MARI4YARD
MARI4ALLIANCE

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Deliverable D6.8
Best practise handbook – Solutions Catalogue

Work Package 6
SUSTAINABILITY ASSESSMENT and REPLICABILITY

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EXECUTIVE SUMMARY

Within the Mari4_YARD project, WP6 (Sustainability Assessment and Replicability) has the important task to **assess, that the solutions developed in the project will be technically, environmentally, and safety-wise suitable to achieve the impact** envisaged in the project, i.e., that they can be successfully applied in real life after the end of the project. Complementary to WP8 (Dissemination, Communication and Exploitation) which will roll-out solutions once being developed, this work package will investigate in more technical and environmental detail of solutions and compare them with known external experiences, relevant to the target community. As this activity is starting in the second project period, the early assessment by WP6 can be seen as an early check and guidance to technology developers to ensure the practical impact of solutions both in partner shipyards and a wider community.

This Deliverable 6.8 gives an overview of the best practices with respect to the different Mari4_YARD technologies. Each technology is presented briefly, and the potential applications are described. Benefits and obstacles to be expected are explained as well. Additionally, the document contains information about the installation and application of the solutions.

1 MISSION, PURPOSE, AND METHODOLOGY

1.1 Role of this Deliverable in Mari4_YARD

1.1.1 Mission and Impact:

The Mari4_YARD project aims to significantly improve **competitiveness and sustainability of European small and medium sized shipyards** by adapting and implementing a set of modular and flexible "human centric" equipment. Small and medium sized shipyards are typical for the European maritime industry and form the economic background of many regions, however due to specific factors they often lack behind compared to larger specialized yards and other industries in terms of productivity and sustainability. This becomes a particular problem in connection with de-carbonization as small and medium sized shipyards will need to build, maintain, and repair and retrofit a substantial portion of the European and world fleet, especially of smaller commercial ships and offshore structures. Target impact figures of the MARI4_YARD project are described in Chapter 2 of the Grant Agreement (Part B).

1.1.2 Role of WP6:

Within the project, WP6 (Sustainability Assessment and Replicability) has the important task to **assess, that the solutions developed will be technically, environmentally, and safety-wise suitable to achieve the impact envisaged in the project**, i.e., that they can be successfully applied in real life after the end of the project. Complementary to WP8 (Dissemination, Communication and Exploitation) which will roll-out solutions once being developed, this work package will investigate in more technical and environmental detail of solutions and compare them with known external experiences, relevant to the target community. As this activity is starting in the second project period, the early assessment by WP6 can be seen as an early check and guidance to technology developers to ensure the practical impact of solutions both in partner shipyards and a wider community.

The work of WP6 is clearly driven by an **end-user perspective**, involving the two shipyards (BIS and NODOSA) involved in the project, two shipbuilding industry associations (CMT and NMTF) as well as two organizations with vast experience on productivity and environmental impact assessment in the shipbuilding industry (CMT and BAL). It is further expected that technology suppliers (GHENOVA, GIZELIS and others, not directly involved in the WP) will actively contribute to a critical assessment putting themselves in the perspective of potential customers in the maritime sector.

1.1.3 Connection to the WP 5 demonstrators

While most of the experience and feedback collected so far is based on the installation and tests in labs and during training, the WP5 demonstrators provided additional valuable information from test runs of the technologies in a shipyard environment. Since these activities were performed during the second half of 2024, their impact on the best practise descriptions was included in D6.8 which is an update of D6.4 at the end of the project. The respective chapters are already included in this document.

1.1.4 Qualitative and quantitative assessment

The assessment activities within WP6 can be roughly grouped into two streams:

- A **qualitative assessment** including the identification of technical solutions, experiences and success stories from outside the project (T6.4), the identification of potential "showstoppers" in legislation, ship related safety rules and work safety (T6.5) as well as the benchmarking of the results towards the technological solutions developed in Mari4_YARD. "Benchmarking" shall not only include a "passive marking" of external versus internal technologies, but also constructive proposals to align the development within Mari4_YARD towards a maximum practical impact.

  The qualitative assessment comprised three main phases: a preliminary **first scouting and assessment** (this Deliverable), feedback round from potential external users through dissemination workshops and the Best Practice Handbook including a questionnaire (D6.4) and the final assessment wrapping up internal and external views in D6.8.

- The second stream of activities in the work package is a **quantitative assessment** comprising a careful data analysis (T6.1), modelling of the relevant production processes (T6.2) and a life cycle cost and environ-mental impact assessment (T6.3). The quantitative assessment is more labour-intensive and requires detailed information about the baseline processes and the envisaged processes after the end of the project, as well as verified impact data for the introduction of new technological solutions.

  Due to the general delay of the project and in particular the late start of WP5 (Demonstration in Shipbuilding and Retrofitting) the activities and deliverables related to the quantitative assessment (D6.3 and D6.6) had to be delayed correspondingly. The quantitative assessment was primarily conducted for the processes in the partner shipyards which will be affected and demonstrated within MARI4_YARD.

In general, it should be noted that the impact of certain technological improvements on the competitiveness and sustainability of shipyards can only be done in the context of specific processes and products (see also 1.2) which requires a certain majority of the technical developments and preliminary testing (WP1 – WP4) as well as specific ideas on demonstration and (post-project) application (WP5).

1.1.5 Best Practice Handbook and Communication with the End-User Community

This Deliverable 6.8 is aimed at potential users of the Mari4_YARD solutions. It will describe in detail what the technologies may be used for, how to apply them and what advantages or disadvantages can be expected. Since the information in the deliverable is public, some internal findings cannot be described in the deliverable. **In case of interest in using any of the technologies it is recommended to get in touch with the developers. Contact information can be found on the project website (www.mari4yard.eu).**

1.2 Methodology used in this Deliverable

The following chapter describes each solution, following a unified structure:

- The description briefly explains the main characteristics of the different solutions.
- Potential applications outline the processes at the yard where the technologies can be applied.
- Replicability provides information about the application at other shipyards, maritime enterprises or even outside the maritime environment.
- Expected benefits are structured into economic, sustainability and societal benefits.

- Guidelines for the application will provide information about the way a technology can be introduced into shipyard processes.
- Potential disadvantages, risks and barriers are also covered in order to describe issues that might prevent the technologies from being introduced.
- Finally, the results of the LCPA analysis have been included.

2 Mari4_YARD Technologies and Potential Impact

2.1 Technology: Logistic Planning Platform for Shipyards

2.1.1 Description

The use of technologies linked to 3D Laser scanning and Lidar are giving to the shipyards a very powerful tool not only for 3D modelling and reverse engineering, also by means the use of specific tools gives the possibility to be useful on the production control.

Three different technologies are combined to create the collaborative solutions:

- 3D scanning by means of 3D laser scan.
- 3D scanning by means of Lidar scan.
- 3D scanning by means of photogrammetry.

One of the most important actives for shipyards is space, as it is required to perform a variety of tasks: materials storage, big element manoeuvring, transit space for vehicles, equipment and workers, etc. Also, lifting equipment requires traveling, making part of the space unavailable. This situation can be very complex if different works are being carried out and the problem is even worse if the shipyard is small, as the installation's size is smaller.

One of the possible approaches to this problem could be using an interactive tool that allows making a planification of the shipyard activities and that allows the user to predict the position of different elements on different moments.

To do so, a 3D point cloud obtained by a lidar of the shipyard will be input in a platform that allows the introduction of 3D modelled objects that can be positioned and that will allow the user to take 'timestamps' of the shipyard configuration in different moments. Such a tool can help to keep track of the available space and allows us to schedule actions during shipyard works.

2.1.2 Potential applications

Main application of this technology consists of keeping track of the available space on the shipyard. This way, it is also possible to keep track of materials, equipment, cranes, blocks and different elements and schedule their positioning for storage, manoeuvring or transportation.

To do so, a 3D point cloud of the shipyard is acquired by means of a drone equipped with a lidar and will be input inside a digital web platform. This cloud is to be created by a LIDAR scanner mounted on a drone as this is the fastest method for point cloud acquisition. Accuracy is not a determinant factor in this application.

Process is adaptable whenever there is need to fast record current state od construction and compare it to plans. Drone reconstruction takes order of magnitude less time to form 3d model than terrestrial laser. On another note, the precision of such technology is below precision obtained by laser. Then it follows that this technology could be applicable for every construction work, where small detail is not important, and where changes happen on a daily basis.

2.1.3 Expected benefits

Economic benefits

- Time saving in specific shipyard operations.
- Decrease in off-time due to lack of storage.
- Improvement in work efficiency.

The correlation between plan and reality is established sooner and more accurate than with previous systems (completion percentages subjective reports) that itself enables faster and more precise response to unplanned events. The system is not complicated or expensive, it is easy to set up and use. All programs are already available (3d model, photogrammetry, cloud compare).

Sustainability

- No environmental impact.

Societal benefits

- Improvement of the work quality as a result of production planning.

2.1.4 Guidelines for the application of the solution

Specific protocols need to be followed to use this technology.

The web tool for planning logistics in a shipyard developed by GHENOVA requires scanning the shipyard from the air using a drone and lidar. to perform this scanning, it is necessary to carry out some preliminary checks, mainly related to the use of drones in a working environment, but also in terms of logistics.

1. Preliminary checks before starting:
   - Flight Permits and pilot licenses.
   - Safety verification: coordination with the company, confirmation about the working areas, activity and operators.
   - Logistics. Target components and materials needed to carry out the task.
2. Data acquisition. Use the drone flown by an expert drone pilot over the area of interest to scan the surfaces.
3. Data collection. The tool displays, in a 3D visual environment, the state of the yard's facilities at a given future date after the workflow planned and simulated by the tool has taken place.

The web application opens the 3D point cloud of the shipyard and allows blocks, parts, etc. To be placed and moved through the shipyard; so, the shipyard logistics can be planned and checked easily.

4. Data analysis.
    - Import CAD models showing at the same time the point cloud of the shipyard and also previous imported elements.
    - Locate imported elements (move and rotate).
    - Measure distances and areas in the 3D model of the facilities and/or elements.
    - Explore the global model on a 3D environment (move and rotate the point of view, change the zoom factor).

2.1.5 Potential disadvantages

The acquisition of the point cloud requires a certified pilot and also depends on the environmental conditions, as weather or local fauna habits. There might be places that are limited to specific periods throughout the year for this task.

Precision of this system is something that needs to be tested. Applicability in a closed environment is something that is desired but at the moment not practically doable.

2.1.6 Potential risks/barriers

Flight permissions paperwork and local fauna problems difficult the point cloud acquisition. However, this can be mitigated with correct flight planning.

Technical

No technical risks expected. A shipyard ERP system must exist (3d model, plan, resources).

Economic

During the drone flight, the yard must stop production, as drones cannot fly over workers, so point cloud acquisition must be carefully scheduled to avoid coinciding with yard activity. However, as the data collection process takes very little time, this should not be a scheduling problem.

On the other hand, flights may be seasonally limited due to the presence of local fauna, especially during birds breeding periods. If this happens, the flights must be carried out at specific moments of the year, to avoid attacks and possible accidents, or it is also possible, but with increased economic cost, to use specific devices that prevent these attacks.

Social

No social risks expected.

Legal (Rules, regulations)

One of the main problems that can arise when carrying out a drone operation is the application for flight permissions. The process of obtaining these permits can vary from country to country (in this particular case, it takes approximately one month).

In addition, other parameters can influence the flight, such as the weather, which implies the need for careful planning in advance.

2.2 Technology: Small drones for confined spaces

2.2.1 Description

We have developed a system to validate the safety of workers inside confined fabrication spaces. It consists of a small drone that should carry out supervision tasks to ensure that the work environment is safe for operators to access, for which an oxygen sensor has been added to the drone.

Reading of sensors through I2C protocol by ESP32 board, for subsequent packaging based on the CRSF protocol and sending through radio frequency communication in the 868MHz band, from small drone to its remote control.

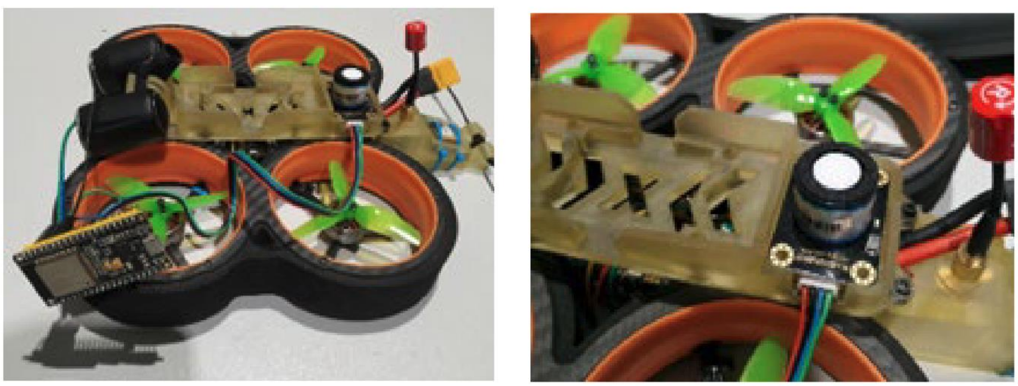


Figure 1 Small drones customized to detect dangerous atmospheres in confined spaces.

2.2.2 Potential Applications

The main application of this system is to monitor oxygen levels inside tanks. It detects the concentration of oxygen in confined spaces and alerts workers in case of any risks. This solution ensures safety in the work environment by the integration of new sensing technologies in small drones.

Another potential application of the technology is the measurement of different parameters inside the tanks, that are valuable not only for safety purposes, but for technical works. An example of this is the measurement of temperature and humidity levels. These measurements were requested by the end users as an assistance for the painting jobs that can potentially be performed inside the tanks.

However, a great variety of sensors can be adapted to the Crossfire telemetry (those ones that can be connected through an I2C port for the ESP32). This makes the possibilities unlimited for any parameter that the end users desire to read from confined spaces avoiding workers to be put in risk.

2.2.3 Replicability

The replicability of the technology is guaranteed as the specifications, materials and configuration for the drone have been documented on the D1.5 deliverable.

On the other hand, the software required to connect the sensors to the drone telemetry made by AIMEN, was also documented in D1.5 deliverable, so it is possible to replicate it.

2.2.4 Expected benefits

Economic benefits

- Reduction of working accidents during inspection tasks
- Improvement of particular jobs quality due to better knowledge of the environment parameters
- Apart from the measurement of the parameters requested from the end users during this project, it is expected that additional uses can be derived for this technology; this means more potential economic benefits.

Sustainability

- No environmental impact
- Low economic investment

Societal benefits

Improved safety and working conditions are expected when using the developed technology, avoiding worker exposure to hazardous working conditions, being even more critical in confined and hard to access spaces.

2.2.5 Guidelines for the application of the solution

- The solution should be applied indoors (these must be this way to avoid flight regulations).
- Drones are sensitive to electromagnetic interference. Welding jobs that could possibly have a direct line of view with the zone where the job is performed, must be avoided.
- This technology must not be applied in explosive environments.
- Pilot training is required.

2.2.6 Potential disadvantages

The only potential disadvantage compared to the current process is the added cost to the production chain related to the purchase/rental of materials. However, these costs are very low and are worth bearing for the benefits they bring.

2.2.7 Potential risks/barriers

Technical

There is a potential risk for the technology used:

Currently, some stability problems are affecting the drone when flying inside a small space due to air recirculation. Different solutions are being tested:

- Pilot training to get more control of the aircraft in these small spaces.
- Flight controller tuning to ensure smooth drone movement.
- Reducing the drone weight can contribute to better control and stability.
- Trimming and centring drone weight distribution will also improve stability and control.

It is expected that all the measures taken above will improve the overall behaviour of the aircraft and will lead to a successful demonstrator.

Economic

No risks expected.

Social

No risks expected.

Legal (Rules, regulations)

No risks expected.

2.3 Technology: Hand-guiding industrial robots

2.3.1 Description

We have collaborated to adapt the hand guiding technology, originally developed by AIMEN for ABB robots. For Mari4_YARD this technology is demonstrated for KUKA robots and adapted for COMAU robots. The main benefit is the adoption of industrial robots for collaborative applications, so working payloads and applications can be increased for industrial robots.

Hand guiding technology consists of moving the robot by direct operator interaction with a device placed at robot's wrist. Robot is also equipped with a Force/Torque sensor and high-speed communication protocol to monitor forces and torques applied by the operator in real-time. The controller can be configured for smooth operations.

Figure 2 Hand guidance tool developed by AIMEN and deployed by LMS for COMAU robots

Figure 3 Hand guidance solution implemented by LMS, validated and tested at Brodosplit premises**.**

2.3.2 Potential Applications

The main application of the hand guiding technology is to assist the user to manipulate the heavier loads. The key impacts are: to reduce the risk of human injuries due to load manipulation, to lower the programming time, and to expand the applications of industrial high payload robots.

2.3.3 Expected benefits

Economic benefits

The use-case involves two operators collaborating to complete the manufacturing task. However, with the implementation of HRT (Human-Robot Teamwork), only one person is required for the manufacturing task, resulting in a productivity improvement of 30 percent.

Sustainability

Societal benefits

- Reduction of accidents.
- Reduction of human errors.
- Improvement of human posture and ergonomics.
- Introduce the risk of collision with the robot.

2.3.4 Guidelines for the application of the solution

To begin with the guidelines for the application of the solution, it is essential to outline the hardware and software components used in the hand-guidance system:

Hardware

- **OnRobot F/T Sensor**: Responsible for measuring force and torque (F/T) applied to the handle by the human operator. These forces and torques are converted into corresponding translational and rotational motions of the robot.
- **OnRobot Control Box**: The control box reads the sensor measurements and, through its interface, shares this data across the connected network.
- **Hand-Guiding Handle (GUARDMASTER Allen Bradley)**: This handle, mounted on the sensor, includes a three-stage selector for enabling the hand-guidance system. By pressing the selector, the operator activates the system, sending IO signals to the robot's controller.

Figure 4 Hardware components of the HGM solution. (a) F/T sensor, (b) F/T sensor control box (c) Hand guiding handle.

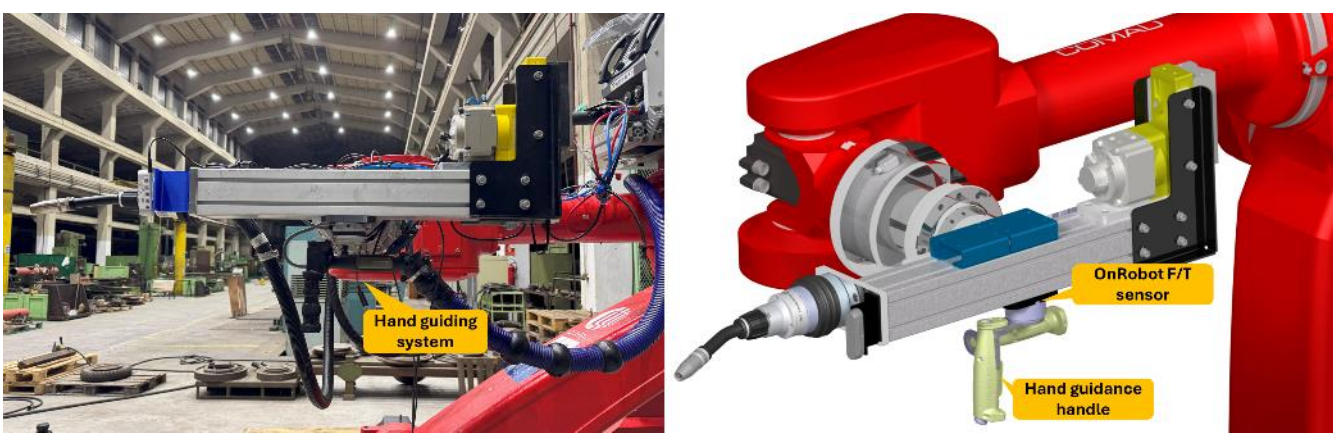


Figure 5 Hand guidance system placed onto the robot.

Hardware

- **ROS**: The ROS middleware serves as an interface between various software and hardware modules. It facilitates the sharing of F/T data from the OnRobot F/T sensor with the manual guidance software module, which calculates the robot's final motions. ROS then transmits these motion commands to the robot.
- **OnRobot F/T Sensor ROS Driver Package**: This ROS package uses the TCP/IP network protocol to connect with the OnRobot control box, enabling the acquisition of sensor readings. These readings are shared with the system via ROS topics.
- **COMAU–ROS Package (ROS Driver by LMS)**: This custom ROS driver package, developed by LMS, connects the robot to the ROS ecosystem. It allows access to robot data such as IO signals, joint states, and emergency status. It also enables the transmission of motion commands and the triggering of IO signals. Expertise in ROS middleware is required for the integration of the hand-guiding system. First, it is important to define the FT sensor pose within the robot's URDF to ensure correct translational and rotational motions. The sensor's pose can be obtained from the CAD file of the gripper. After establishing proper hardware connections, the appropriate scripts must be executed on the robot side to activate the COMAU–ROS driver.

Next, the engineer must ensure that the hand-guiding software is running. Once all hardware and software components are in place and activated, the operator can use the HMI application to press the MGD activation button (in the sequence specified by standards) to enable the manual guidance function.

