, getting quantitative feedback from the experts on the efficiency and quality of the solution, according to the tasks that were successfully completed, and being able to compare their achievements with respect to previous teams.

Students visiting the CERN-EN-SMM-MRO Robotics Lab are divided in teams and are offered different learning paths according to their education level (Figure 1). Independently from their age, the teams are required to solve a set of missions on the antimatter mock-up (Figure 2), using different appropriate tools adapted to their educational background.

It is worth mentioning that CERN offers education activities for primary school (e.g., demonstrations and labs), high-school (i.e., summer education program), Bachelor's (e.g., final project and summer internships), Master's (e.g., final master project), and Doctorate levels (i.e., collaborating with Universities). Bringing recent discoveries to society via education and dissemination is one of the goals of the institution. The MINICERNBot platform has been designed to help in this task, focusing, at the first stage, on High-School, Computer Engineering and a Master's on Robotics&Artificial Intelligence students, as can be appreciated in the current Learning selected Paths (see Figure 1). The selected education levels try to demonstrate that the system offers students a tool to develop knowledge based on incremental and multidisciplinary problems, motivated by real experiences. High school students need a tool to discern a vocation, showing both the problems and the possible solutions. Engineering and Master's students need the tool to better develop their technical capabilities, as well as enhancing their motivation in the subject.

Figure 1. Learning activities using the MiniCernbot platform.

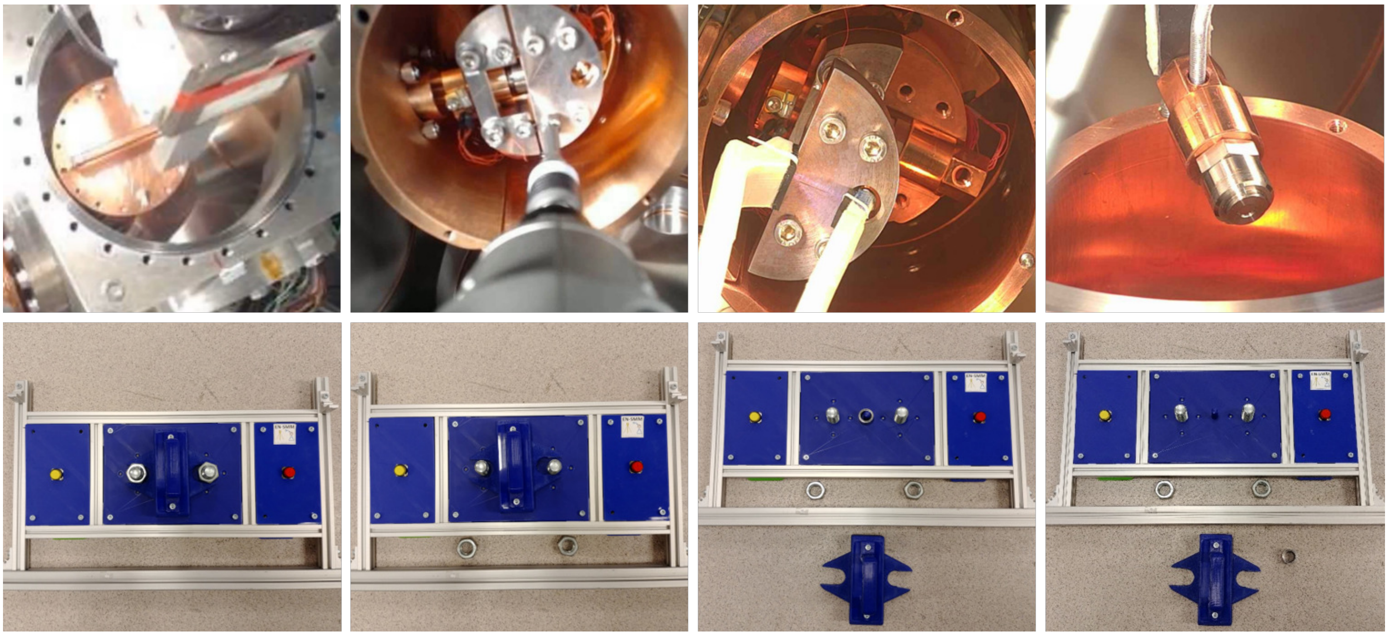


Figure 2. (First row) Antimatter factory real intervention performed by the CERN-EN-SMM-MRO team to recover a radioactive source; (Second row) Educational Mockup simulating the necessary steps to recover a source.

2.1. Study the Problem and Solution in Groups

The education activity starts with the introduction to the problem, where scientific experiments must be performed in radioactive scenarios, which do not allow humans to directly interact with the equipment and tools.

As an example of such activities, the students are introduced to a previous experiment performed in the Antimatter Factory, where a radioactive target had to be replaced. In fact, the students are provided with the simplified Antimatter Factory Mockup, as shown in Figure 2, where they are invited to reproduce the real intervention in more simple way.

The second step is the introduction to the robotic facilities at CERN, where the students can face real demonstrations of the modular robots, such as the TIM, CERNBot, CERNBot2, Cranebot, Charmbot, etc., (see Figure 3). In addition, they can better understand the way the robots are remotely operated via the Unified Graphical User Interface (GUI [7]), which guarantees human safety by avoiding their exposure to radioactive scenarios. In addition, the students are able to better understand the meaning of «Science for Peace», focusing exclusively on research and applications that have an outstanding social benefit (e.g., medical applications).