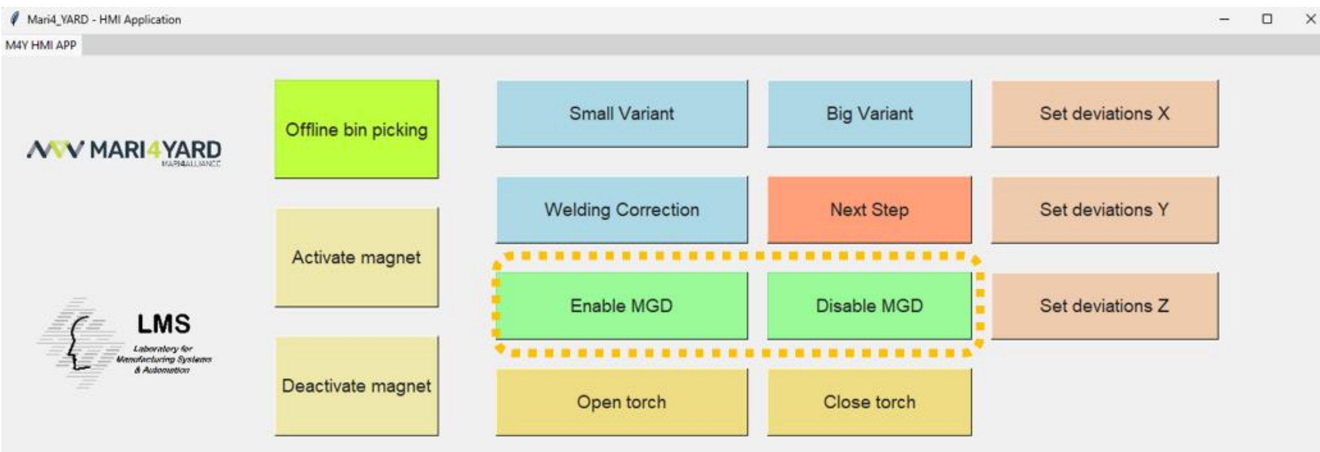


Figure 6 HMI control panel - within yellow dashed square the MGD activation/deactivation buttons are displayed.

After pressing the activation button, the operator needs to complete two additional steps to operate the manual guidance system. First, they must press the calibration button to correct inaccuracies in sensor readings caused by drift over time. Then, the operator must press the enabling selector to its second stage and hold it down while the robot is in motion. If the enabling selector is released or pressed into its third stage, the robot will stop moving immediately.

Figure 7 Calibration button press (left) and enabling button press (right).

2.3.5 Potential disadvantages

Potential disadvantages that can be examined for the hand guiding system are mainly referred to system usability, operator trust and safety.

Validation activities demonstrated that operators do trust the hand guiding systems, however it is possible that a few people might not feel comfortable working with robots in close proximity as manual guidance operations require.

Manual guidance systems have to strictly comply with the relevant EU legislation, so depending to the application manual guidance systems might not be indicated by the ISO directives.

Lastly, based on the application manual guidance might not be the best solution for robot control, and alternatives e.g. a joystick could replace it due to cost effectiveness and ease of integration.

2.3.6 Potential risks/barriers

Technical

- Integration difficulties with ROS framework – requires expert for integration
- Sensor positional “calibration” required expert users
- System requires multiple devices to operate

Economic

- Prices for the hand guiding systems are high

Social

- Not all people might feel comfortable working in close proximity with robots.

Legal (Rules, regulations)

- Proper hand guiding system deployment (hardware aspects, software aspects, application aspects) might face difficulties due to the strict ISO directives for HRC robotics.

2.4 Technology: Collaborative robots

2.4.1 Description

Use of small robots to perform semi-autonomous operations to extend the workers capabilities in the pre-fabrication and outfitting stages. It is considered the possibility of deploying the solution in confined spaces and inside the ship for both new construction and retrofitting.

Three different technologies are combined to create the collaborative solutions:

- Collaborative robots with Power and ForceLimiting (PFL) operational mode (conforms to the TS 15066).
- Fast programming by means of hand-guiding and localization using perception and CAD matching.
- Advanced perception for semi-autonomous operation.

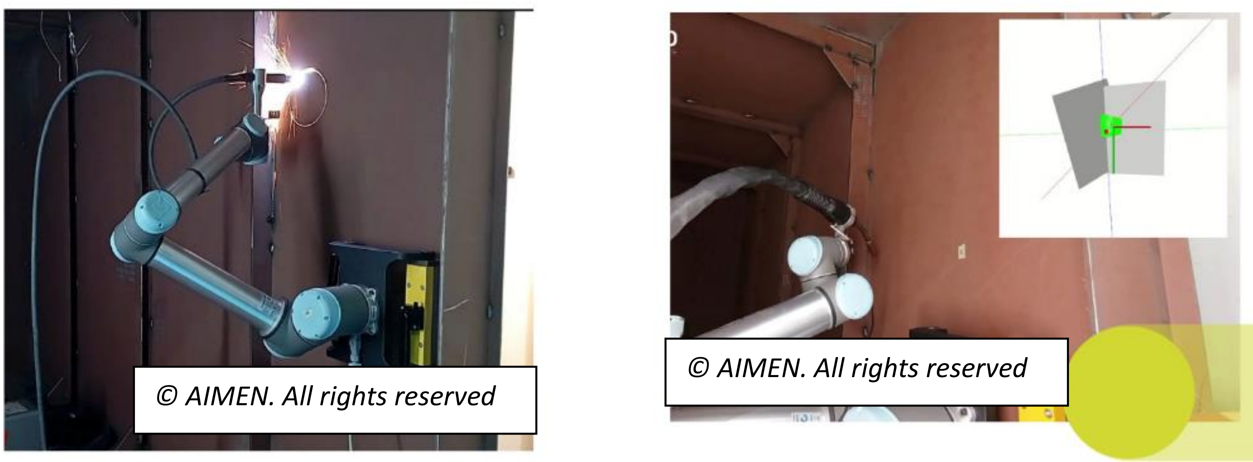


Figure 8 Collaborative robotics for cutting and welding application

2.4.2 Potential Applications

The use of collaborative robots in welding and cutting operations is an excellent way to increase productivity and efficiency. Collaborative robots are an ideal choice for small and medium-sized manufacturers who deal with low-volume, high-mix production. They can perform different tasks in a day and can adapt to new sizes and geometries. Mari4_YARD collaborative technology solutions are designed to work with humans in a shared space, and they can help reduce the chance of impact with human co-workers.

2.4.3 Expected benefits

Economic benefits

- High portability can help deploy the system in less time and hence contribute to more productivity and economic benefits.

- Improve resource management, hence improving productivity.
- Help retain the knowledge and skills for the welding processes and include customization and flexibility to the process.

Sustainability

- Processes and products become more sustainable with less reliance on the expert human and human resource shortage.

Societal benefits

- Improve the quality of life of the workers by shifting to more operational and monitoring of the job process than execution which is error prone.
- Reduce accidents as the robot will perform the cutting/welding process.
- Possible improvement in the work satisfaction as the technology can help in improving the quality of life of the worker.

2.4.4 Guidelines for the application of the solution

- Safety aspects considerations
- Hardware deployment
    - Attach adaptor to robot
    - Deploy and connect robot
    - Deploy and connect plasma cut machine
- Software deployment
    - Meeting pre-requirements
    - Initialize the robot
    - Computer connections
    - Network configuration
    - Parameter configuration
    - Launch application.

In the following sections, these guidelines are explained in more details.

Safety aspects

This application requires considering some safety aspects to ensure the correct deployment and task execution without damage to the rest of equipment and operators. It may present risks during the deployment and when performing the cut. Therefore, it is important to use the personal protective equipment and know the risks of cutting operation.

Personal protective equipment

	Eye protection / welding filter shade number=W8 (current=85A)	Mandatory during operation.

	Hearing protection	
	Respiratory protection / masks	
	Foot protection	Mandatory during hardware deployment and operation.

Associated Risks during operation

<table>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Noise, high levels during cutting.</td><td colspan="2">Electrocution. High voltages during cutting. Power supplies cords of equipment damaged</td><td colspan="2">Intense light, radiation, sparks.</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="6">Risk of fire. Sparks can cause fire or explosion if reach some liquids/materials.</td></tr>
</table>

	
Heavy equipment. Ergonomics.	Air quality, smoke and gases. Renew air in enclosed spaces.

Other considerations

- Keep in hand a fire extinguisher due to the risk possibility.
- Heating transfer from metal plate to magnetic robot base can damage magnets (Faulty temperature » 100ºC. Curie temperature » 250ºC).

Required materials

The needed materials for this application are stated below:

 Universal Robot UR10	 Robot controller	 Hypertherm Powermax 85 Hypertherm Duramax Hyamp 180
		

Intel RealSense d435i	Camera Protection and support for tooling	MagSwitch cobot UR10
 Industrial PC for robot control and data processing	 [Optional] Smart Shift Robot Base (Master Base and Base Plate)	

HARDWARE

First part of the system deployment is to transport all the hardware elements. In the following sections, this sequence is represented.

Figure 9. Init Attach Robot to Smart Shift Adaptor (Optional)

1. Attach the Master Base of the adaptor to the magnetic base with 4 screws.

Figure 10. (Left) Master Plate; (Right) Master Plate placed on MagSwitch.

2. Attach the Base Plate to the robot base with 4 screws and nuts with the down part of the image component to the robot base as shown in Figure 2.

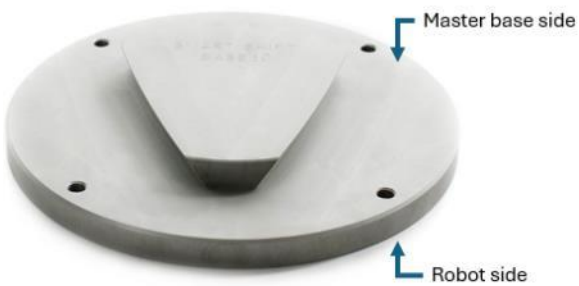


Figure 11. Base Plate for UR10.

3. If we have used this equipment, we can move the robot and the magnetic base separately. When placed the components, we must rotate 180º the plate and attach the fixture as shown in Figure 3.

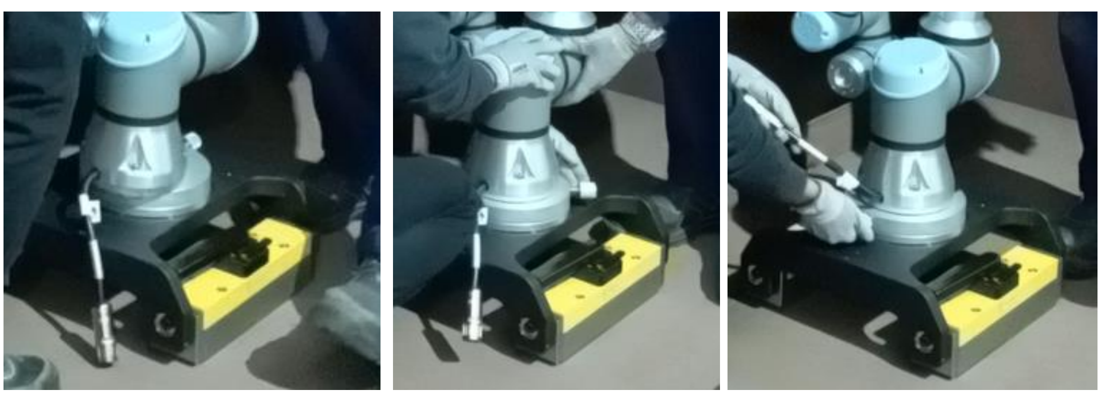


Figure 12. (Left) Place robot into the MasterPlate; (Middle) Rotate 180º plug; (Right) Screw plug.

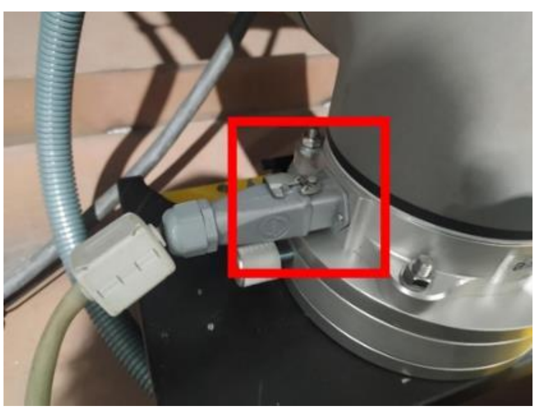
Deploy and connect robot

Independently of using the robot or the Smart Shift Robot Base, we need to move the magnet to the scenario as a whole or in two parts. For doing this, we need to move the robot and its controller and connect them to the power supply. This connection relies on a common 12VAC power supply and the connector from the controller to the robot.

The full sequence is explained in the following table:

<table>
<tr><td>1.Robot and MagSwitch transportation.

Move the robot system (MagSwitch and Robot base). Enable MagSwitch (both handlers) to attach the system to the structure. It can be attached to the floor, wall or ceiling.</td><td>2.Robot wall configuration and robot controller.


Move the robot controller and connect it to the 12VAC plug</td></tr>
<tr><td>3.Connect robot controller to the robot

Connect robot controller to the robot</td><td>4.Robot ethernet connector

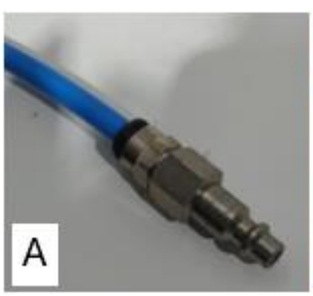
Connect an Ethernet switch to the robot controller in the down connector</td></tr>
<tr><td colspan="2">5.Deploy and connect plasma cut machine. Clamp and triphasic plug.</td></tr>
<tr><td>After moving the plasma cut machine to the environment with its cables, it is necessary to connect the air</td><td>After moving the plasma cut machine to the environment with its cables, it is necessary to connect</td></tr>
</table>

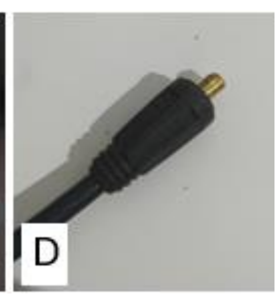
supply, the triphasic plug and **the clamp to the structure**.

the air supply, the triphasic plug and the clamp to the structure.

6.Plug the rest of the connectors must be plugged into the machine. Connection mapping.

A: Air supply (6 bar) **B**: Signal Connector **C**: Torch Connector **D**: GND to clamp





__Note__: we must connect the signal cable to the robot and map them to control the plasma cut machine through the control PC.

SOFTWARE

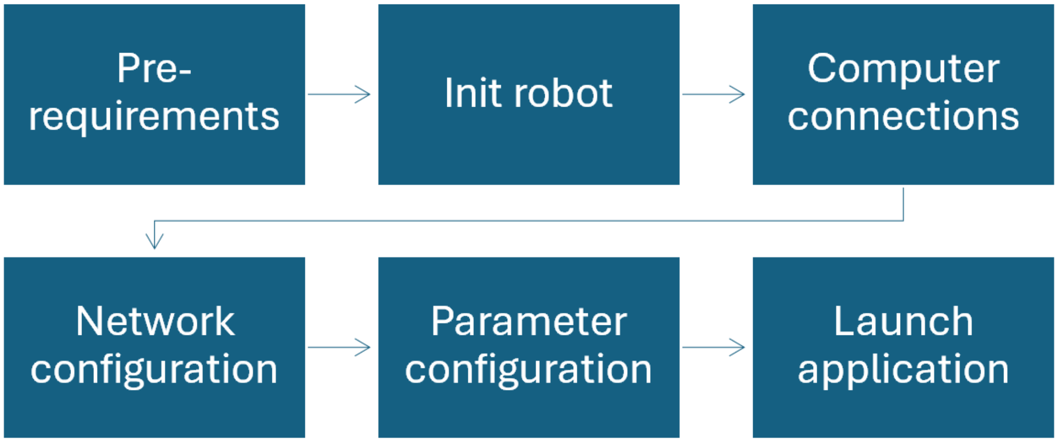


Figure 13. Previous requirements

- Poincloud (in m and .pcd) of the working environment.
- Hand in Eye camera calibration must be previously done.
- Torch tool calibration must be previously done.

1. **Init robot Sequence**: 1) Start motors; 2) Set active TCP.

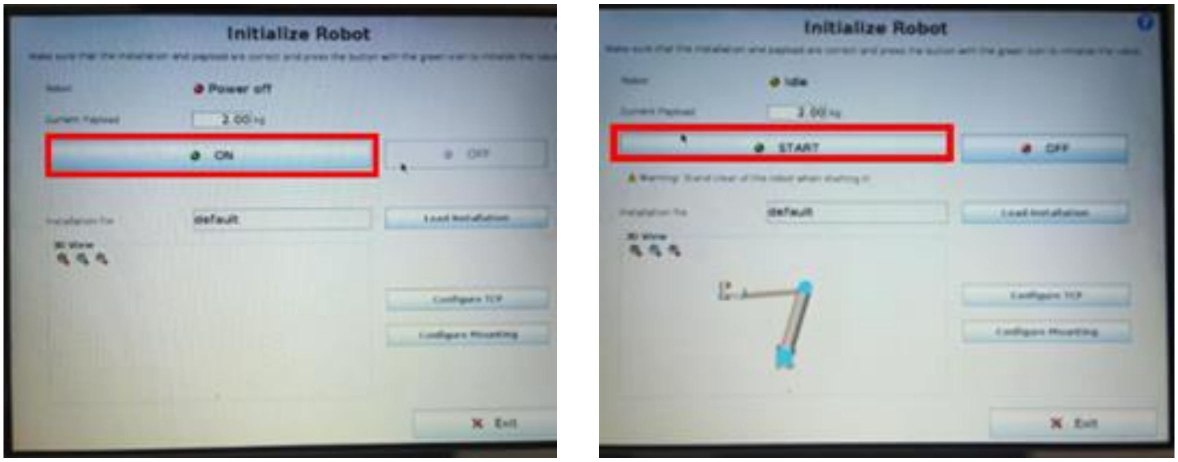


Figure 14. Init robot sequence: **Start motors**

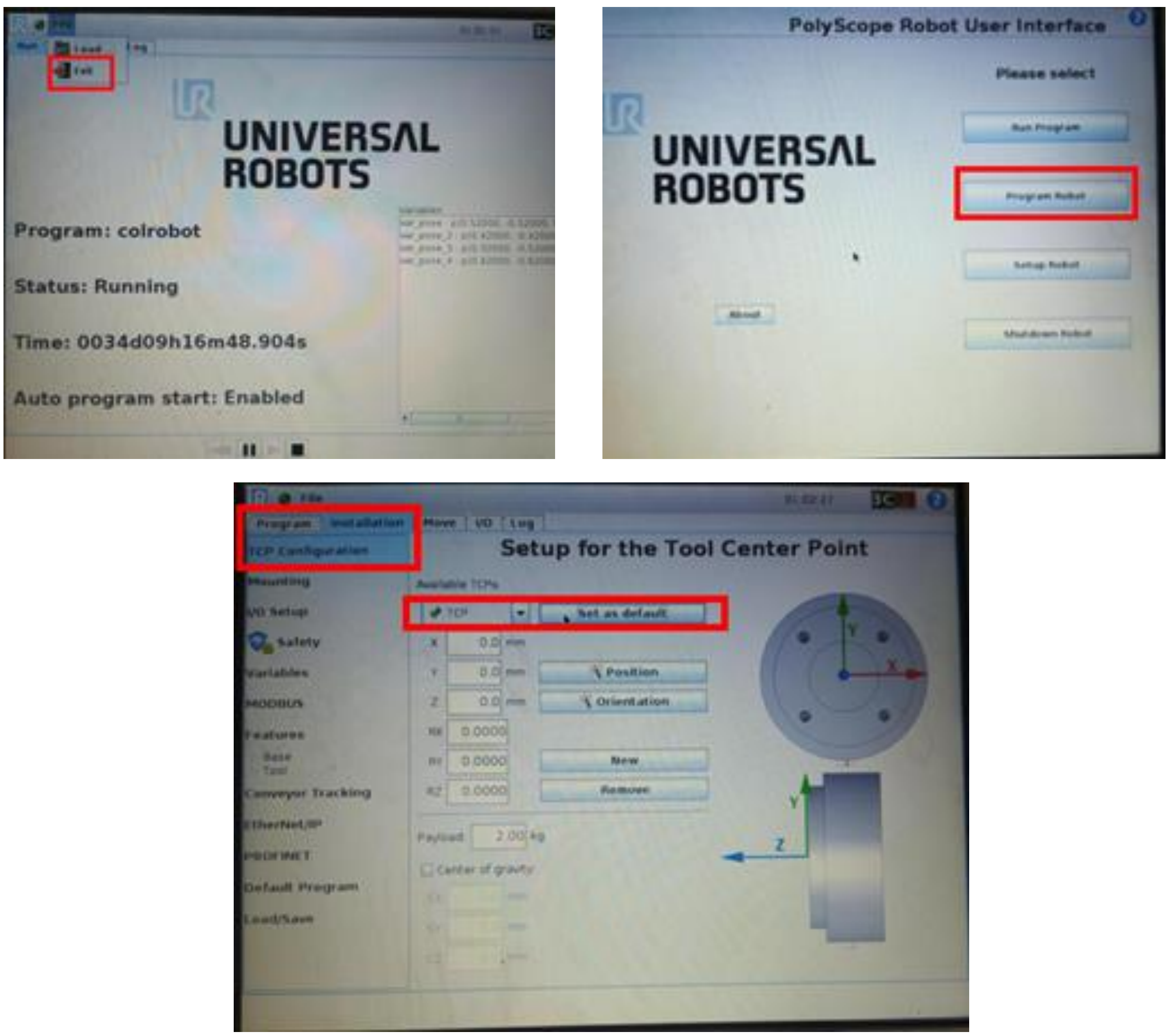


Figure 15. Init robot sequence: **Set active TCP** sequence

2. Computer connections

For being able to communicate the control computer to the robot and camera, we need to connect the other termination of the Ethernet cable of Figure 7 to the computer. Besides, USB3.0 for the Intel RealSense camera must be plugged into the computer. These connections are represented in Figure 12.

Figure 16. Connections on the control PC.

3. Network configuration

- Robot network: 192.168.0.2
- PC network: 192.168.0.30

4. Parameter configuration

Signals for plasma cut machine configuration

File *"ur_welding_control/config/signals_read_config.yaml"*

- signal_pin: match this value with the one from the physical connection between the robot and the plasma cut equipment.

Tool calibration configuration

File *"indoor_robot_localization/config/tool_calibration.yaml"*. Modify position and orientation of the calibrated tool.

Reconstruction

File *"indoor_robot_localization/config/config_UR.yaml"*

- cad_cloud_path: complete route to the pcd file of the environment CAD.
- Pointcloud_save_file: set to a known route to check result.
- Calibration_matrix: camera calibration matrix from the hand in eye procedure.

5. **Launch application**

For launching the program, we have developed a GUI that runs all the required environment, but it is needed to modify the parameters from the previous section. To launch the interface, ROS MASTER should be running, to do that:

a. Open a terminal
b. Write: cd QtProject/latests/bin
c. Write: ./qtcreator
d. Open project and run the application

The result will be the following GUI which works as explained below:

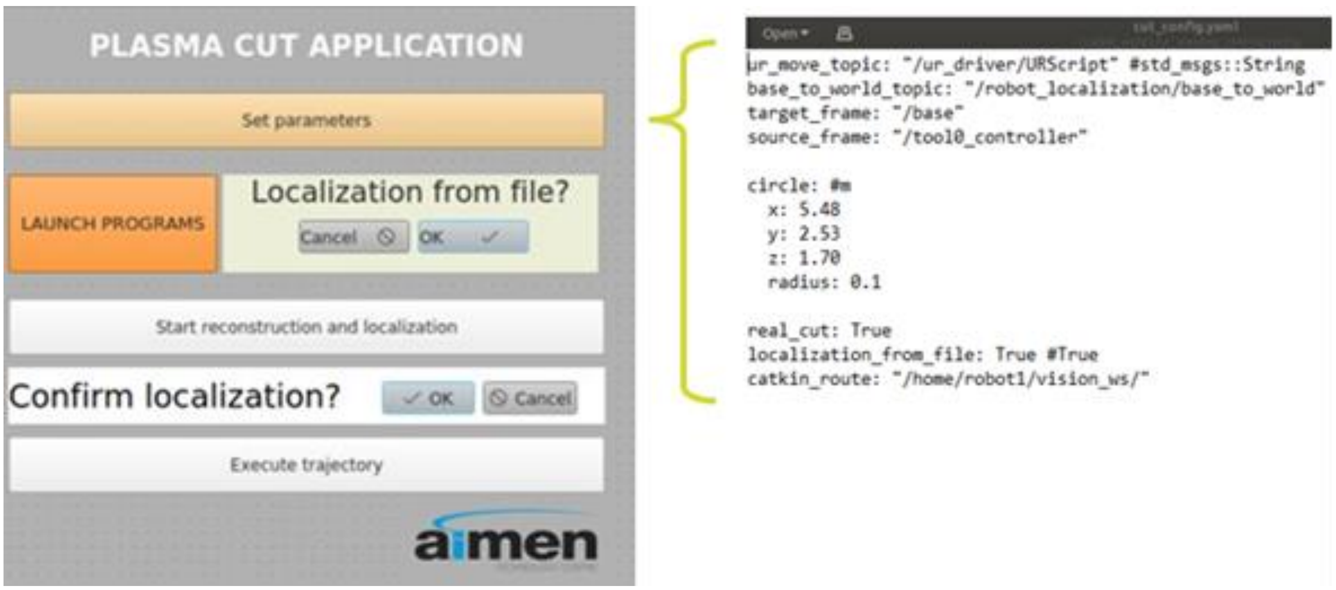


Figure 17. GUI for plasma cut application.

1. **Set parameters**: change circle centre position (represented in CAD coordinates), as well as the options *real_cut* and *localisation_from_file*.
2. **Launch programs**: will launch all the programs required for this application.
3. **Localization from file**: click OK / Cancel depending on whether or not we want to run the localization in the real system. If we already had performed the localization and we have not moved the robot, this step is not required.
   a. *OK*: the **"Start reconstruction and localisation"** button will appear.
   b. *Cancel*: the button **"Compute trajectory points"** will appear.
4. When we press **"Start reconstruction and localisation"**, the robot will start moving relative to the initial position. The objective is that the robot should be scanning zones that have relevant features.

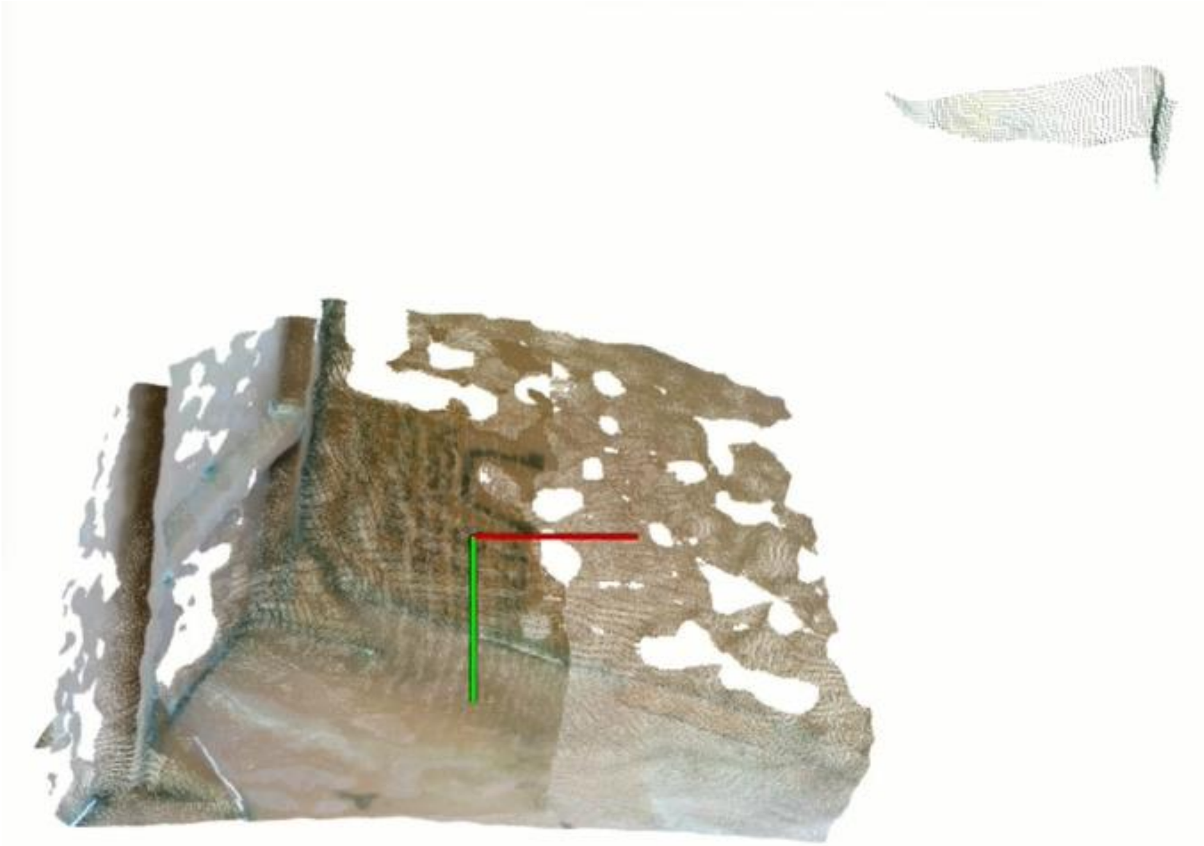


Figure 18. Reconstruction result of an environment.

On this step, the user will need to interact with a visualization window to tell the system where the camera is approximately to be able to perform the refinement process. To do this, the user will zoom/rotate the environment until the view is achieved. Here, we press "Space key" to select the initial view.

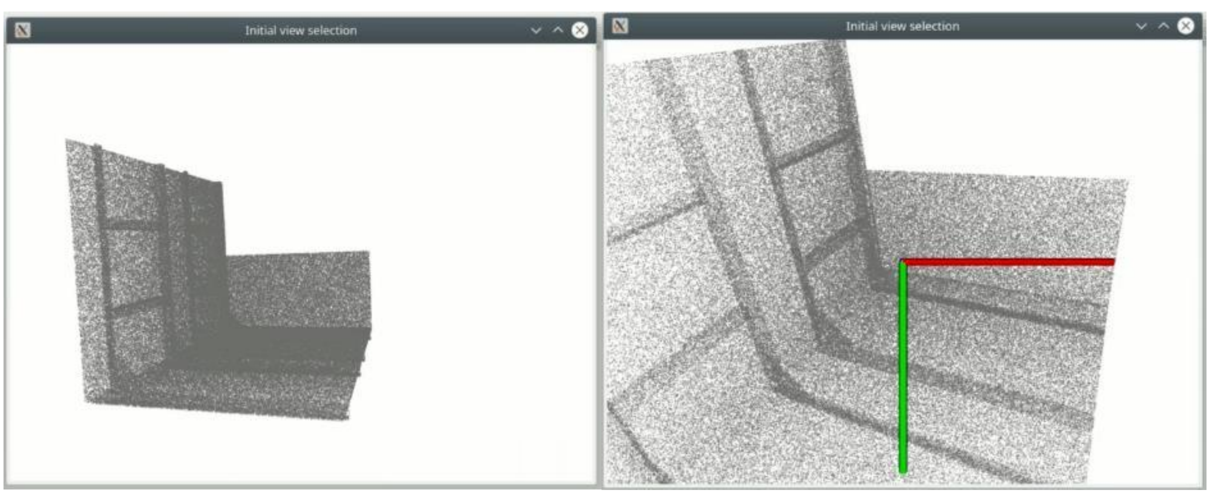


Figure 19. View selection*.*

Now, an additional window will be opened with the refinement process. We will use the following keys:

- *Space*: compute a new iteration.
- *Enter*: Confirm refinement. We will press this key when reconstruction cloud is aligned to the CAD cloud.

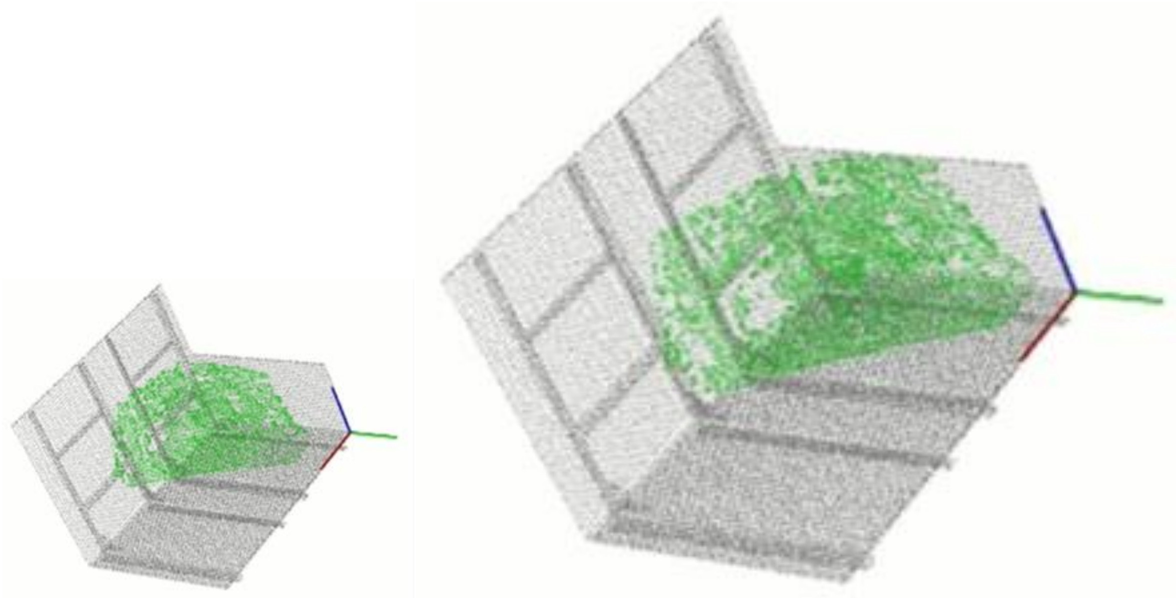


Figure 20. Refinement process.

Once the matching process is completed, the user will be asked to confirm the localisation:

a. OK: we can continue with the cutting sequence.

b. Cancel: the window will open again to select the view and apply the ICP algorithm again.

5. By pressing **"Calculate path points"**, the robot will go to the centre of the cutting point with a certain displacement (~30cm) to take a capture and process it.

6. Then **"Execute trajectory"** will appear where the robot will execute the extracted trajectory.

2.4.5 Potential disadvantages

- CAD dependence as well as the dependence on the initial pose estimation.
- Weight of the system could be one disadvantage mainly for long manual manipulation.
- The base of the robotic system is static meaning for profile outside or on the boundary of the robotic work envelope, the system should be moved manually.
- Limited to simple profiles execution.
- Non integration with the standard CAD/BIM software.

2.4.6 Potential risks/barriers

Technical

- CAD dependence
- Ergonomic injuries due to the manipulation of load

Economic

- The risk of losing the investment as full process was not addressed. Additionally, depreciation of the robotic system with training and maintenance expenditures.

Social

- Adoption of technology due to the fear of losing jobs.
- Lack of skilled workers and interest of the people in acquiring cutting/welding skills.

Legal (Rules, regulations)

- Strict regulation on deploying robotic systems around humans (ISO 13849-1:2023, ISO 13849-2:2015, ISO 10218-1:2011, ISO 10218-2:2011, ISO/TS 15066:2016)

2.5 Technology: Autonomous mobile robots

2.5.1 Description

The use of autonomous mobile manipulators to transport raw materials and individually manufactured parts between warehouses and workshops, as well as between workshops and subassembly areas, increases the intra-logistic process efficiency while freeing up human resources for higher-value tasks.

Four different technologies are combined to create a collaborative solution:

- Mobile Manipulator composed of an autonomous mobile platform and a collaborative robot.
- Skill-based programming for fast and intuitive teaching of new robotic tasks.
- Intuitive Human-Robot Interaction based on augmented reality.
- Advanced perception for long-term autonomy (autonomous navigation and CAD-based perception and grasping).

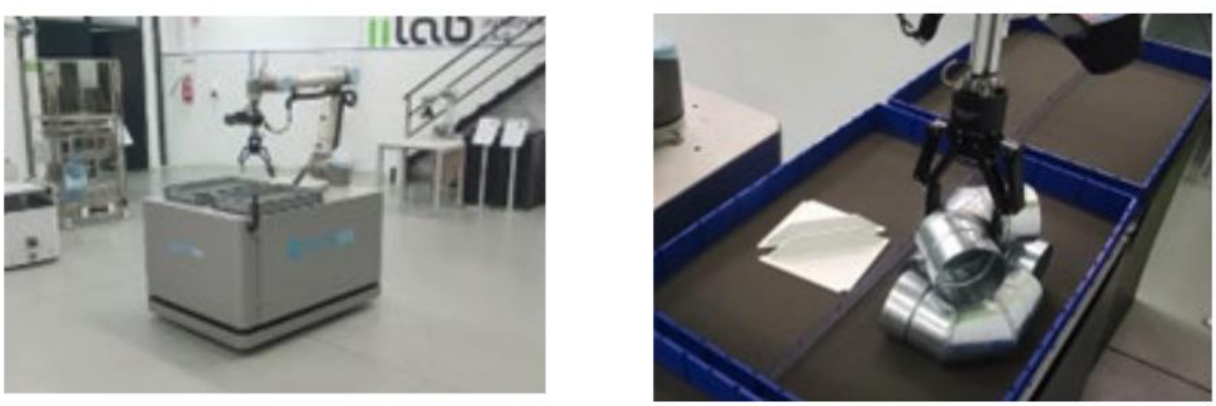


Figure 21. Autonomous mobile manipulator.

2.5.2 Potential Applications

Nowadays, the transportation of individual parts in shipyards is still heavily reliant on human operators. This transportation is typically performed by hand or using self-propelled, pulled, or pushed platforms. The logistical complexity of the shipyard extends across warehouses, worksites, various parts, and components. During the shipbuilding process, a wide range of components, including structural steel, pipes, cables, valves, and outfitting, are supplied, normally stored in shelves, big containers and boxes.

Typically, and from the human operator perspective, these logistic operations involve the execution of tasks that are dull, dirty, and dangerous. As the European population ages and shipyards struggle to hire and retain their workforce, it becomes critical to liberate and empower the current human workforce to perform more added value.

As a result, there is a pressing need in the shipbuilding industry to automate its intra-logistic processes. To address these concerns, Mari4_YARD proposes the use of a Mobile Manipulator to retrieve individual parts from containers, shelves, and other locations, combining the mobility of autonomous mobile robots with the manipulation dexterity of a robotic arm.

In the Mari4_Yard project, the demonstration scenario involves the operation of a Mobile Manipulator in a warehouse at Nodosa Shipyard. The robot is responsible for taking parts from shelves and containers and delivering them to the human operator, in a specific location at the entrance of the logistic warehouse. Despite the chosen scenario, there are others where the solution could be used, e.g., machine tending in a machining centre, transportation of tools/equipment across the construction/production facilities, and quality control, among others.

2.5.3 Replicability

The developed solution fully applies to other shipyards and even application sectors (automotive, aeronautics, metalworking, and others). The Mari4_YARD solution was built modularly, with the upper layers of the robot software being hardware agnostic, allowing for easier customisation of the robotic solution to meet different application requirements.

2.5.4 Expected benefits

Economic benefits

- Reduction of the number of operators working on logistics. Require that part of their time be allocated to monitoring and assigning tasks to robotic systems.
- Better usage of the available workforce.
- Improve traceability of the consumed resources.
- Non-expert robot programming.

Sustainability

- Increased traceability of the parts used/produced during production, contributing to the digitisation of the production process, resulting in better control of the consumed resources.
- Companies become more resilient to fluctuations/shortness in the available human labour force.

Societal benefits

- Workers will be relieved from dull, dirty, and dangerous operations, owing to the specific characteristics of the parts to be transported.
- Reduction of accidents.
- Workers will also be transferred from low-value to higher-value production activities that are also more noble for the worker (Worker Satisfaction/Valorisation)

2.5.5 Guidelines for the application of the solution

- The developed solution can be applied indoors, such as in a warehouse.
- The parts need to be stored so that the robot can easily access them.
- The floor where the robot will operate must be in good condition.
- Robot mechanical characteristics and capabilities must be considered (e.g. mobile robot size, robotic arm reachability and payload, robotic grippers) when considering their application.
- Operator training is required.

Short user-guide

Initialising the robot

To turn the mobile manipulator on, the user needs to follow the steps visualised in the Figure 1, where the control panel, located in front of the robot, is presented. The represented buttons should be triggered in sequence to power the robot. Below there, each functionality is presented.

- **Step 1 (Button 1):** The general power button (smart battery interface).
- **Step 2 (Button 2):** Power the robot motors drivers.
- **Step 3 (Button 3):** Turning on the embedded computer.
- **Step 4 (Button 4):** Active the robot motor drivers, which should be pressed after the embedded computer is on.

Notice that two emergency buttons are presented in the robot. One is for the robotic manipulator (button B), and the other is for the mobile base (button A). When pressed, these buttons break the robot's operation and should be released to a proper initialisation.

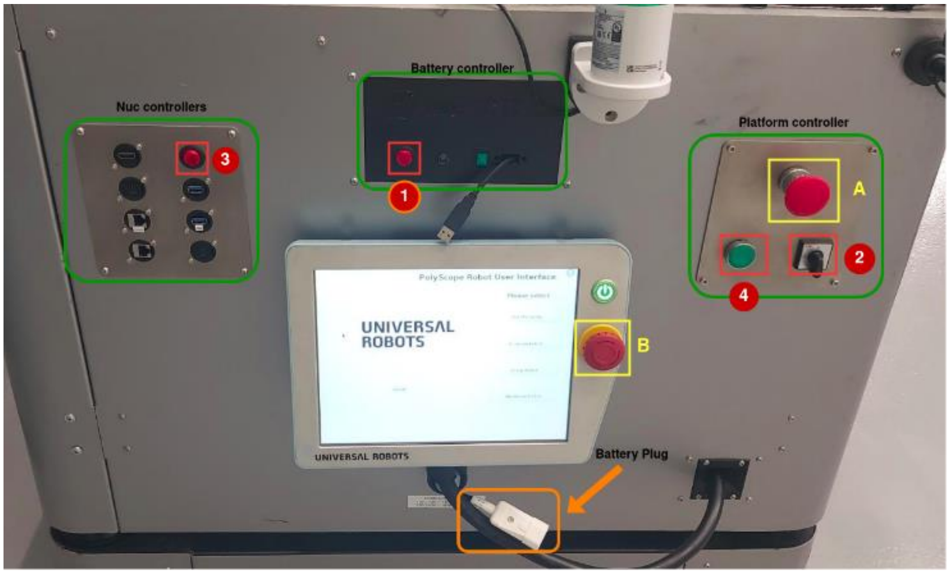


Figure 22. Robot control panel.

The robot is embedded with an Ubuntu Linux operating system, and the user can directly interact with the system by accessing any remote access software, such as Remmina, AnyDesk, RustDesk or SSH. The operator should be under the same network.

Build the map

The user needs to map the operation environment once to enable the robot to locate and navigate through the environment. This is performed by following the instructions presented as follows.