The main contribution of this pool of robots is their modularity, which permits adapting the robot configuration to the specific operation to be performed. New tools have to be designed and assembled for each specific intervention, which needs a continuous development and improvement of the robot platforms. In addition, the software used by the operators to control the robots is also explained, so that they can better understand the different ways to interact with the robots, from manual to supervisory control, according to the specific necessity and the expertise of the operator (see Figure 4).

Once the students understand the robotic platforms, adapted tools, and user interface, the Minicernbot educational robots are explained in detail (see Figure 5). As will be seen later in this paper, the new educational robot is inspired by the CERNBot one, and enables the student to reconfigure the position and number of robotic arms, as well as the camera head. In addition, it allows the students to use tracks or omnidirectional wheels, according to their specific necessities. The robot can be also enhanced mechanically by the students by attaching tools and components to the gripper and aluminium frame structure, according to their specific solutions.

The next step in this first learning group (i.e., «Study the Problem and Solution in Groups») is a comprehension of the problem to be solved. According to a previous real intervention in the radioactive Antimatter Factory, the robot had to disassemble a cover and replace a radioactive source. This inspired realistic scenario was simplified for education, so the «Antimatter Factory Mockup Panel» was designed (see Figure 2).

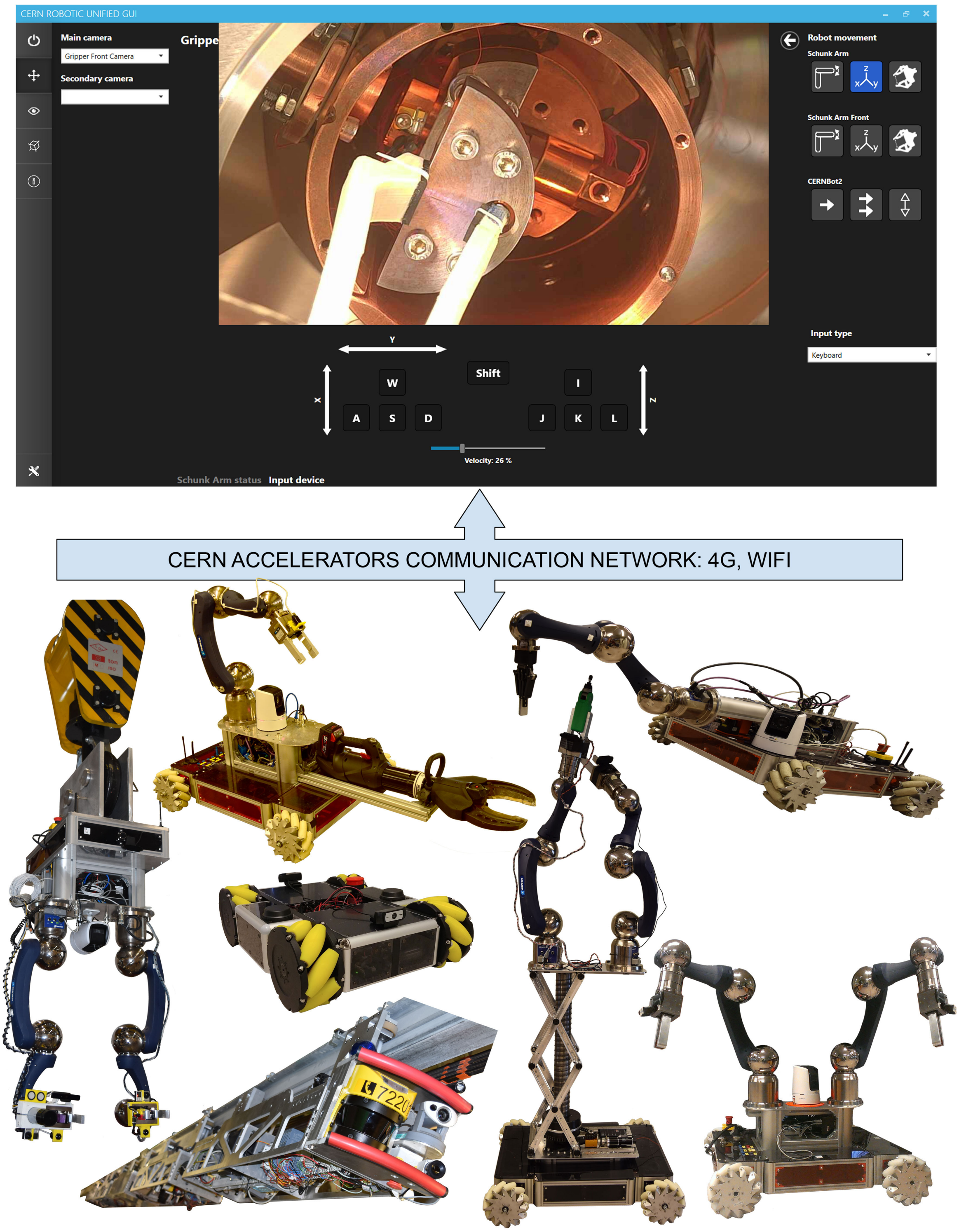


Figure 3. Set of modular robots developed at CERN-EN-SMM-MRO section to perform safe operations in radioactive and hazardous scientific facilities (i.e., Cranebot, Charmbot, CERNBot, CERNBot2, TIM, and Unified GUI).