1. Access the **Activities** button in the top left screen corner and click on **IRIS** application (Figure 23).

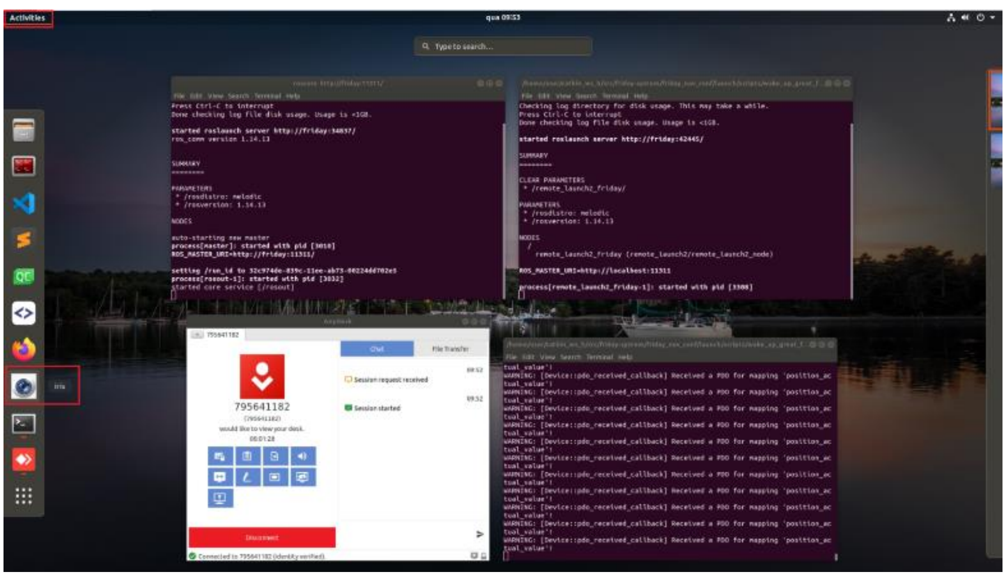


Figure 23. Accessing the IRIS application**.**

2. Click on the **Mapping** tab to start the mapping operation autonomously (Figure 24).

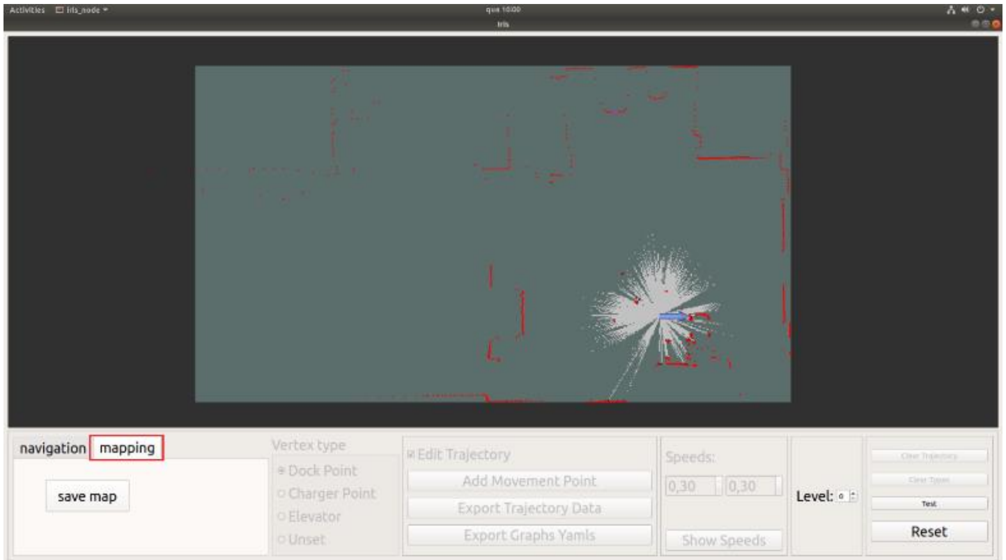


Figure 24. The map building interface.

3. Use the joystick to move the mobile platform (Figure 25) to visit all the areas where the system will operate (Figure 26).

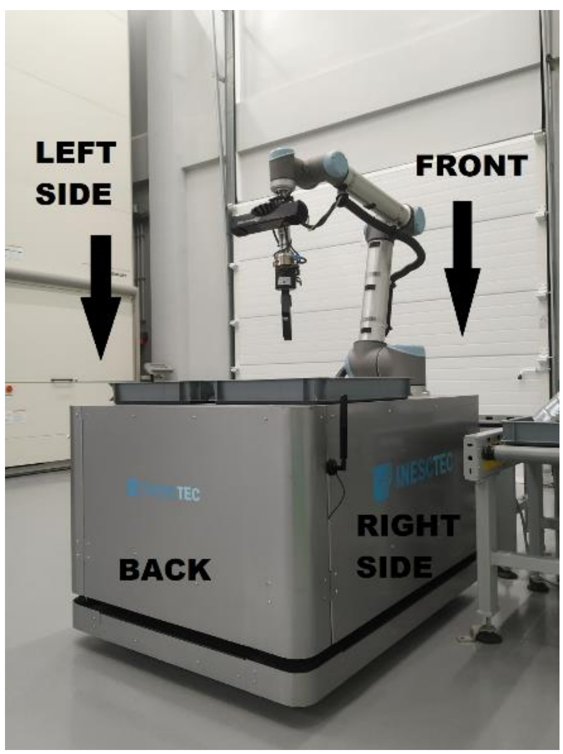


Figure 25. The robot orientation.

Figure 26. (left) The Left Analogue button controls the robot forwards, backwards, left and right. (right) The Right Analogue button is reserved for the rotation movement**.**

4. IRIS displays the generated map in real time during the mapping operation.
5. Once the mapping process is completed, click on the **Save Map** button to save the robot's map (Figure 6).

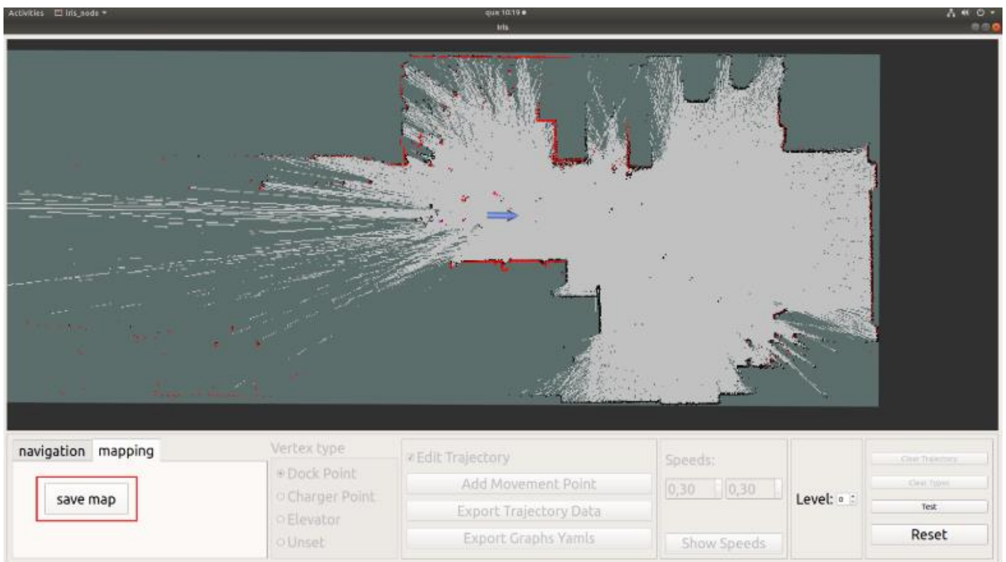


Figure 27. Exporting the generated map**.**

6. If there are more floors to map, move the robot to the new floor, click **Reset** and repeat the previous steps.

Set the targets and the trajectories.

With the map built, the user must define the robot's target locations over the environment. To do so, the user needs to perform the following steps:

1. Click on the **Navigation** tab to switch from the previous operation. The system launches, autonomously, the latest created map.

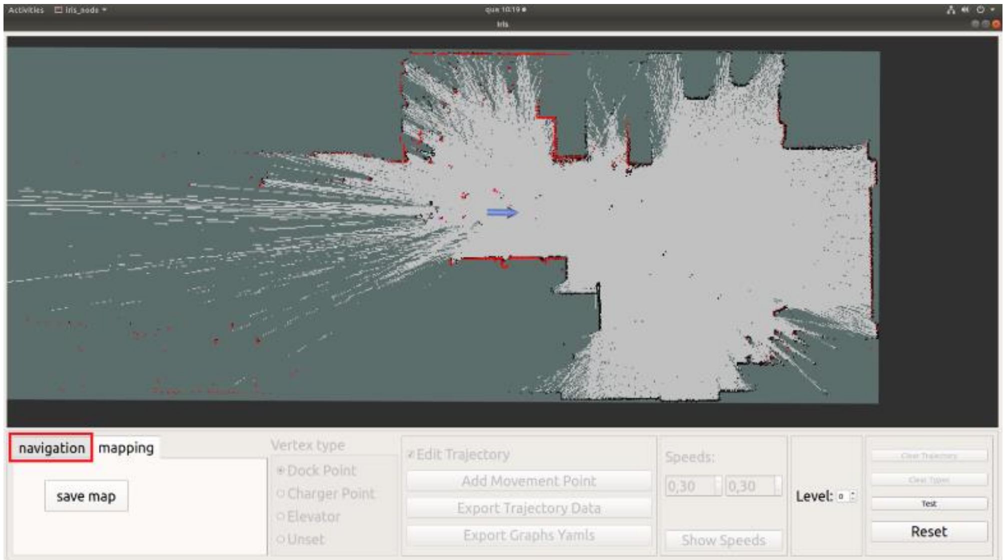


Figure 28. Navigation setup**.**

2. Click the **Clear Trajectory** button and then the **Clear Types** button to erase the latest stored trajectory. The system creates just one vertex in the origin map position.
3. After it is necessary to locate the mobile platform in the new map. Click on the **Set Pose** button and follow the next steps:

- Move the mouse to the supposed robot's position.
- Hold the Left Mouse Click and then drag it in the orientation the robot is in.
- If you find that the robot is not located on the new map, repeat the steps.

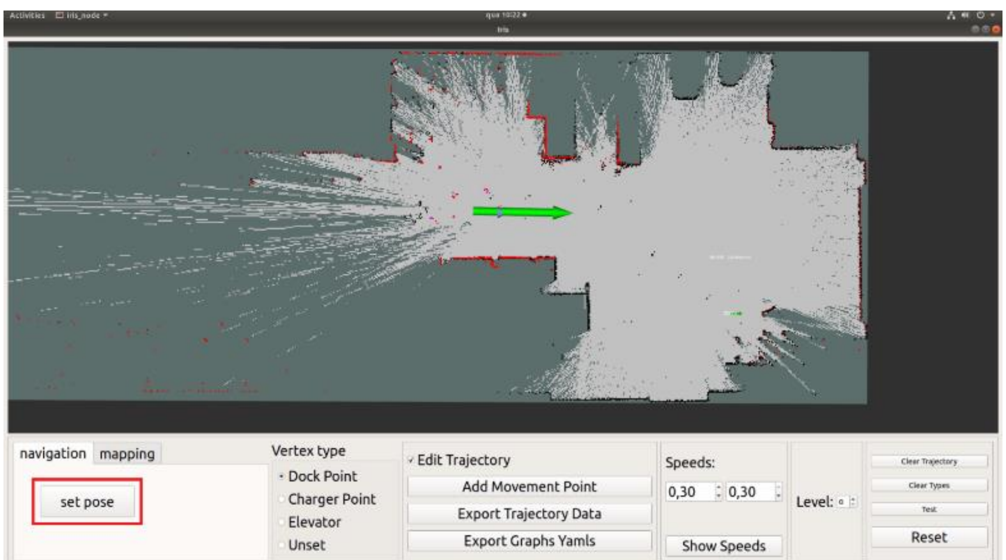


Figure 29. Locating the mobile platform. The robot is located only when the red laser points match the black wall points on the new map**.**

4. After locating it, add the second vertex to the robot's pose. Click on **the Add Movement Point** button. The system will create a new vertex with the robot's orientation.

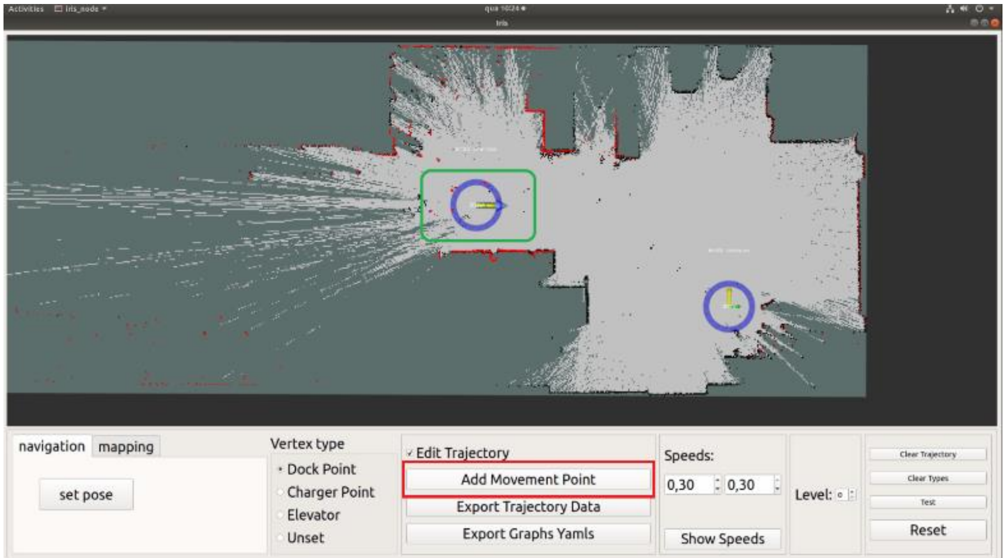


Figure 30. Inserting new move targets. Inside the green rectangle, it is possible to see the new vertex and the robot's location. The red points are the real-time laser point data.

5. Build the path by creating and configuring new vertices by (Figure 10):

- Right Mouse Click on the blue circle of a vertex.
- Click on **Add New.**
- Hold the Left Mouse. Click on the green arrow on the created vertex, and move it to the desired map point.
- Hold the Left Mouse Click on the blue circle of the moved vertex and rotate the circle until you get the direction of the desired trajectory, represented by the green arrow direction.
- Finally, adjust the yellow arrow to the robot's orientation at that waypoint/vertex by holding the left mouse, clicking on the yellow arrow, and rotating it until the desired orientation is obtained.

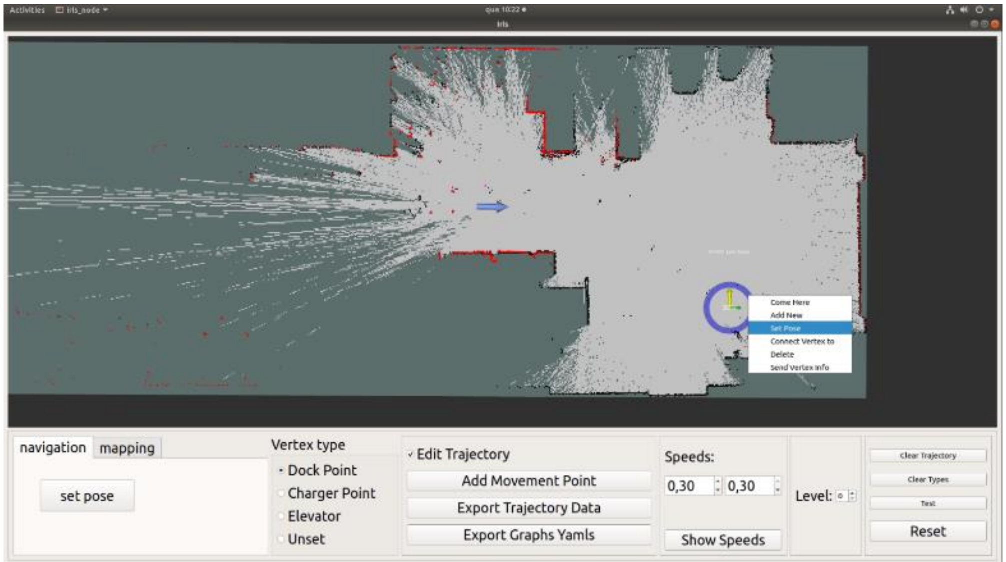
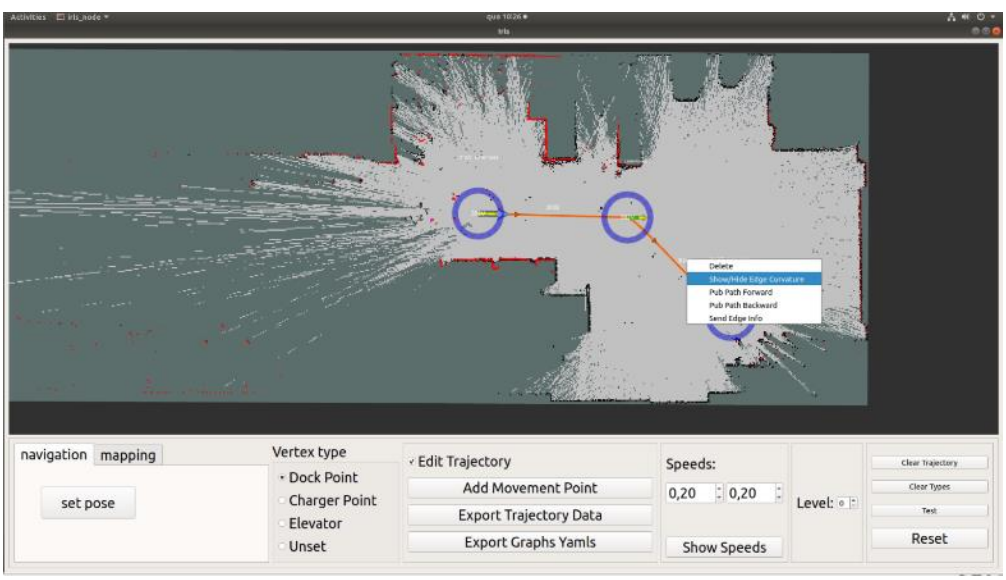


Figure 31. Building the trajectory.

6. Edit the path by creating and configuring the edges between vertices:

- Right Mouse Click on the blue circle of a vertex.
- Click on **Connect Vertex To**.
- Left Mouse Click on the blue circle of the second vertex - it is essential that the two vertices do not have opposite orientations.
- The new Edge is created between the two defined vertices.
- Right Mouse Click on the orange line of an edge to adjust it;
- Click on **Show/Hide Edge Curvature**.



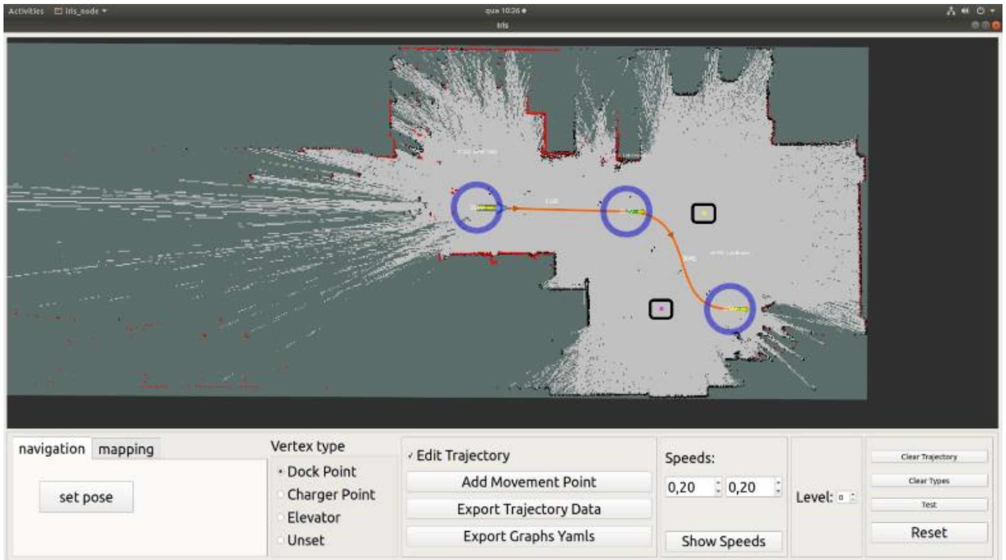


Figure 32. Adjusting the trajectory.

7. Once the path configuration process is completed, Click on the **Export Trajectory** button**.**
8. Use the Data and **Export Graph Yamls** buttons to save the robot's trajectory.
9. After these steps, click the **Reset** button to check that the robot is located and that the new map and trajectory are launched autonomously and correctly.
10. If so, it is possible to move the robot by right-clicking on the vertex you want to move it to and clicking the **Come Here** button (Figure 12).
11. The robot moves from where it is to the desired point autonomously if there is a path to get there.

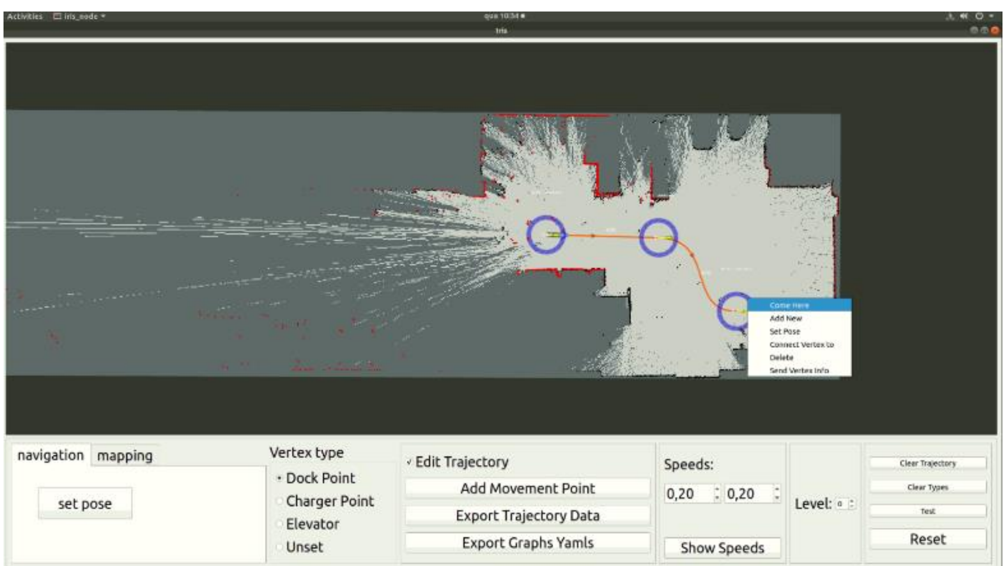


Figure 33. Send the displacement order to the robot.