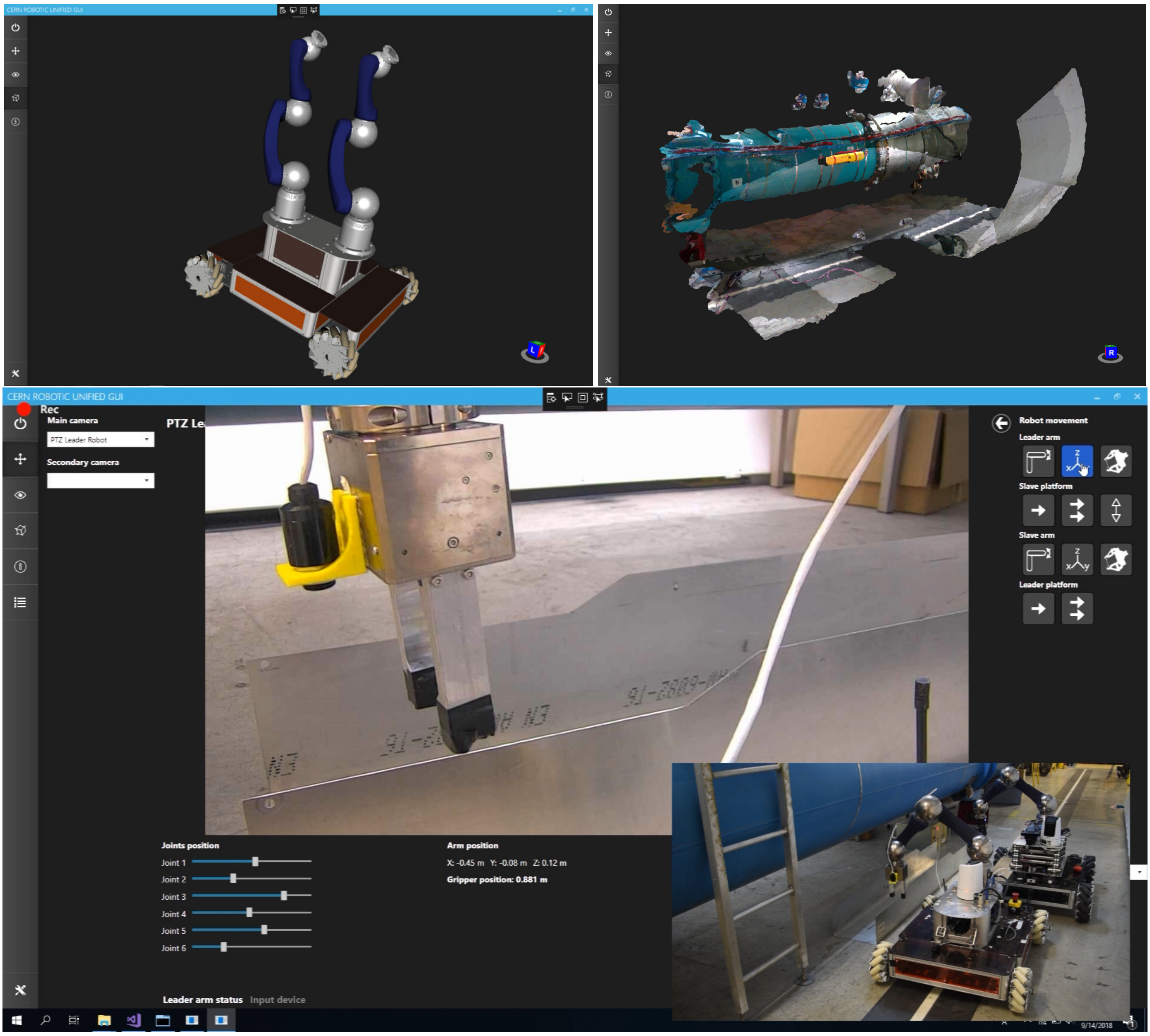


Figure 4. Unified Graphical User Interface to let the operator remotely control the robots in the accelerators and scientific facilities.

The students are required to organise themselves in multidisciplinary groups and face the development of a software and mechatronic solution, based on the Minicernbot platform, to solve the following missions:

- *Mission 1: Press Red Button*. The robot has to approach the Panel, from the base station, and press the red button, which stops the machine, in order to allow the robot to disassemble it.
- *Mission 2: Unscrew the Radioactive Source Cover*. The robot has to unscrew two nuts that are holding the cover of the radioactive source. If the nuts are brought to the base, the mission gets extra points.
- *Mission 3: Uncover the Pretended-Radioactive Source*. Once the nuts are released, the robot has to uncover the radioactive source by grasping the handle of the cover. If the cover is brought to the base, extra points are assigned to the team.
- *Mission 4: Release the Pretended-Radioactive Source*. The team is asked to, once the cover is removed, grasp the pretended-radioactive source and release it from the holder.

If the pretended-radioactive source is brought to the base, extra points are assigned to the team.

- *Mission 5: Press Yellow Button*. The robot has to press the yellow button to set up the machine.