Set the picking locations

After defining the map and the locations of interest in the environment, the next step is calibrating the picking zone using an augmented reality marker. The following steps are performed to acquire the picking pose:

1. Open the **Scene Calibration** button in the **Application** bar (step 1 in Figure 34).

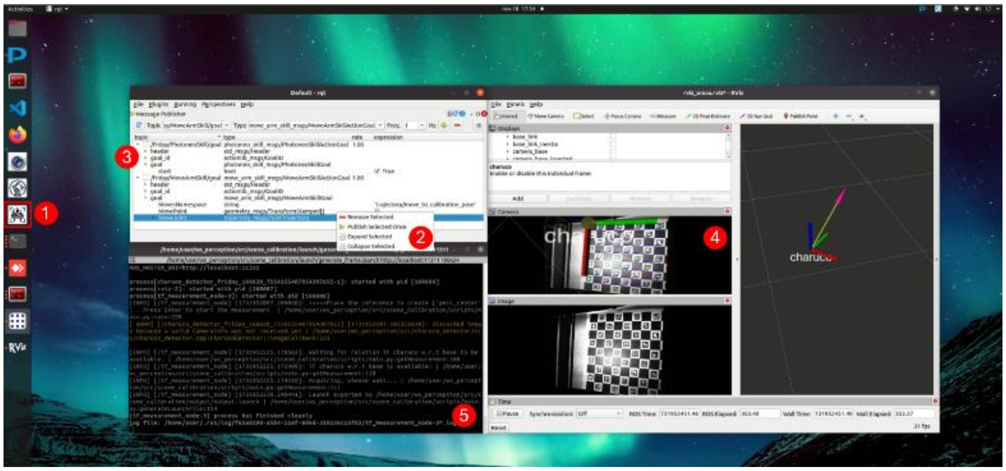


Figure 34. The scene calibration interface.

2. Place the augmented reality marker on the picking zone (Figure 35).
3. Send order to robot manipulator movement to scan position (step 2 in Figure 34).

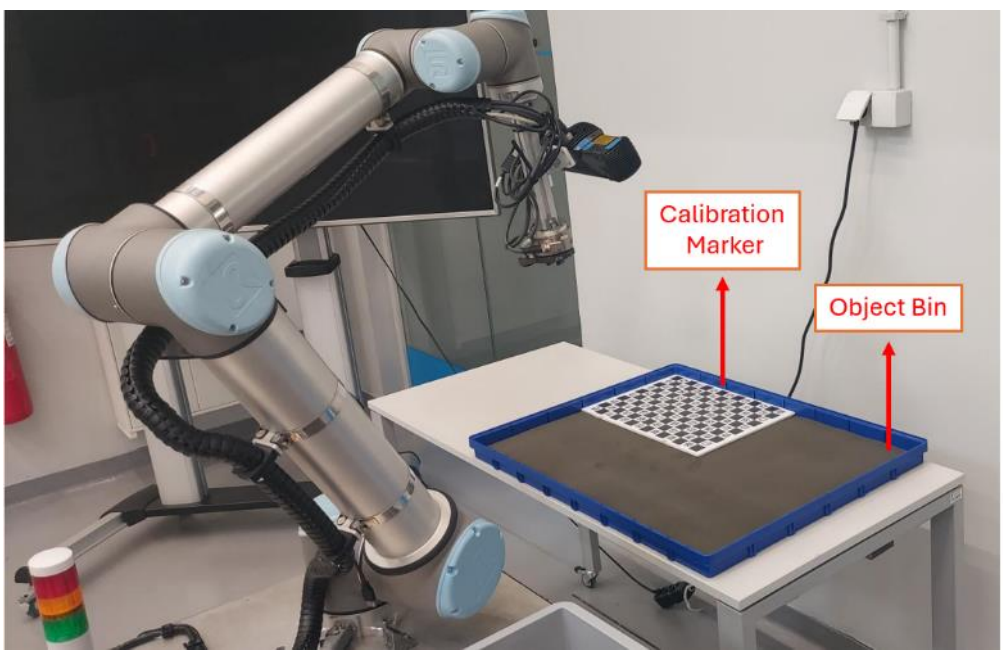


Figure 35. Scenario calibration to picking operations. The marker is placed on the picking table to calibrate the object bin location. Therefore, the robot is moved to the scan position, and the calibration software calculates the calibration parameters.

4. Send the order to trigger the image (step 3 in Figure 34).
5. Check if the marker is visible. It will show a reference frame in the image (step 4 in Figure 34).
6. Collect the information by typing **Enter** in the pop-up terminal (step 5 in Figure 34).
7. Close the software, and the calibration will export the calibrated data (Figure 36).

```xml
<?xml version="1.0"?>
<launch>
  <node pkg="tf" type="static_transform_publisher" name="measurement_tf_1731943373231703519"
  args="-0.525153 -0.478372 0.055665 0.006151 0.002912 0.92556 -0.37854 base perc_center 100" />
</launch>
```

Figure 36. Calibration output file**.**

Running a picking mission

1. To run a picking mission, the user just needs to click Open the **Picking Software** button in the **Application** bar (Figure 37).

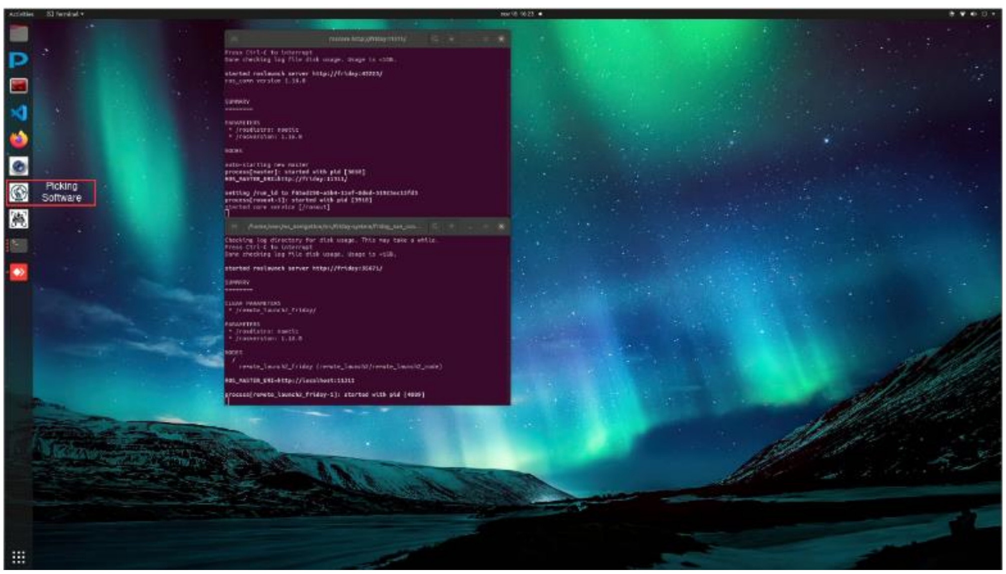


Figure 37. The Picking Software button.

2. Go to any browsing software and type the address: **http://manager.localhost.**
3. Select the robot by clicking on the red **F button** on the left side of the Production Manager GUI (Figure 38).

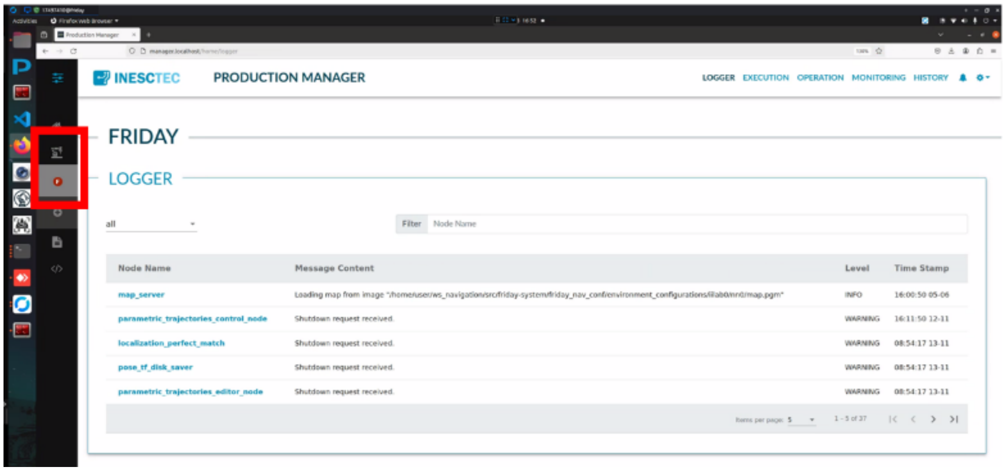


Figure 38. Production Manager GUI.

4. Then go to the **Operation** panel on the interface top right (step 1 in Figure 38).
5. A list of possible objects to pick and the quantity can be selected by the combo boxes represented by steps 2 and 3 of Figure 18. The order could be sent to the robot by clicking on the **Play** button (step 4 in Figure 18).
6. Just wait for the robot to realise the pick mission.

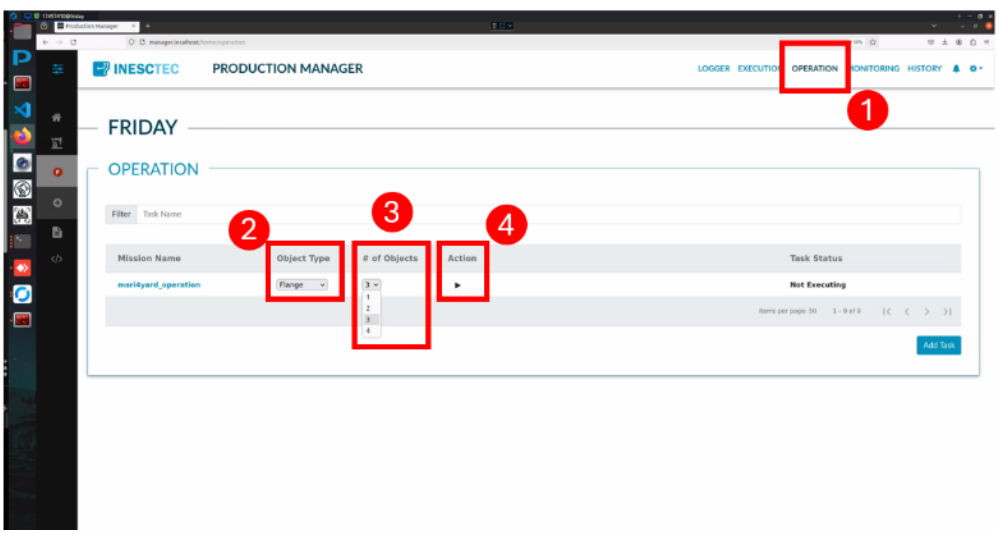


Figure 39. Production Manager operation interface**.**

2.5.6 Potential disadvantages

- To apply the solution, the working environment should be adapted. These adaptations include:
  - Define clear corridors where the robot can navigate.
  - Parts need to be stored so the robot can easily reach them.
  - The working floor must be in good condition.

- Robotic picking can be slower compared to human operators. Nevertheless, transportation requests can be planned sooner in time.

2.5.7 Potential risks/barriers

Technical

a. CAD model of the parts to be picked are required. In the future, and with ongoing research work, the solution is expected to work without this requirement.
b. Limited performance regarding highly reflective and transparent workpieces. Research regarding sensing (considering new sensing technologies already reaching the market) and perception in future work should address this problem.

Economic

- Comparatively with other proposed solutions, the initial investment in these robotic systems is relatively high due to their inherent technology complexity. It is expected that their price will decrease with the increased use of Mobile Manipulators across various sectors, pushing for lower-cost robots, sensors, and grippers.

Social

Need for technical personnel that can manage advanced robotic solutions. Upskilling the workforce to interact, perform high-level programming, and maintain complex robotic equipment.

Legal (Rules, regulations)

- Strict regulation on deploying robotic systems around humans (ISO 13849-1:2023, ISO 13849-2:2015, ISO 10218-1:2011, ISO 10218-2:2011, ISO/TS 15066:2016)

2.6 Technology: High-payload collaborative robots

2.6.1 Description

A high-payload robot, empowered by AI, is used in shipyards for the picking, positioning, and welding of heavy metal parts. Precise parts positioning is supported by manual guidance while welding path teaching is supported by intuitive AR programming interfaces. Safety systems are properly integrated for Speed and Separation Monitoring HRC.

The proposed solution combines several technologies: Speed and Separation Monitoring HRC, direct and indirect human-robot interaction for parts positioning and AR-assisted welding path teaching, advanced perception for bin picking operations, multilayer safety system, and a multimodal gripper (with magnets for picking tasks, welding torch for welding, F/T and vision sensors.

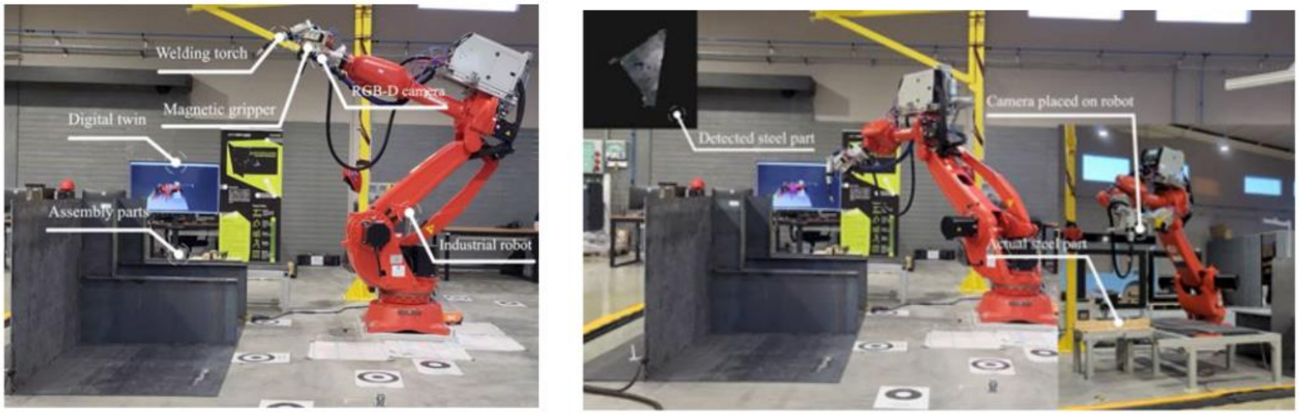


Figure 40. High payload robot for the picking, positioning, and welding of heavy metal parts

2.6.2 Potential Applications

High payload robots are being utilised in shipbuilding to enhance productivity and working conditions. They handle strenuous tasks like manipulating heavy parts, while human operators guide them. The tools developed offer adjustability and ease of use for non-expert users. AI-enhanced machine vision and AR technology support operators in detecting and manipulating parts, programming robot paths, and ensuring safety through a multilayer safety system.

2.6.3 Replicability

The technological modules developed under the high level “High payload collaborative robots” are applicable not only to shipyards but also to various other sectors such as automotive, steel industry, and more. Those technological modules are designed and developed in a modular and reconfigurable fashion allowing easy integration and technology deployment in different robotic setups, towards high customization and production reconfigurability, for dealing with various products in different quantities.

2.6.4 Expected benefits

Economic benefits

- Reduces the number of assembly errors that occur from human mistakes.
- By decreasing the cycle time, more variants/ orders can be delivered.
- Dependent to project requirements overtimes expenses are saved

Societal benefits

- Reduces the costs corresponding to the worker’s health, due to fewer accidents, addressing chronic unergonomic postures and weightlifting.
- Less exposure to fumes leads to decreased risk for respiratory health issues.
- Less exposure to UV radiation (concerns for skin cancer, eyes irritation etc.)
- Improved working conditions, allowing also people with disabilities (e.g. shoulder pain etc.) to be employed in the very demanding shipyard environment.
- People with different physiques, gender etc. to be employed in the shipyard settings.

2.6.5 Guidelines for the application of the solution

To replicate and implement the solution at a production level, we need to address several specific requirements. These requirements have been categorized into sections, which are hardware, software, network, and structural needs

Hardware needs:

- **Robot:**
    - The **Comau NJ-130-2.6** is a high-performance 6-axis industrial robot designed for tasks requiring precision, strength, and reach. It supports payloads up to 130 kg on the wrist and 50kg on the forearm, and has a reach of 2616 mm and repeatability within 0.07 mm. The robot can withstand harsh conditions, due to his high protection rating of IP65/IP67.
    - The **COMAU C5G Safe** is a high-performance robot controller designed for efficient multi-axis management. It features energy-saving functions and advanced safety controls for secure robot motion.
- **Vision Systems:**
    - The **Intel RealSense D435** is a depth camera that combines RGB and depth sensing capabilities to capture high-quality 3D images. With its dual-lens design, it provides improved depth accuracy and a wide field of view.
- **Hand Guiding System:**
    - The **OnRobot HEX 6-Axis Force/Torque Sensor** is designed to provide precise force and torque measurements across six axes.
- **Welding System:**
    - The **GYS NEOPULSE 500G** is a pulsed MIG/MAG generator for automated welding.
    - The **GYS NEOCOOL 400** is a cooling unit for automated welding.
    - The **GYS NEOFEED 4W is** a wire feeder for automated welding.
    - The welding torch consists of **METZ 542, RETZ 663** and **ADFL 6307** components.
    - The **SAM1N** is a communication device for the PLC and the GYS welding machines.
    - The **Siemens SIMATIC S7-1500F** is a safety PLC acquired from Siemens suitable for controlling the welding unit.
- **AR programming interface:**
    - The **Microsoft HoloLens 2** is a mixed-reality headset that blends digital content with the real world. It features improved comfort, better visuals, and hand tracking, allowing users to interact with 3D holograms easily.

  - The **Stylus XR** is a precision augmented reality tool designed for the Microsoft HoloLens 2, offering advanced tracking and interactive capabilities. It enables users to measure spaces accurately, manipulate 3D content in real time, and enhance collaborative tasks by adding virtual annotations

- **Safety Systems:**
  - The **SICK Microscan3** is a compact safety laser scanner designed for reliable area monitoring and protective applications in industrial environments. It features a 275-degree scanning angle and a range of up to 5.5 meters, ensuring effective detection of obstacles and personnel.
  - The **PILZ PSS4000** is a safety PLC acquired from PILZ suitable for controlling the safety functions of the robot, via its dedicated safety hard/wired digital IOs. The PILZ also integrated the various safety systems of the cell as for example the safety buttons for the robots, the welding machine, the IO handling of the laser scanners and others.

- **General Hardware:**
  - **One PC** that has Ubuntu 20.04 OS and ROS noetic with a GPU, that its processing power can handle the computational requirements of the vision systems.
  - **One network router** and **one switch** for the network configuration.

Software needs:

- **Robot:**
  - **ROS** is an open-source framework for robot software development. It provides tools, libraries, and conventions for building complex robot applications across platforms. With a modular architecture, ROS simplifies tasks like perception, motion planning, and control by enabling different components (nodes) to communicate easily. It supports various programming languages, mainly C++ and Python, and is widely used in research, industrial automation, and autonomous systems, fostering collaboration in the robotics community.
  - **MoveIt** is a motion planning framework for robotic arms in ROS. It provides capabilities for collision detection, trajectory planning, and manipulation tasks, enabling robots to move smoothly and efficiently in complex environments
  - **Octomap** is a library for 3D occupancy mapping, allowing for the creation of volumetric maps in real-time. It uses a probabilistic approach to represent space as an octree, efficiently storing occupancy information and supporting applications in robotics for navigation and obstacle avoidance
  - The **RViz** is a 3D visualization tool in ROS that helps users visualize sensor data and robot states. It supports the display of maps, trajectories, and sensor data, making it essential for debugging and monitoring robotic applications

- **Vision Systems:**
  - The **pyrealsense2** is a Python wrapper for the Intel RealSense SDK. It allows users to access depth and colour data from RealSense cameras, facilitating tasks like 3D reconstruction and object detection in computer vision applications. It was used for the interfacing with the Realsense D435 sensors.
  - The **SAM (Segment Anything Model)** from **Ultralytics** is a state-of-the-art deep learning model for image segmentation. It enables precise segmentation of objects in images, allowing for advanced applications in computer vision, such as autonomous driving and medical imaging.
  - The **OpenCV** is a comprehensive library for image and video analysis, featuring implementations of algorithms for tasks like object detection (Haar cascades, HOG), image filtering (Gaussian blur, median filtering), and feature matching (ORB, SIFT). It also supports real-time computer vision applications through its optimized functions and extensive.
  - The **Open3D** is designed for 3D data processing, offering algorithms for point cloud processing, mesh reconstruction, and 3D registration. Key implementations include RANSAC for outlier removal, ICP for point cloud alignment, and various surface reconstruction techniques, making it suitable for applications in robotics and computer graphics
- **Welding System:**
  - **TIA Portal (Totally Integrated Automation Portal)** is an integrated software platform from Siemens designed for automation engineering. It allows users to program, configure, and manage various automation devices and systems, such as PLCs, HMIs, and motion control systems, in a unified environment
- **AR programming interface:**
  - The **rosharp** is bridge that connects Unity with the ROS. It allows developers to create and visualize robotics applications in Unity while leveraging ROS features for communication, sensor data processing, and robot control.

The **StylusToolKit** is a library for Unity game engine that is designed for integrating Stylus XR input in Unity applications. It enables precise drawing and manipulation of objects, facilitating the development of interactive applications that require fine control.

- **Safety Systems:**
  - The **SICK Safety Designer** is a software tool that simplifies the planning and configuration of safety applications. It allows users to design safety-related systems using a graphical interface, enabling easy integration of SICK safety devices. The software supports project documentation and compliance with safety standards, helping to streamline the design process. It also features simulation capabilities to test safety concepts before implementation, ensuring efficient and effective safety solutions for industrial environments.

- The **PAS4000** is a software platform that makes configuration and programming of the PSS 4000 automation system simple. PAS4000 comprises various editors and a multitude of software blocks. In PAS4000, the tools for configuration, programming, commissioning and operation are closely matched to each other. The data interfaces are standardised, making information easier to exchange in all phases of automation. This allows you to quickly and intuitively create programs for safety and automation functions.

Network needs:

For the network configuration a basic internet connection will require for the communication between the modules, although most of the communication between the robot and the rest of the software is done through the TCP/IP protocol a network line with a larger bandwidth will be significant more stable. The rest of the communication consist of some other more advanced protocols that is used in automation sector. More specifically:

- **TCP/IP (Robot/Siemens PLC/Hololens 2)**
- **Profinet (Siemens PLC/SAM1N)**
- **Profinet Safe (SICK PSS4000)**
- **Modbus (Siemens PLC/SICK PSS4000)**
- **Bluetooth (Stylus XR/Hololens 2)**

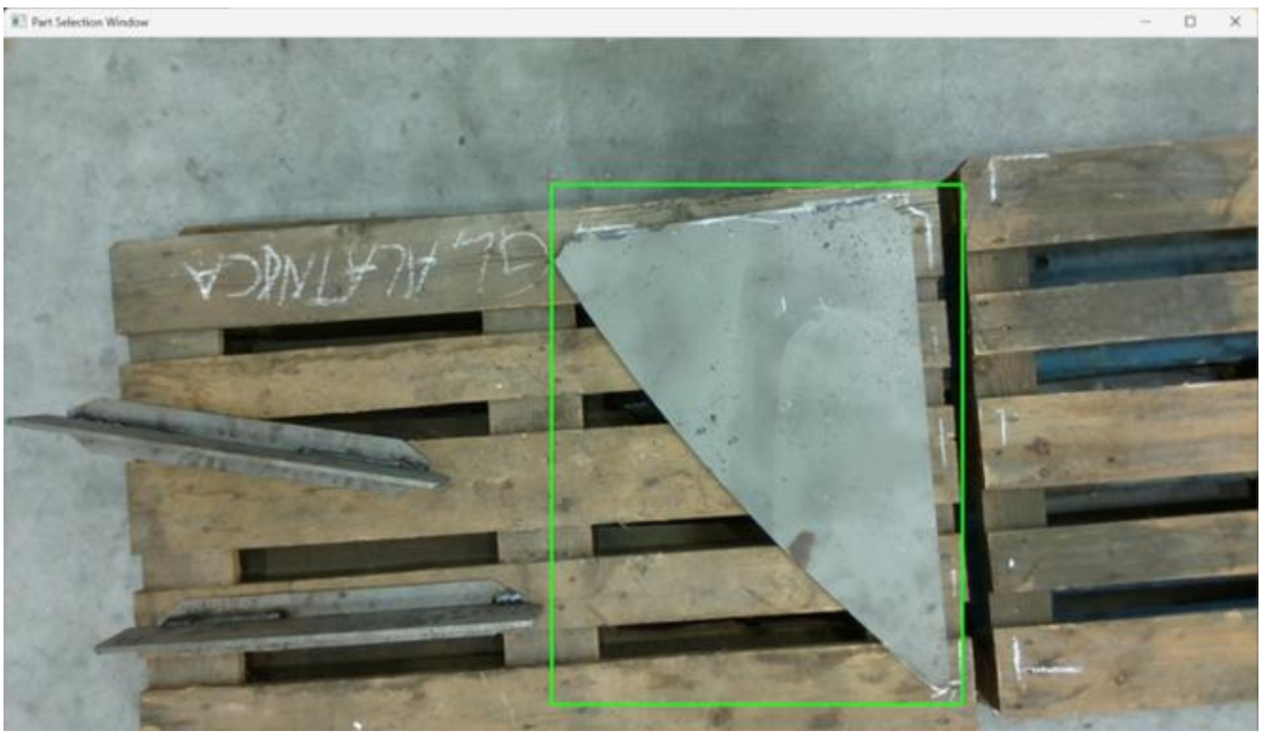
Structural needs:

- The developed solutions can be applied indoors, in a prefabrication stage.
- The workspace needs to be inside the boundaries of the active workspace of the robot.
- The floor where the robot should be integrated should comply with the installation requirements of the robot manufacturer.
- Electrical/pneumatic systems should comply with the standards

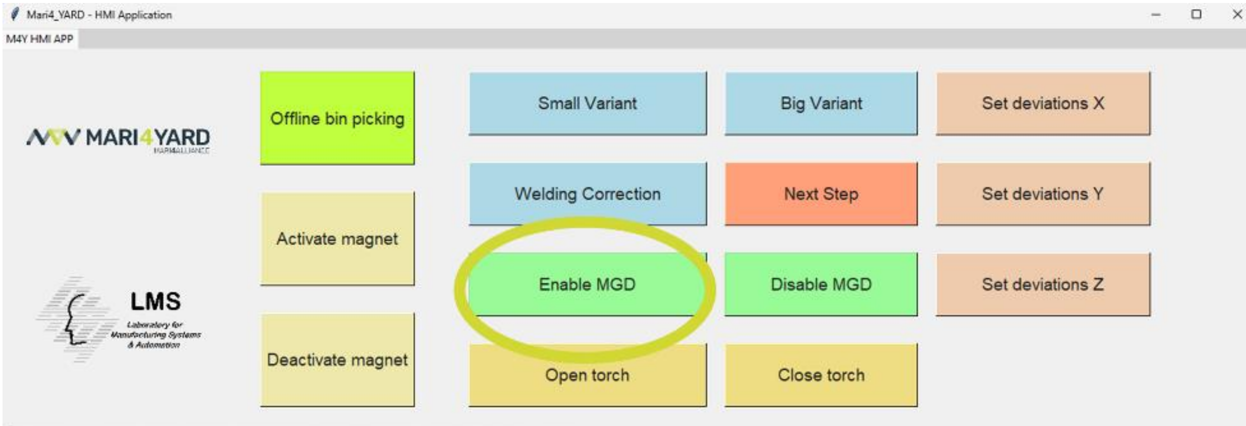
User Manual:

1. Select the desired bin variant from the UI.

2. Select the desired part inside the selected variant bin.

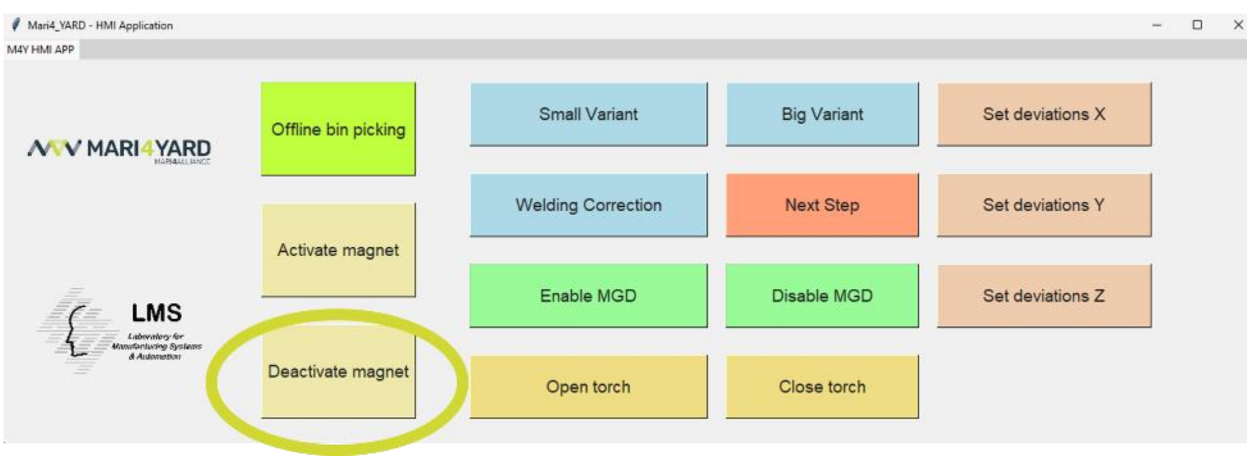


3. Confirm the selected part by press ‘ESC’.
4. Enable manual guidance from the UI.

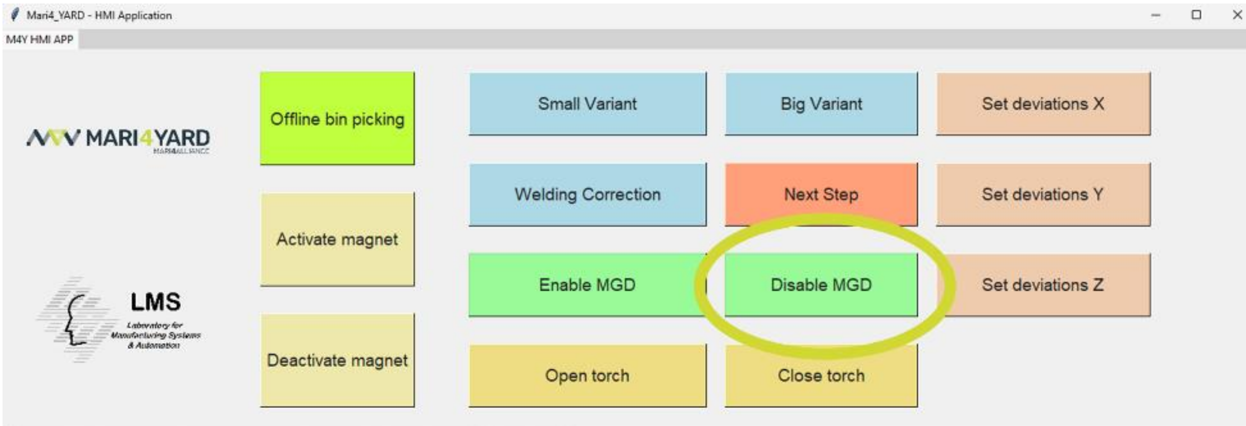


5. Place the part in the desired position using manual guidance.

6. Detach the part from the magnet after the manual tack welding.



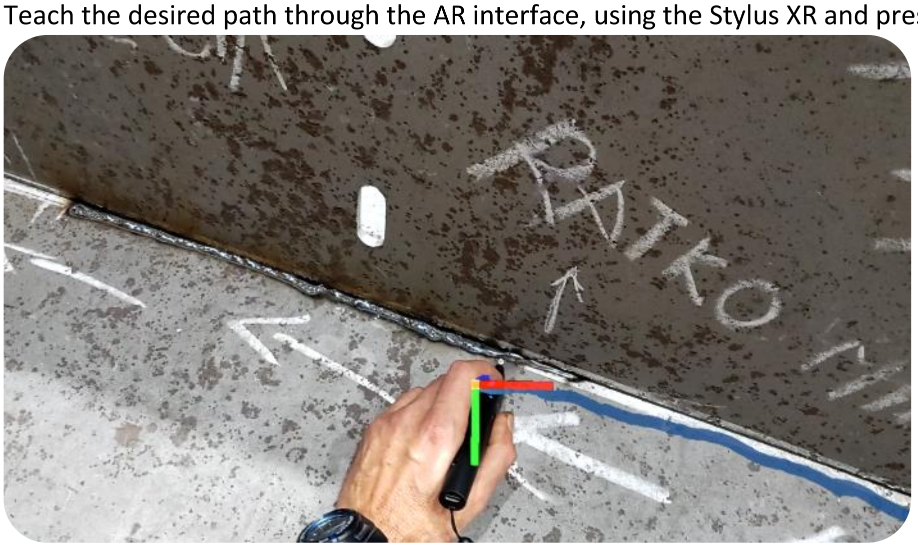
7. Deactivate manual guidance from the UI.



8. Select the welding process from the UI.

9. Select the path teaching from the UI in the AR interface.

10. Teach the desired path through the AR interface, using the Stylus XR and press the back button to start



11. Confirm the path through the AR interface.

12. Use the ‘Send to Robot’ voice command to send the path to the robot.

2.6.6 Potential disadvantages

There are a number of shortcomings presented below, related to the nature of the process and the nature of the technologies:

- Augmented reality path teaching for robotic welding is challenging due to AR environment limited calibration accuracy (*machine vision is used to correct inaccuracies*)
- Speed and Separation Monitoring Human-Robot Collaboration might be in a number of occurrences difficult to implement to guarantee that all safety precautions are taken into allowance without compromising productivity.
- Machine vision for bin picking is difficult to be applied in parts with high differentiation.

2.6.7 Potential risks/barriers

Technical

- Difficulties in highly accurate AR system calibration
- Difficulties in bin picking systems for variants with many differences
- Difficult safety measures application

Economic

- High initial investment for purchasing safety compliant robots for speed and separation HRC, for AR headset and special for the safety equipment/devices.
- Cost on training personnel
- Cost on maintaining used equipment

Social

- Personnel is not always familiar with digital technologies. Workforce upskilling and continuous learning/training is required.

Legal (Rules, regulations)

- Strict regulation on deploying safe HRC systems (ISO 13849-1:2023, ISO 13849-2:2015, ISO 10218-1:2011, ISO 10218-2:2011, ISO/TS 15066:2016)

2.7 Technology: High-precision projection

2.7.1 Description

The spatial augmented reality system relies on a projector with a 3D sensor mounted on a wheeled tripod for assisting human operators performing marking, cutting and assembly operations on ship's structures. The projection system lowers the amount of operator measurement errors and improves productivity, because the operator no longer needs to analyse the ship schematics, make environment measurements and perform surface markings for preparing the cutting and welding operations. Instead, the operator only needs to load the ship section CAD model, move the projector tripod to the target ship structure and trigger the projection system.

The system has several software modules, which include computer vision algorithms for performing the initial hardware calibration in the setup phase, while relying on a 3D perception system, a 3D rendering library and a GUI during the deployment phase, for providing an intuitive interface that the operator can use to quickly load new CAD models, trigger the 3D perception module and project task-oriented information into the environment for marking, cutting and assembly operations.

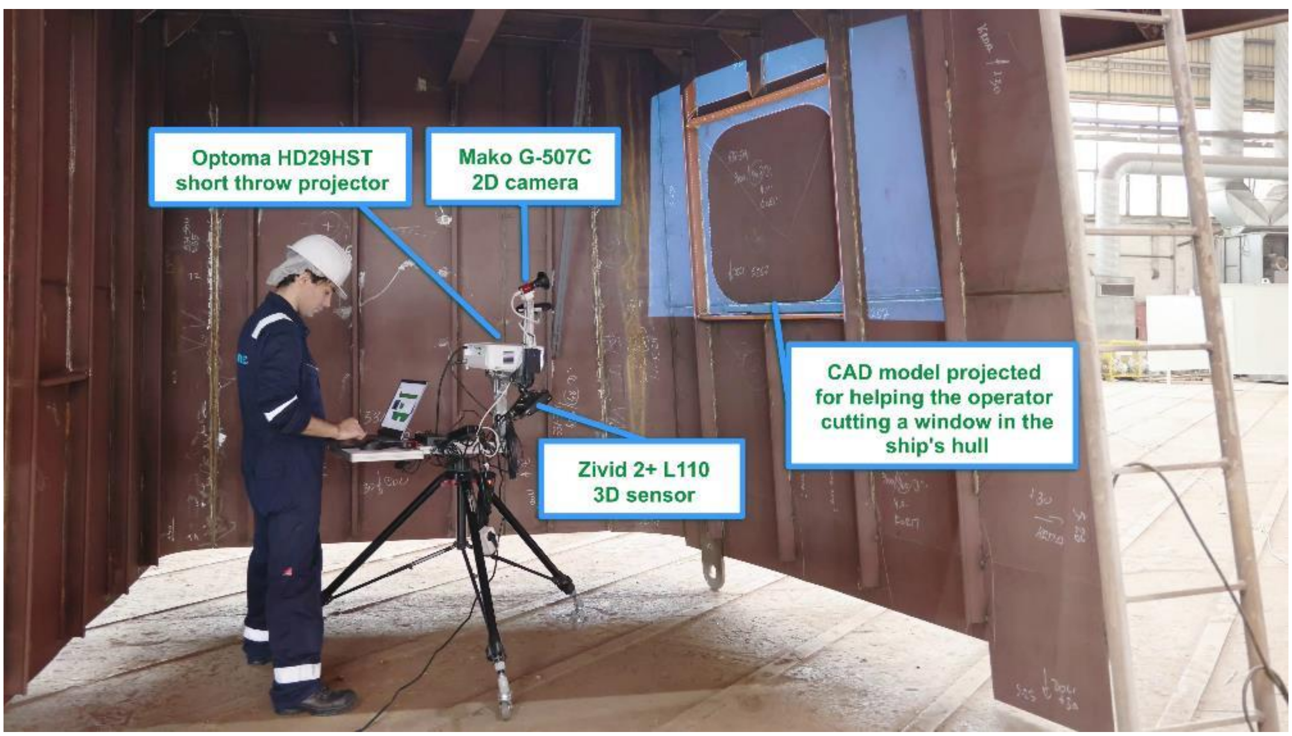


Figure 41. High- precision projection system.

2.7.2 Potential Applications

Shipbuilding is a complex and arduous industry that has a lot of manual work, with associated documentation and specifications that evolve during the planning, designing and construction phases. As such, tools that make the documentation easier to use and less prone to human error can reduce the amount of rework necessary and improve overall productivity. With these goals in mind, the projection mapping system was developed to provide an immersive Human-Machine Interface for helping human operators perform marking, cutting and assembly operations. The immersive interface enables the direct transmission of the design specifications into the environment, and as such, allows the human operators to perform these tasks faster, more accurately and with fewer mistakes, without relying on error-prone measuring devices and printed documents.

2.7.3 Replicability

Considering the application context described, the developed solution can be applied in many different scenarios in shipbuilding and in other relevant industrial use cases, such as construction and metalworking, guiding the operator during cutting, welding, drilling, assembly and other related activities.

2.7.4 Expected benefits

Economic benefits

- Avoids the usage of printed drawings and manual measuring tools.
- Improves reliability and process efficiency.
- Reduces operator errors leading to less rework.

Sustainability

- Reduction of errors and need for rework, which also translates in a reduction on the consumed raw materials, energy and other associated resources.
- Reduction of the number of printed drawings.

Societal benefits

- Advanced technology will support workers, making them feel more valuable to the company and increase their satisfaction and valorisation.
- Reduction in the level of attention/focus required to execute the tasks. Less anxiety, less stress, less fatigue.
- The calibration and operation of the system do not require advanced users with extensive knowledge. A short user manual and quick hands-on practice are sufficient for training new users of the projection system.

2.7.5 Guidelines for the application of the solution

- 3D models of the structure, containing the information to be projected are required.
- Due to the use of a DLP projector, the surface where the information will be projected should not be under direct sunlight.
- The recommended projection area for maintaining projection error below 5 mm should be around 2.5 by 1.4 meters. The projection error will increase with a wider projection area.