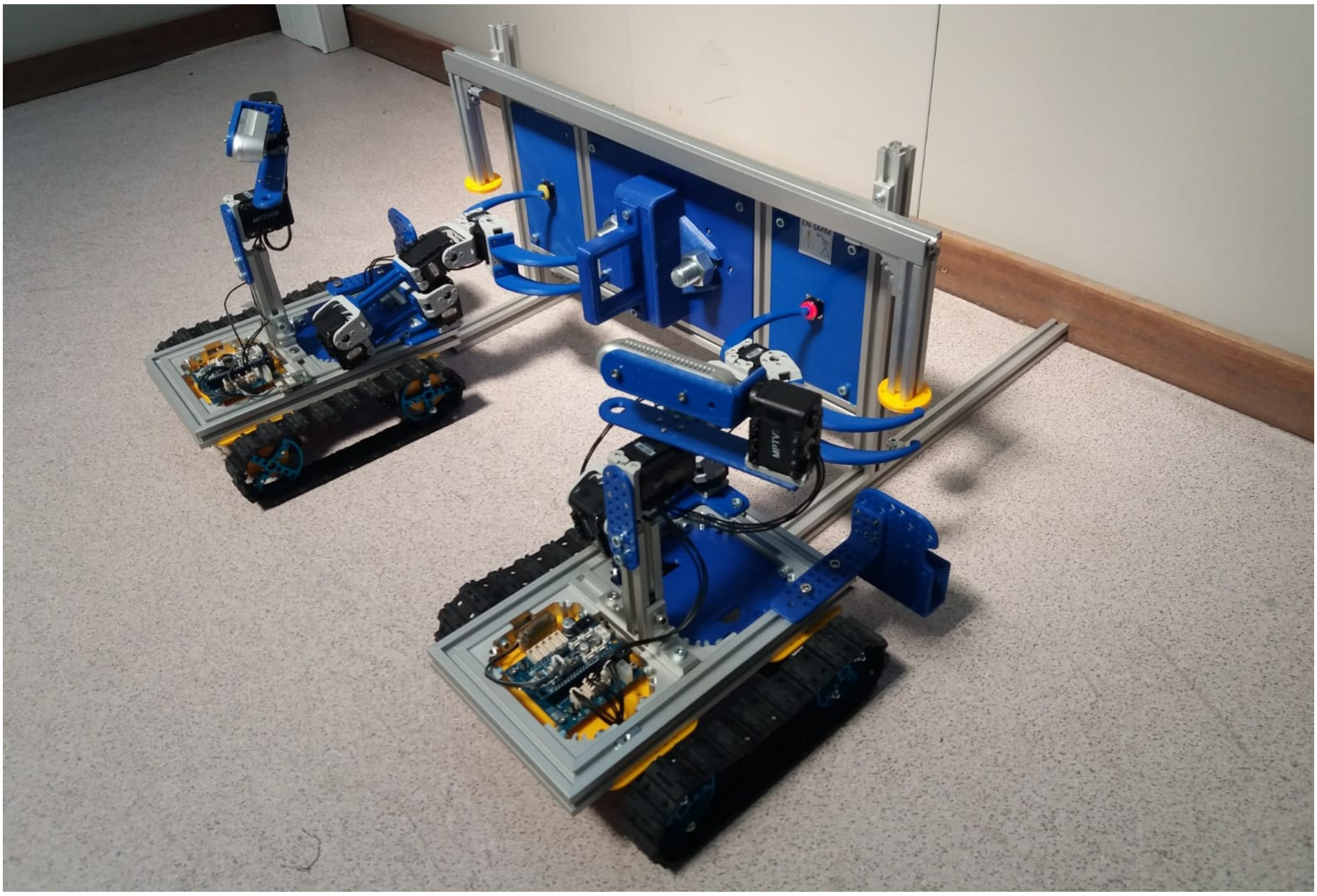


Figure 5. The MiniCernbot platforms and antimatter factory intervention panel mockup.

The missions proposed have demonstrated to be accessible for the students and also challenging. For further educational experiments, or longer projects, they can be updated by letting the students replace the pretended-radioactive source by a new one, cover it, and screw the nuts. This would require much more effort to design the solution.

The panel also includes a long pipe aluminium frame with two handles, which has been provided in order to let the students recover it to the base by using two Minicernbot platforms, in a cooperative way. This mission has been reserved as an extra exercise.

2.2. Mechanical Engineering

Once the students understand the problem to be solved on the panel (e.g., unscrew, remove the plate, recover the pretended-radioactive source, etc.), and the team has been organised appropriately, they are given an introduction to 3D design and printing, in order to provide their own solutions of tools used to perform the operation on the panel.

In Figure 6, an example of a tool designed by high-school students to be able to solve the Mission 2 (i.e., Unscrew the cover of the pretended-radioactive source) can be appreciated.