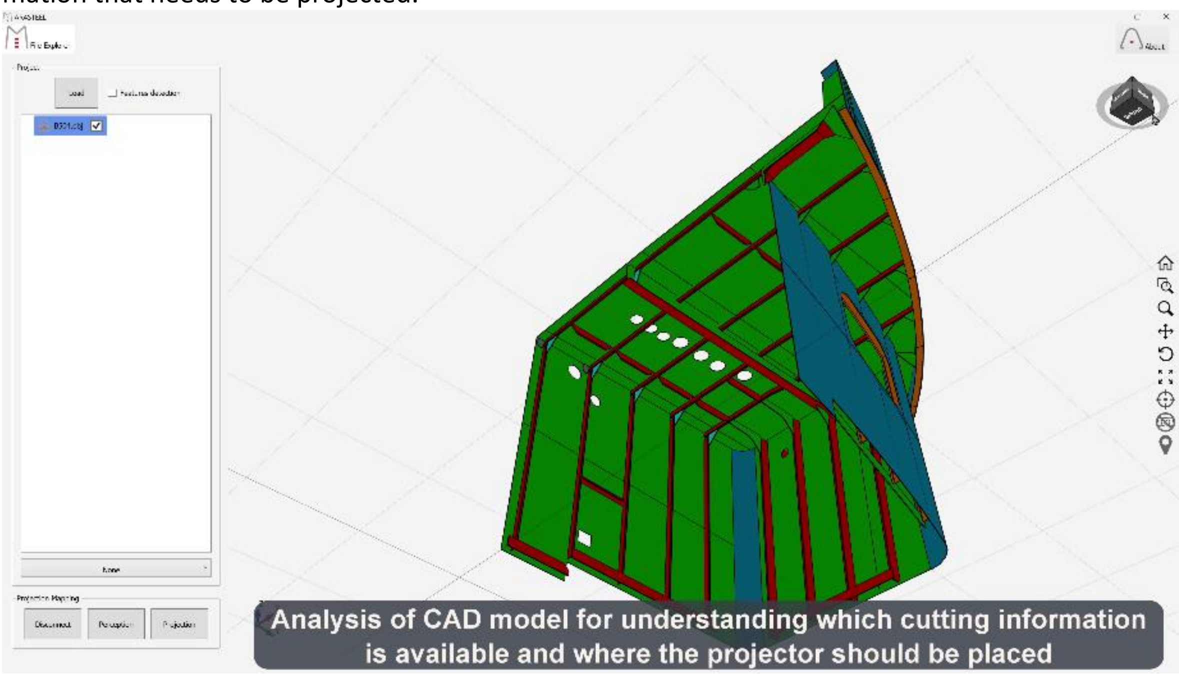
System deployment

A short overview of the operation of the projection system can be seen in the video below:

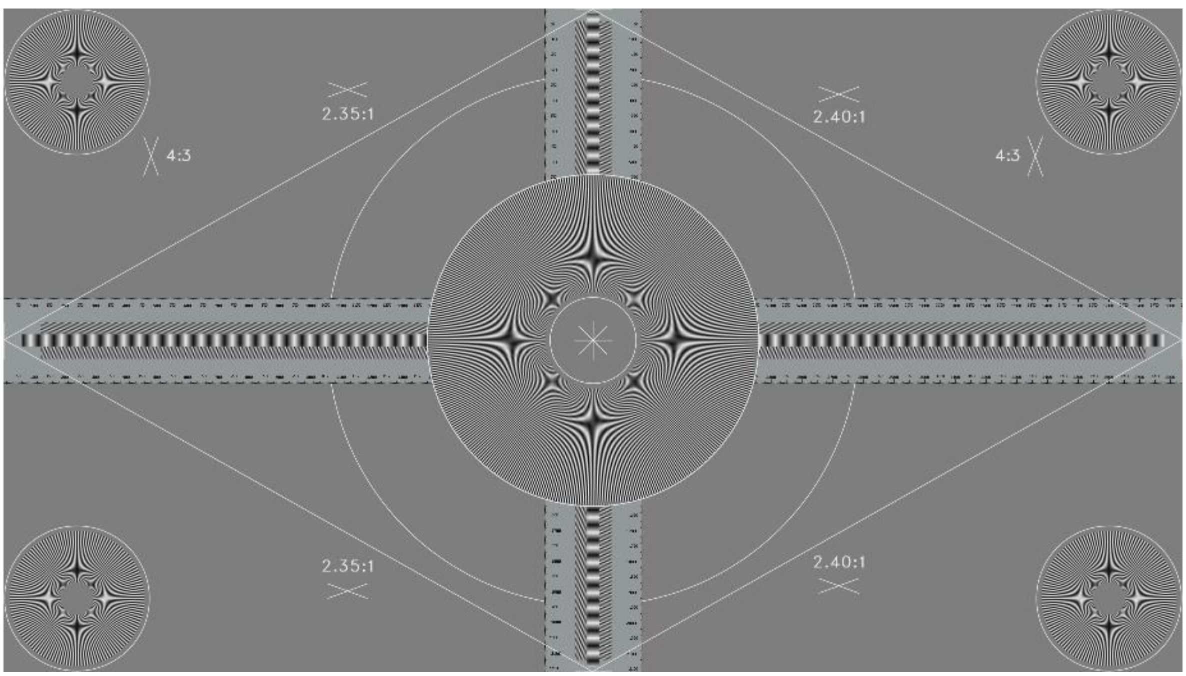
https://www.youtube.com/watch?v=2VTDdGHoWj8

Below is a short user manual for operating the projection system:

1. Turn on the AC power for the laptop, projector and 3D sensor.
2. Open a terminal in Ubuntu and run the following command:
   rosrun pointcloud_registration_for_projection_mapping bringup_zivid_and_optoma.bash
3. Open VirtualBox, start the Windows 11 virtual machine and run the AR4Steel application, which will be the main GUI for the operator.
4. Click on the Load button on the top left corner of the GUI, open the CAD model and analyze the information that needs to be projected.

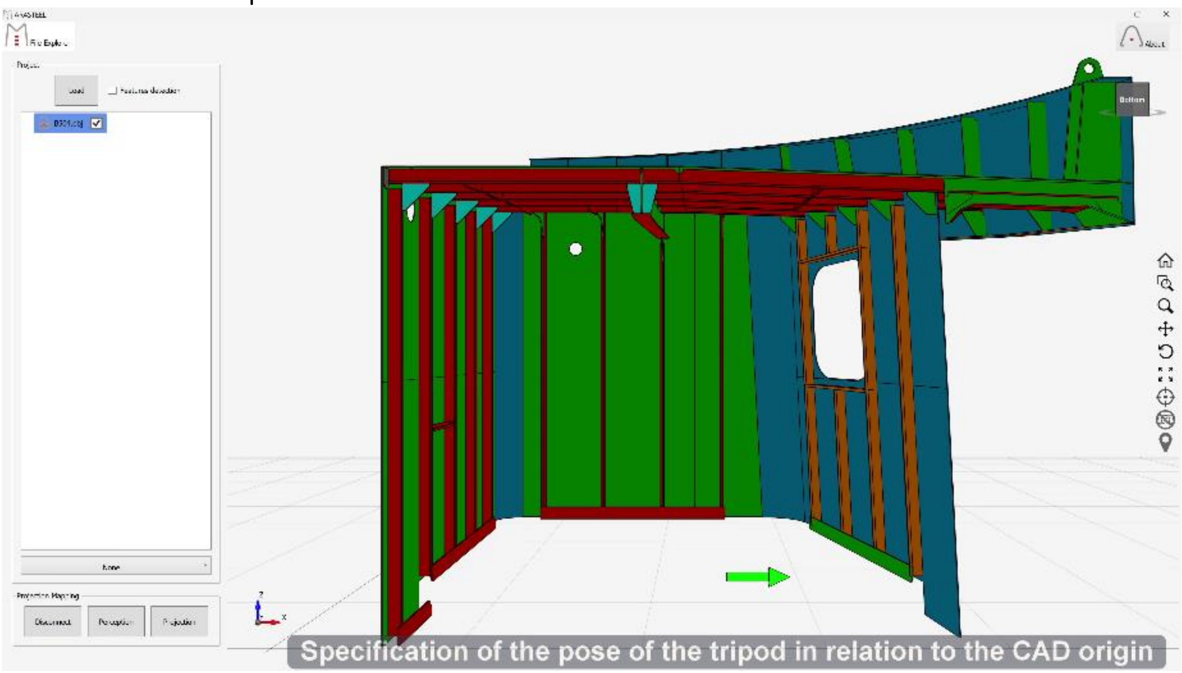


5. Click on the target icon on the side bar of the GUI (on the right) for projecting the guiding pattern shown below, which helps visualize the centre of projection and the field of view of the projector. This pattern is used for making it more intuitive to the operator to move the tripod to a pose that has the field of view necessary to project the desired information on the ship's structure.

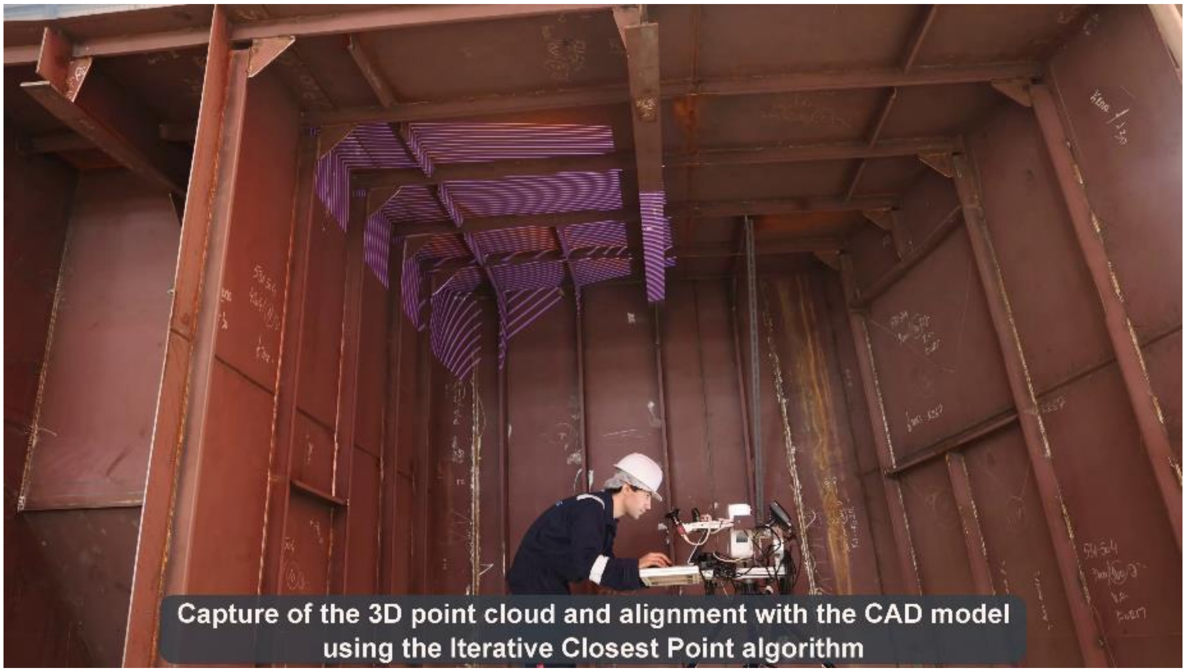


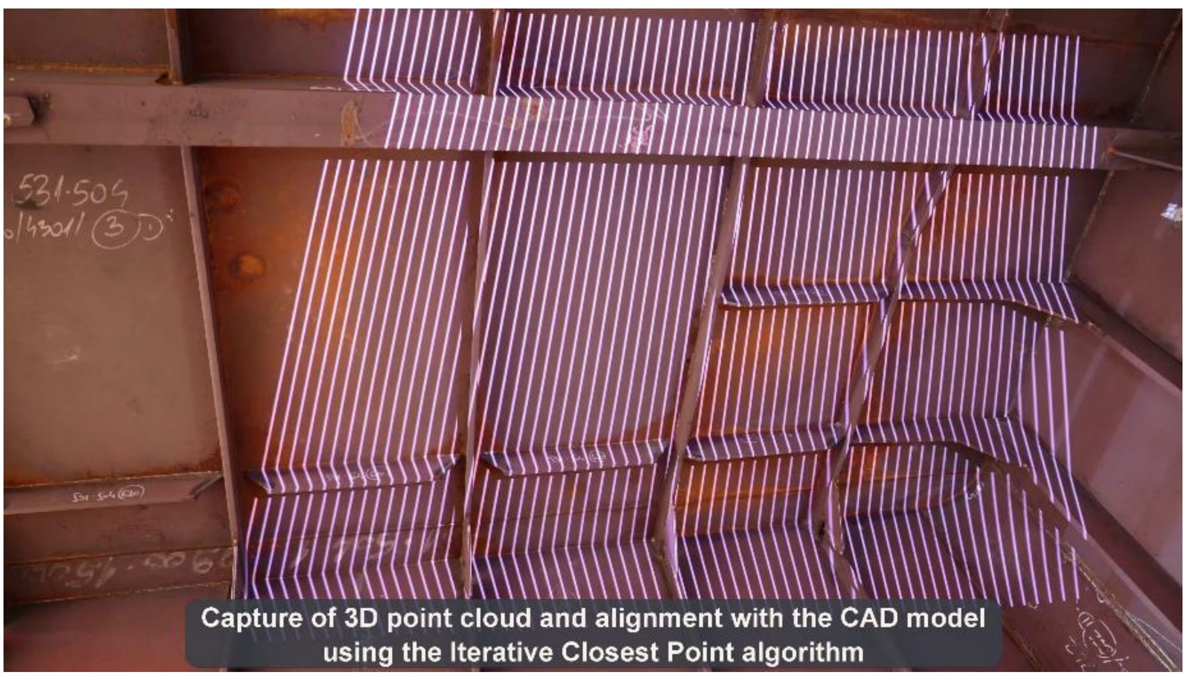
6. Specify an approximate initial pose of the projector wheeled tripod in relation to the CAD origin, by clicking on the landmark icon on the side bar of the GUI (on the right) and then clicking on the GUI CAD plane for specifying the centre of the tripod base on the floor, followed by a second click of the mouse for indicating the tripod direction. This 6 DoF pose is used as an initial alignment for the Iterative Closest Point Algorithm (ICP) and as such, does not need to be very accurate. The precision of the projection will rely on the final alignment of the ICP algorithm and will depend on the overlap of the CAD model and the 3D point cloud (it should be noted that the physical ship's structure is slightly different than the CAD model due to construction and assembly tolerances and also hull bending due to welding. As such, the

higher the deviation of CAD vs reality, the higher the alignment overlap error will be and the projection error will also increase). This step is necessary because a ship may have a lot of subsections with similar geometry and given the limited field of view of the 3D sensor, the operator needs to provide a rough initial pose for allowing the 3D perception system to achieve an alignment that converges to the correct subsection of the ship.

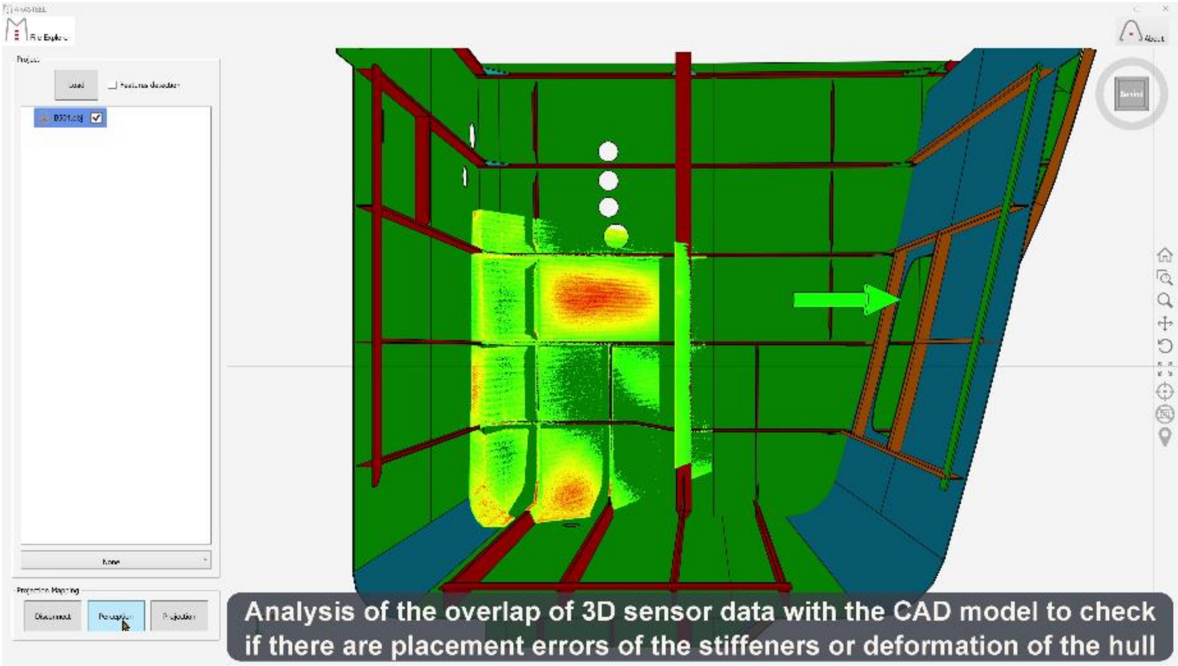


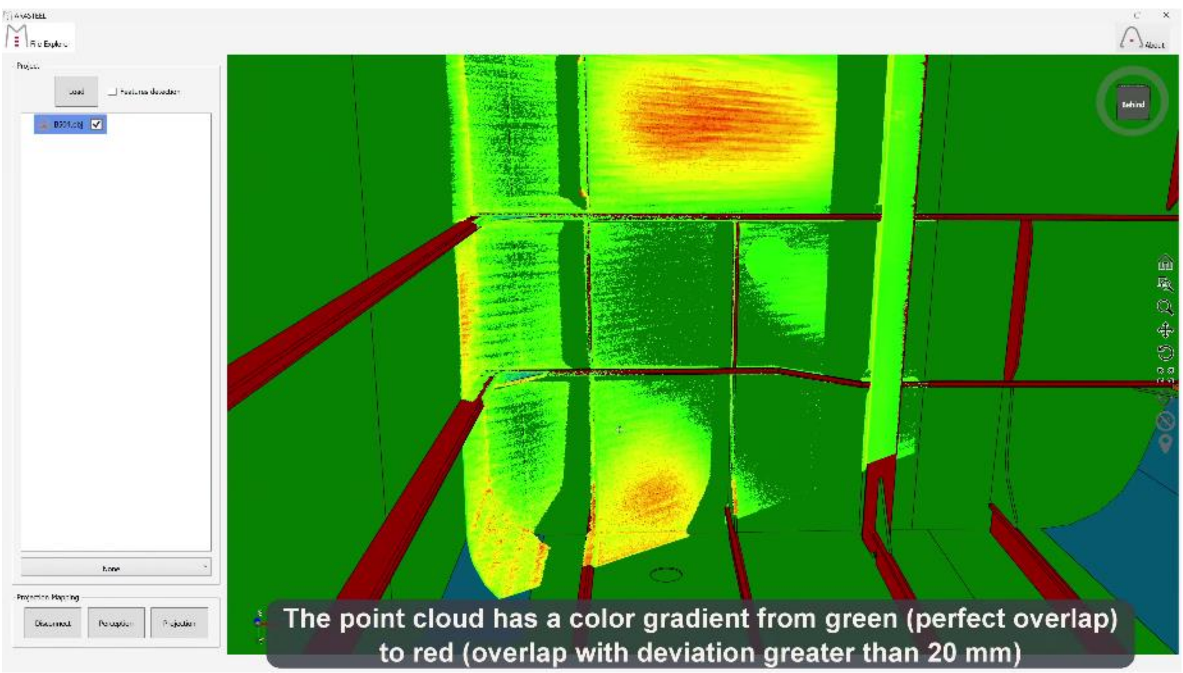
7. Click on the Perception button on the bottom left corner of the GUI for triggering the capture of the 3D point cloud and start its alignment with the CAD model.



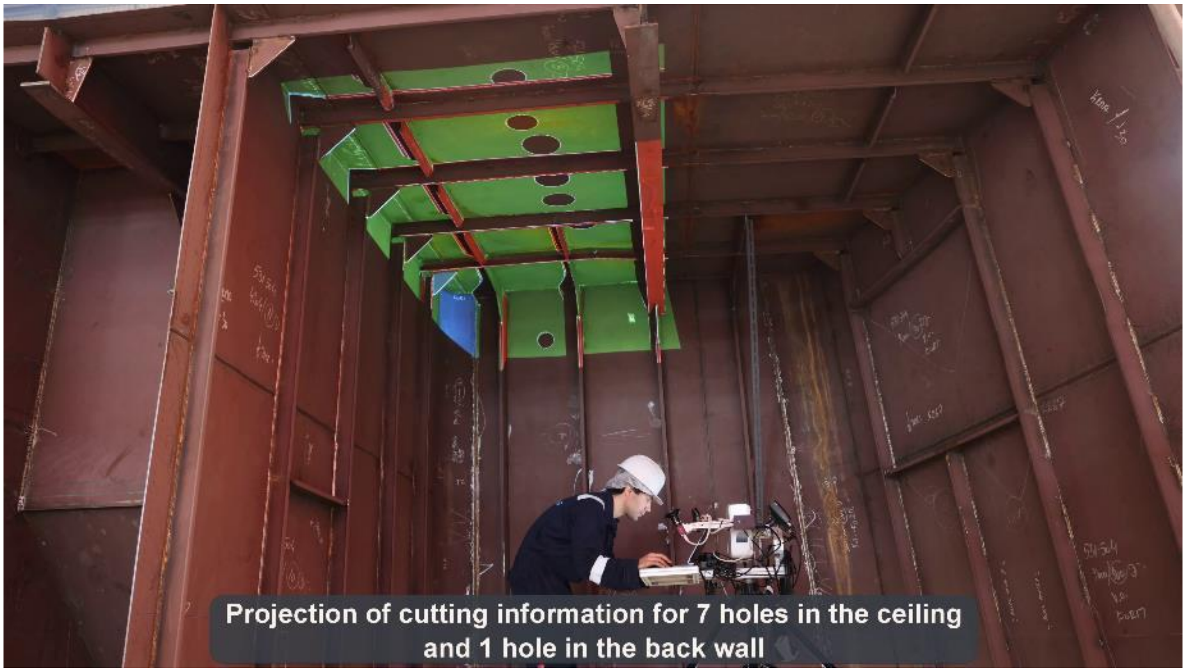


8. After the alignment is done, analyse on the GUI the point cloud colour gradient, that represents the overlap between the point cloud and the CAD model. Points with red colour have an overlap deviation above 20 mm, while points with green colour have perfect overlap. This colour gradient can be useful to spot stiffeners that have high error of assembly placement and also check the bending of the ships hull due to welding.





9. Finally, click on the Projection button on the bottom left corner of the GUI to project the information into the ship's surfaces. Below is an example of projection of information for cutting 7 holes on the ceiling and 1 hole on the back wall.



2.7.6 Potential disadvantages

- The system needs to be transported by the human operator. It is heavier when compared with other AR approaches based on hand/head-held devices.
- It could be difficult to be used in very confined spaces. This might happen with hull openings, because sometimes they will not be defined until the associated equipment is contracted, and it could be after the hull and block assembly phase.