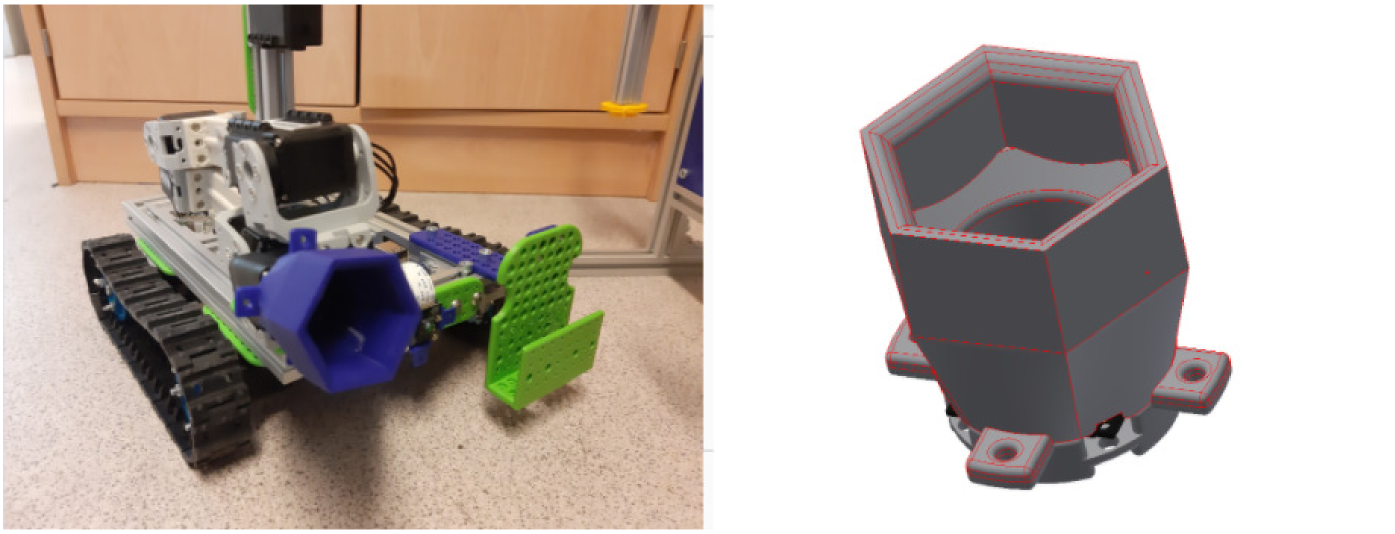


Figure 6. Example of tool designed by a high-school team during a stage at the Robotics Lab.

The high-school students get a step-by-step guidance in order to get introduced to 3D design and printing. At the moment of writing this article, the tool that has been used for high-school teams is Tinkercad [27], which enables them to create accurate designs by using primitive shapes and operations via a single web interface (see Figure 7).

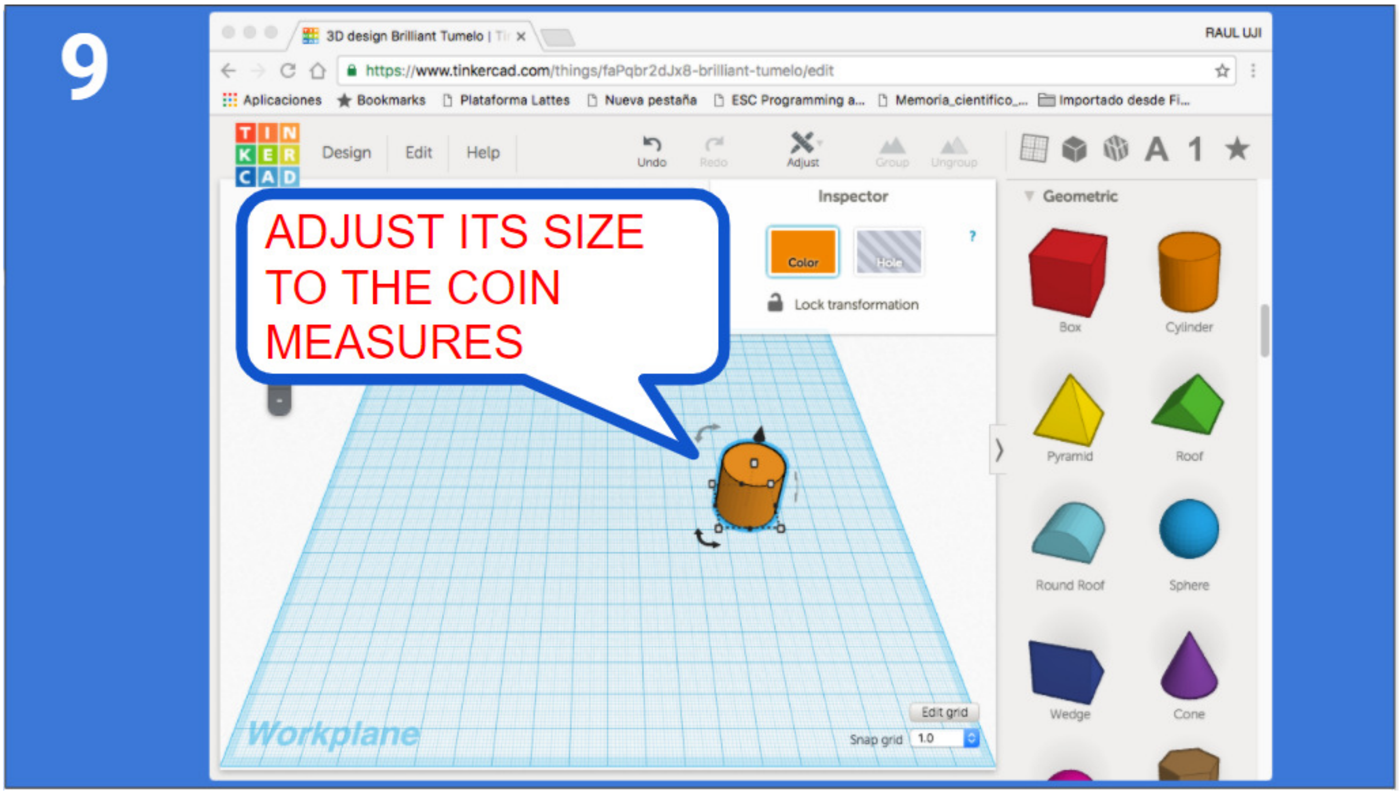


Figure 7. Example of orientations given to the high-school students to introduce the 3D tools design.

Tinkercad is a free, online and easy to use app used to teach the basic concepts of 3D designing. The students are provided with a step-by-step presentation that helps them create their first 3D design, and explore the Tinkercad platform. Once they are confident on 3D design, they are encouraged to proceed with the tool design for the MiniCERNBot, and reminded to be creative when approaching the task (see Figures 8 and 9). Different orientations and examples of real solutions are provided, and for the students that are struggling to accomplish the task, an already designed base piece is provided with exact measurements for the attachment with the robot's motor, which is normally the area where most common errors occur.

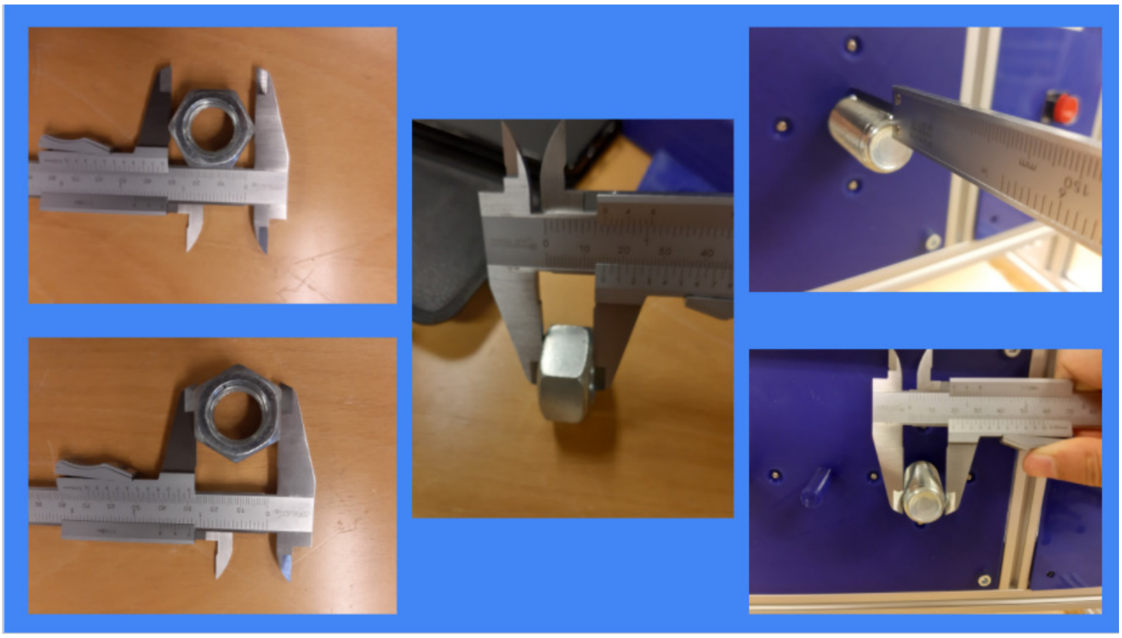


Figure 8. Students measuring the panel in order to design the tool to accomplish the Unscrew Mission.

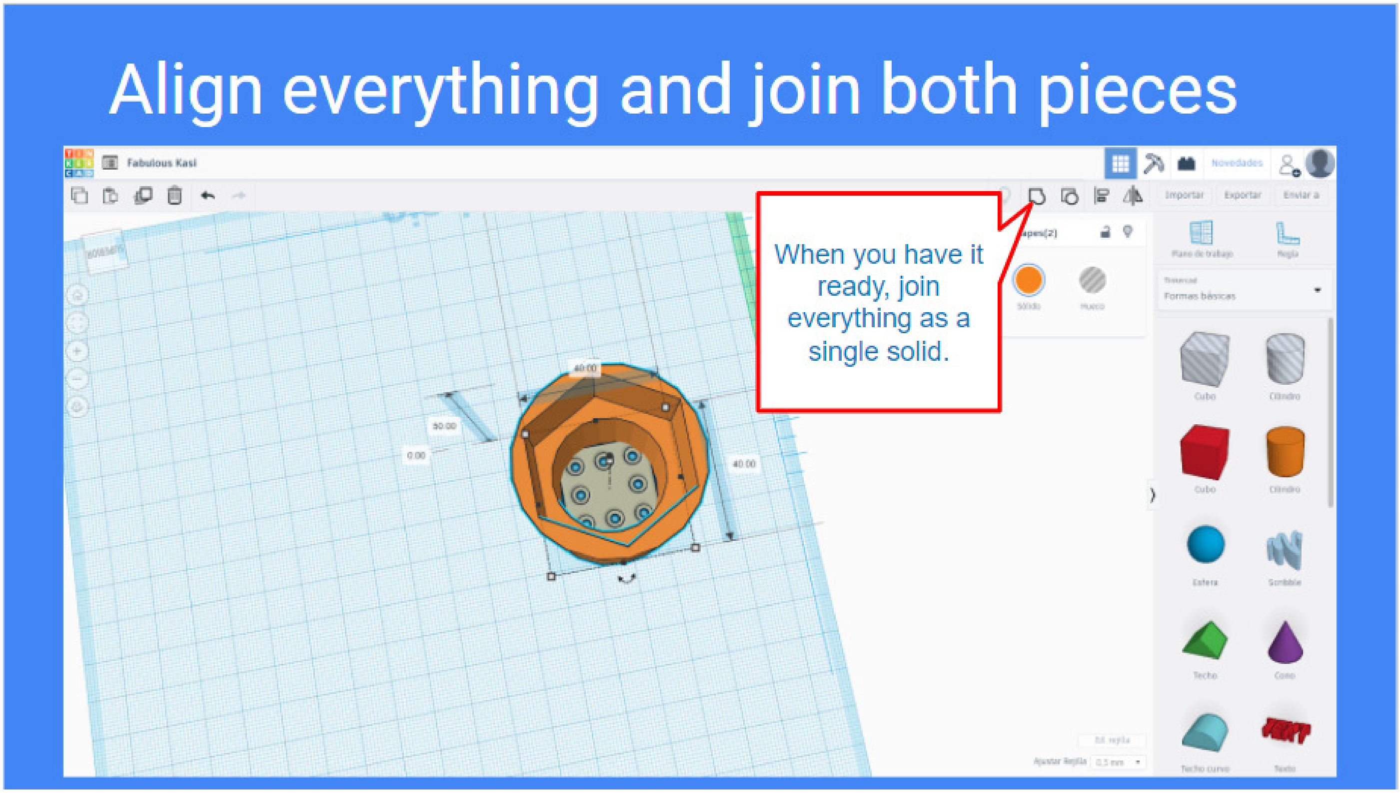


Figure 9. Tool designed by students to unscrew.

The Bachelor's and Master's students and given a tutorial on advanced 3D design with parametric tools. At the moment of writing, the tool used is Autodesk Inventor [28], as can be appreciated in Figures 10 and 11. This is a tool that permits more advanced designs, using both primitives and parametric extrusions based on 2D sketches, as well as assemblies, joints, and renderings, among others. The students are given a detailed tutorial on the way advanced parts are designed and manufactured using this tool.

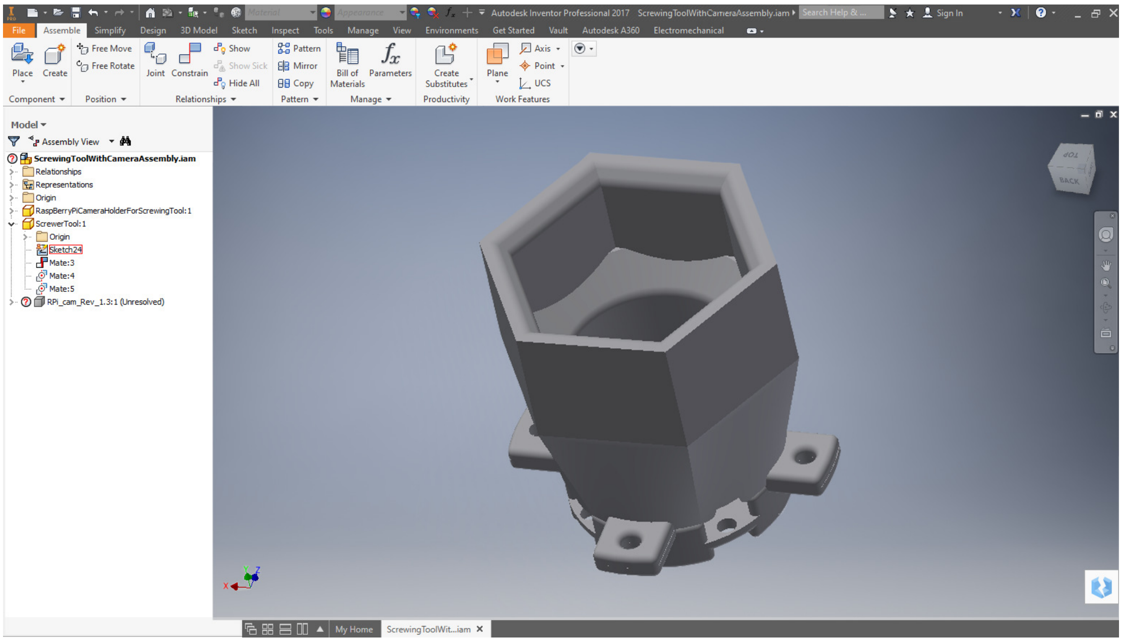


Figure 10. Example of tool designed by advanced students using Autodesk Inventor.

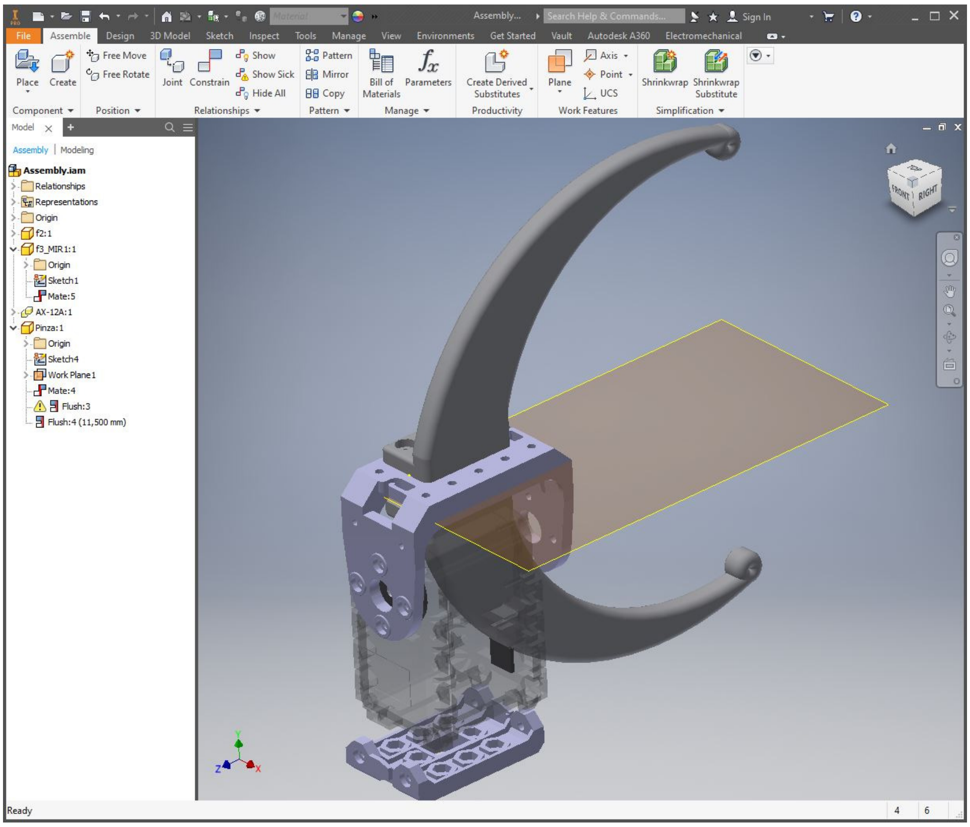
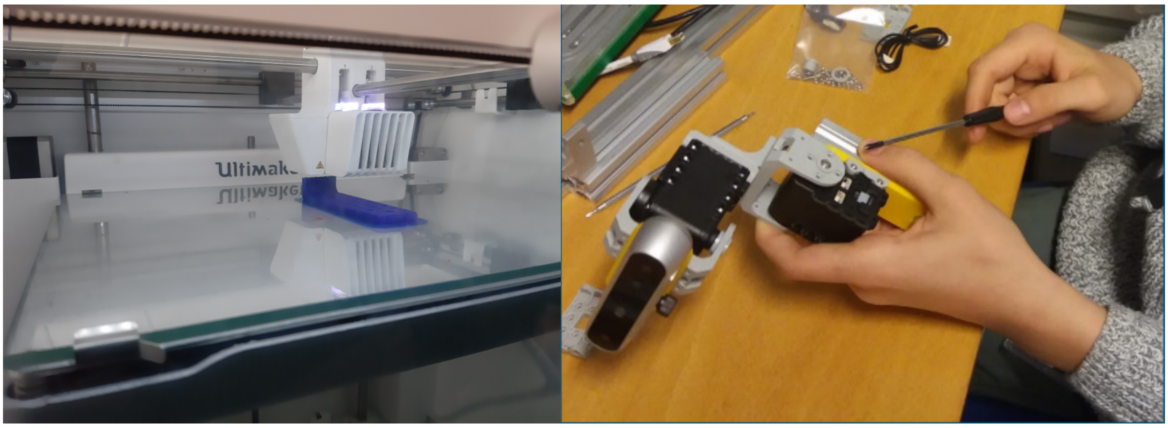


Figure 11. Example of orientations given to Bachelor's and Master's students to design a gripper.

Once the designed tools have been reviewed, they are printed in plastic and assembled in the robot by the students for real validation, as shown in Figure 12.



(**a**) (**b**)

Figure 12. Students assembling their printed tool: The students also learn about how 3D printers work as they print their piece (**a**) printing tools in 3D; (**b**) assembling the tool in the robot to solve the missions.

When they have finished the design, they are taught how to export their design in 3D format so that they can print it with a 3D printer, and, once printed, they learn how to assemble it into the robot with bolts and nuts previously provided, in order to get the robot ready for the intervention (see Figure 12).

2.3. Computer Engineering Level 1 (Blocks)

In Figure 13, the software architecture for the Computer Engineering Level 1 exercise is shown. The students are given a tutorial on Android Programming by using the MIT App Inventor Tool, which is based on the use of simple programming blocks. The application they develop (see Figure 14) establishes a Bluetooth connection to the robot sensors/actuators controller, so that the students learn how to solve the robot missions by having a direct field of view to the robot from the Android User Interface, so no camera feedback is required in this exercise.

In order to design the first Human–Robot Interface, the MIT App Inventor tool is used by the students to practice Block-Programming (see Figure 15). This gives them a quick way to get the robot working and solve the simple operations. With the help of the step-by-step tutorial they are provided with, the students start to add buttons and other components to their app (see Figure 16). Afterwards, they start programming each component individually with different blocks that they can attach together. The MiniCERNBot robotic platform already has a bluetooth server firmware running on its micro-controller, which starts running as soon as the robot is turned on. This program makes the robot move whenever the robot is sent a character via Bluetooth. This makes programming much more simple as the students only need to connect to the robot and send one of the characters that are provided to them to start the movements. Once they have programmed the basic buttons (forward, backwards, left, right), they already understand what is going on in their app; therefore, they are given different optional tasks to improve their human–robot user interface such as:

1. Adding images to the buttons.
2. Using the Android phone accelerometer sensor to send movements.
3. Controlling the speed.
4. Improving the control.
5. Controlling the robot with the orientation sensor.
6. Optionally, for advanced high-school students, they are given a second Android phone with an HTTP camera application, which provides camera feedback via Wifi, so they can add an HTTP client controller to their blocks program, in order to obtain the robot images on the user interface.