- The physical state of the ship has small deviations in relation to the 3D CAD model due to construction and assembly errors and structures bending due to welding. These errors are typically below 10 mm. If these errors are much higher, they will influence the precision of the projected information, since the 3D perception system uses the ship's stiffeners to perform relative 6 DoF alignment and projection.

2.7.7 Potential risks/barriers

Technical

- It requires a 3D model of the structure of interest, where the information to be projected is already represented.
- Requires a relatively flat surface for the tripod to be mounted.
- Projection should be done on relatively flat surfaces. Surfaces that have a large depth range may cause the projected information to be out of focus due to the limited depth of focus of the lens of the projector.

Economic

- The return of investment will be faster if there are a lot of cutting operations in which the projector can be used without the need to be moved a lot. For very few operations and in hard to move ship zones, it might be faster to rely on the traditional methods.

Social

- Generating the CAD models and PLY point clouds requires knowledge of software capable of manipulating CAD, mesh and point cloud models. It might require the upskilling of the workforce.

2.8 Technology: Cost-effective projection

2.8.1 Description

This system extends the workers capabilities to perform semi-autonomous operations at the pre-fabrication and outfitting stages. The aim is to replace the traditional paper-based drawings and project such drawings on the target with accuracy and precision.

Scanning the area: This feature is exercised with the help of the pan-tilt unit and low cost RGB-D camera.

Localization algorithm: It consists of matching the point cloud acquired in the scanning phase with the CAD of the area by user initial guess, ICP algorithm, and projection of elements.

2.8.2 Potential Applications

Projection systems in construction and retrofitting increase productivity and efficiency. They are ideal for small and medium-sized manufacturers dealing with low-volume, high-mix production. These systems reduce paper documentation and human errors, allowing technicians to focus on operations. They also serve as a quick verification tool for new designs and features. Mari4_YARD's projection technologies work in shared spaces, reducing the chance of impact with human co-workers.

2.8.3 Expected benefits

Before any outfitting projector could make hull cut-outs for pipes and other equipment. In that way there is no time lost afterwards, when those equipment was really scheduled to be installed (and found out that hull cut-outs are not being open).

Economic benefits

- Avoids the usage of printed drawings and manual measuring tools.
- Improves reliability and process efficiency.
- Reduces operator errors leading to less rework.

Sustainability

- Reduction of errors and need for rework, which also translates in a reduction on the consumed raw materials, energy and other associated resources.
- Reduction of the number of printed drawings.

Societal benefits

- Advanced technology will support workers, making them feel more valuable to the company and increasing their satisfaction and value.
- Reduction in the level of attention/focus required to execute the tasks. Less anxiety, less stress, less fatigue.
- The calibration and operation of the system do not require advanced users with extensive knowledge. A short user manual and quick hands-on practice are sufficient for training new users of the projection system.

2.8.4 Guidelines for the application of the solution

- Prerequisite compliance
- System deployment
- Software installation
- System start-up and GUI

These guidelines are explained in more detail below:

Requirements

To use the projection system on the PanTilt unit, the following requirements must be met:

- Electrical connection of 220 volts and 50 hertz AC power.
- Computer equipped with GPU and ROS Noetic.
- Horizontal ferromagnetic surface of at least 0.5 x 0.5 meters.
- Projection distance between 2 and 3 meters.

- On the software side, packages and dependencies need to be installed. This process is automated through the installer, and this aspect will be addressed again later.

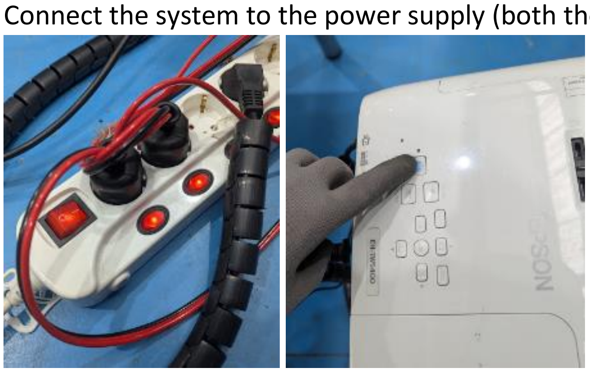
System deployment

To set up the system, please follow these steps:

- Place the system on the ferromagnetic surface (floor or ceiling) and activate the electromagnet located on the bottom of the unit by pulling the lever.

- Turn on the computer.
- Connect the PanTilt unit's USB controller to the computer, along with the USB for the Zed2i camera, and the projector HDMI.

- Connect the system to the power supply (both the power source and projector), and turn on projector



Software installation

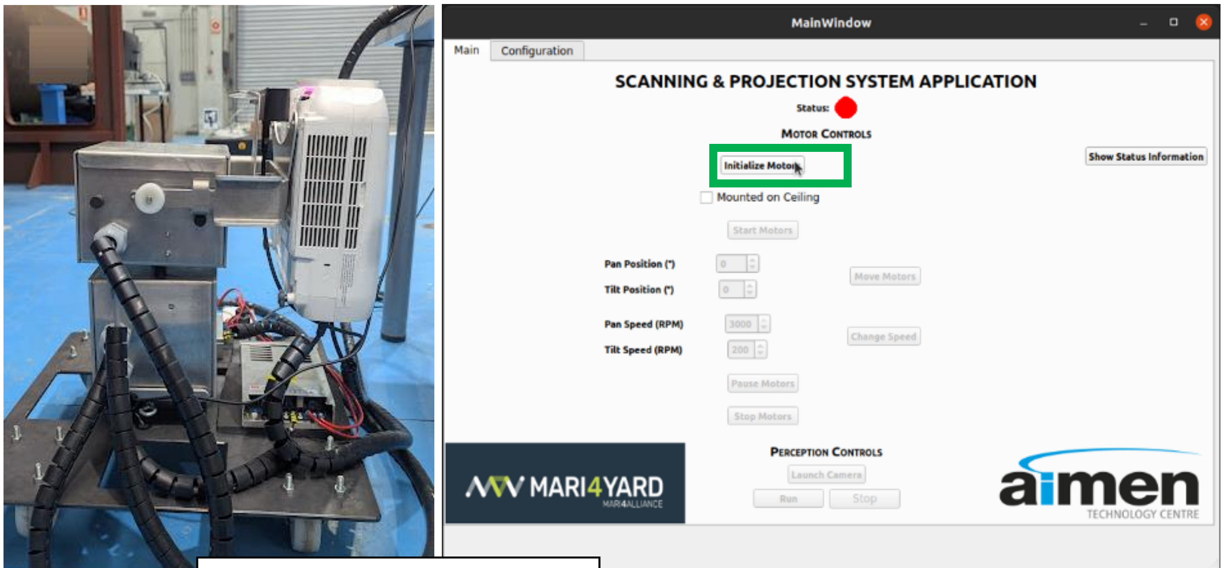
To install all the software required for using the system, open a terminal and run the installer with the following commands. Make sure you are in the same directory as the provided installer file.

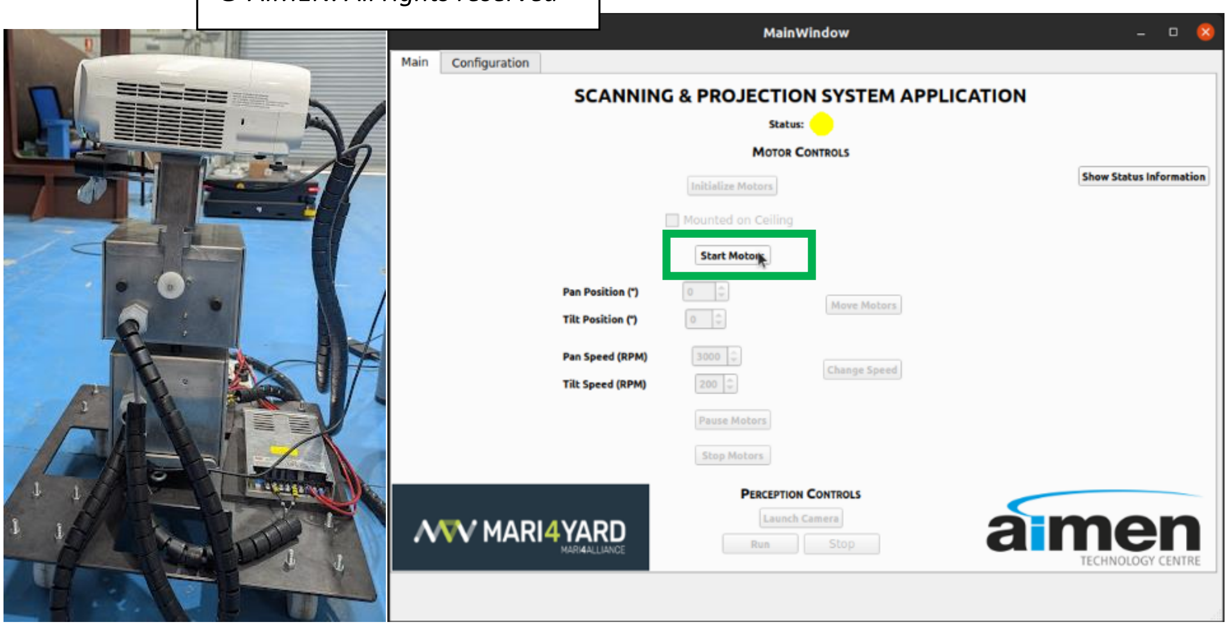
```
chmod +x install.sh

./install.sh
```

System Start-up and GUI

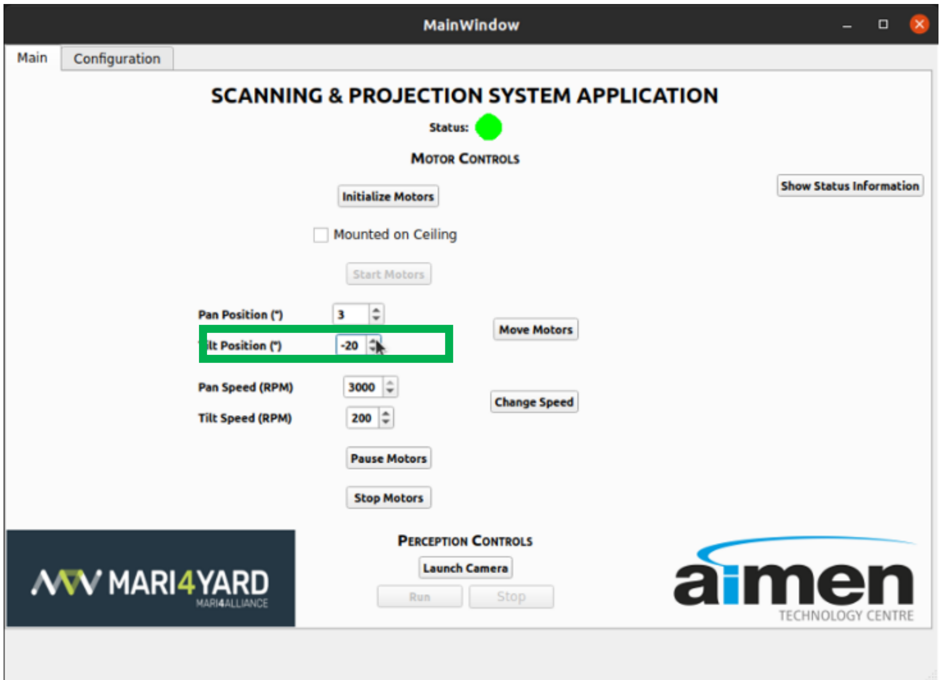
Once the system has been deployed with all components installed and configured, the system startup can proceed. From this point on, everything will be managed through the graphical user interface (GUI). The steps to follow are as follows:

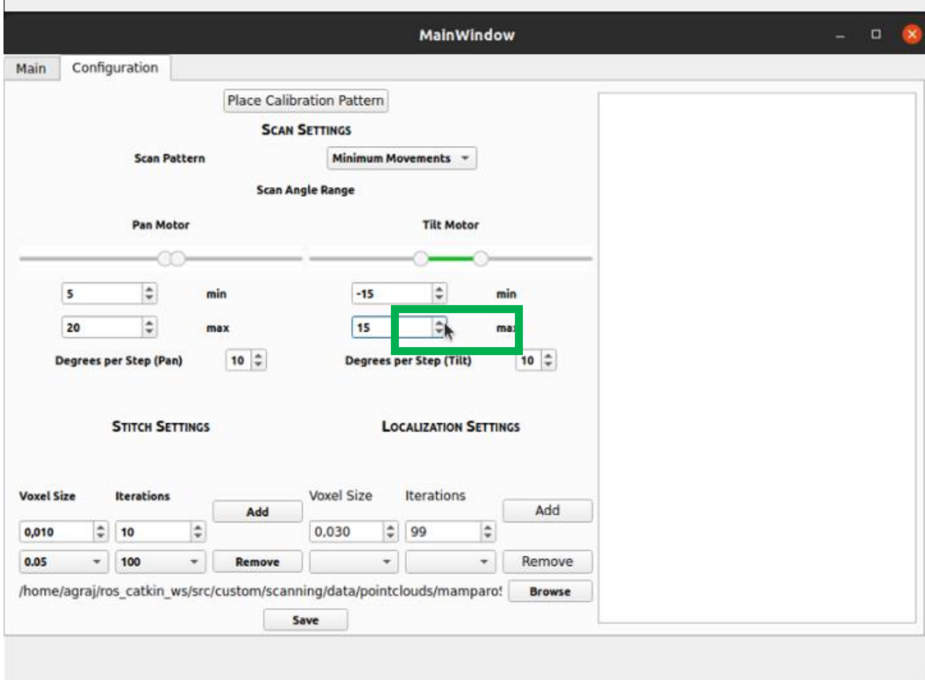
1. Initialize the motors.



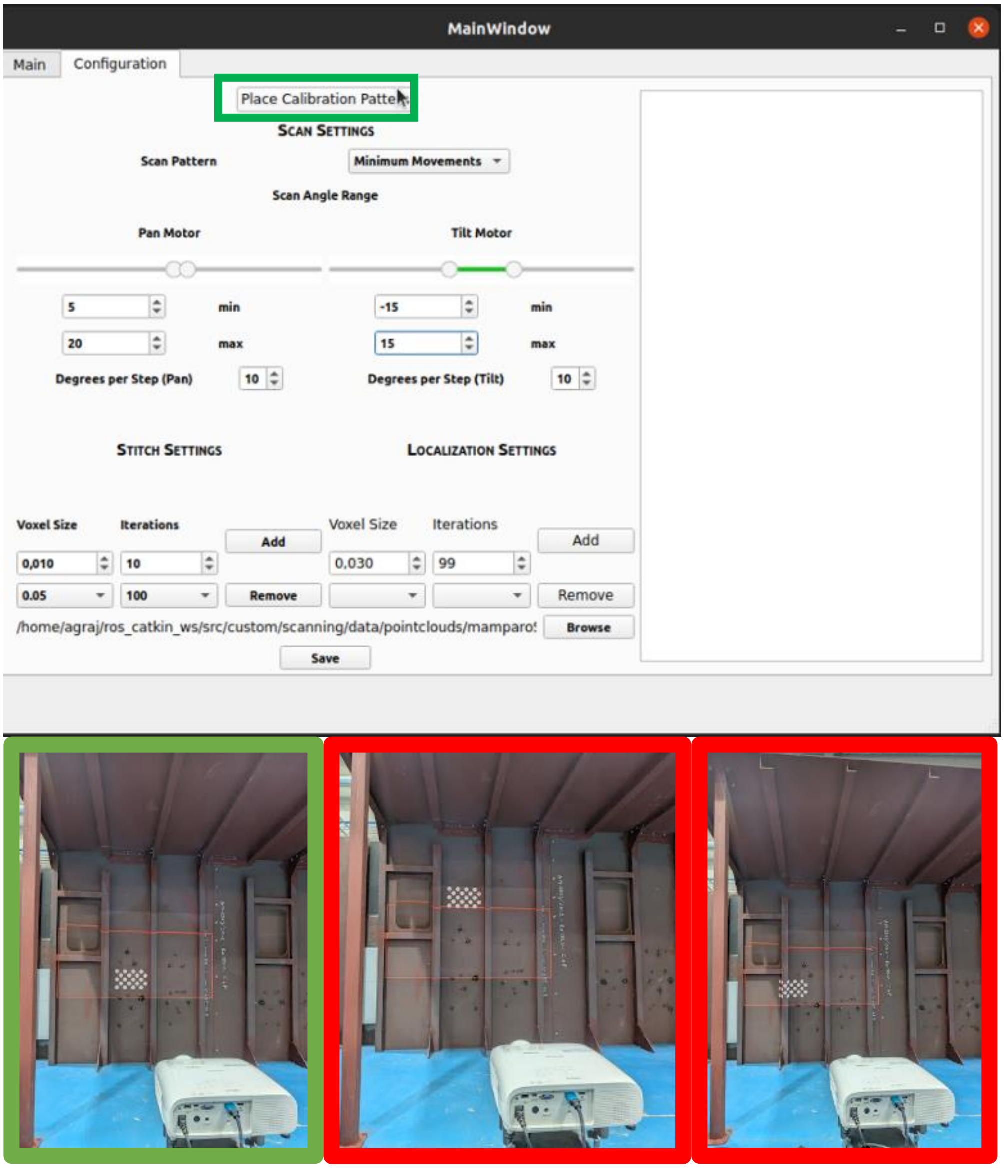


2. Set up the preliminary configurations.

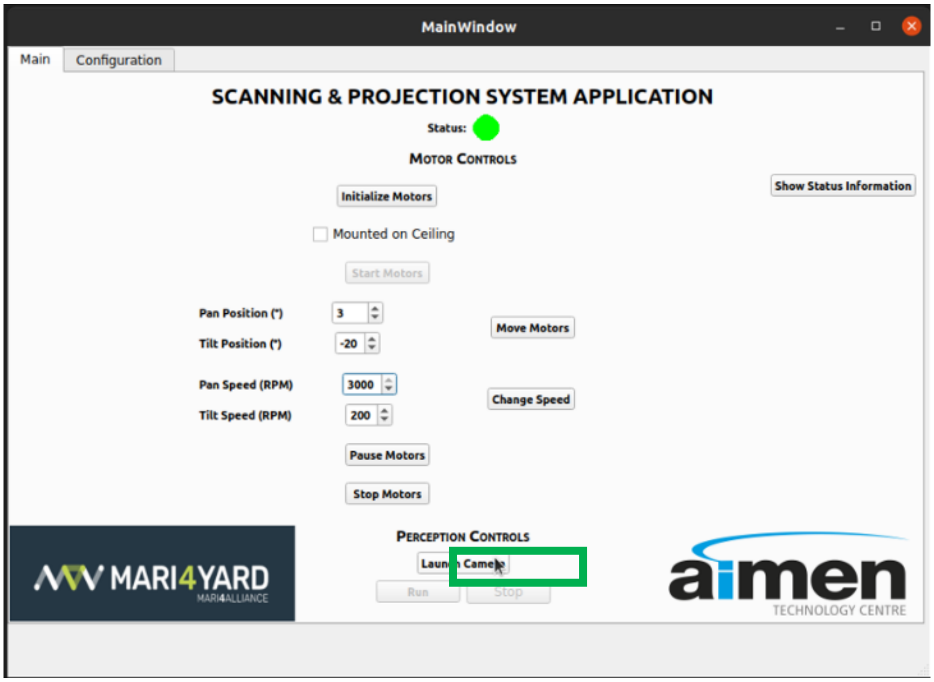




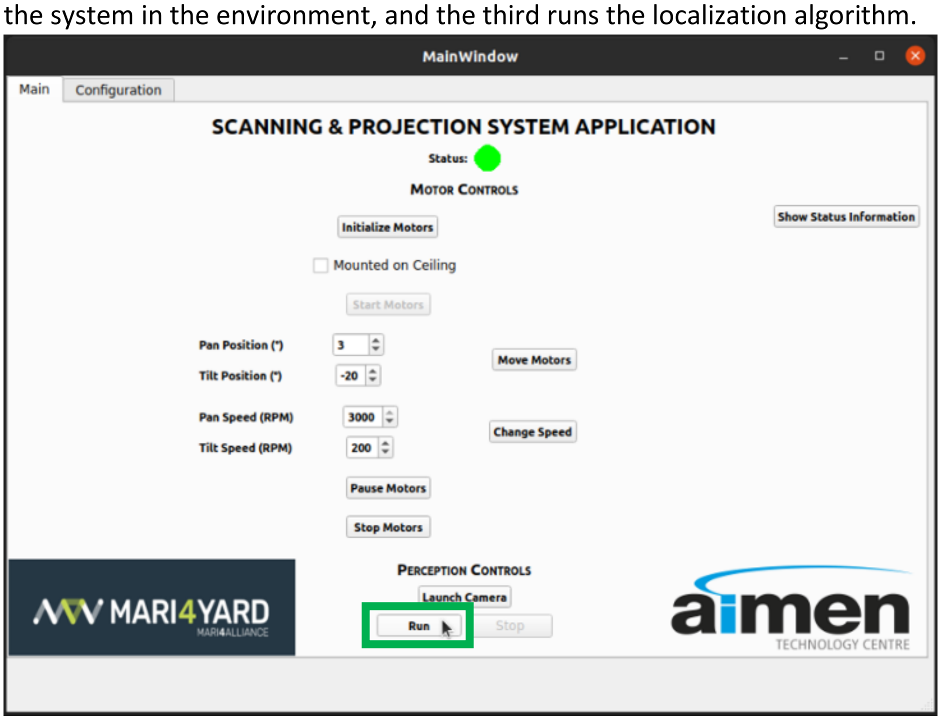
3. Define the location of the calibration pattern. The calibration pattern must be inside the red rectangle and on the main projection surface, as shown in the first photo below. The other photos are examples of incorrect calibration patterns.

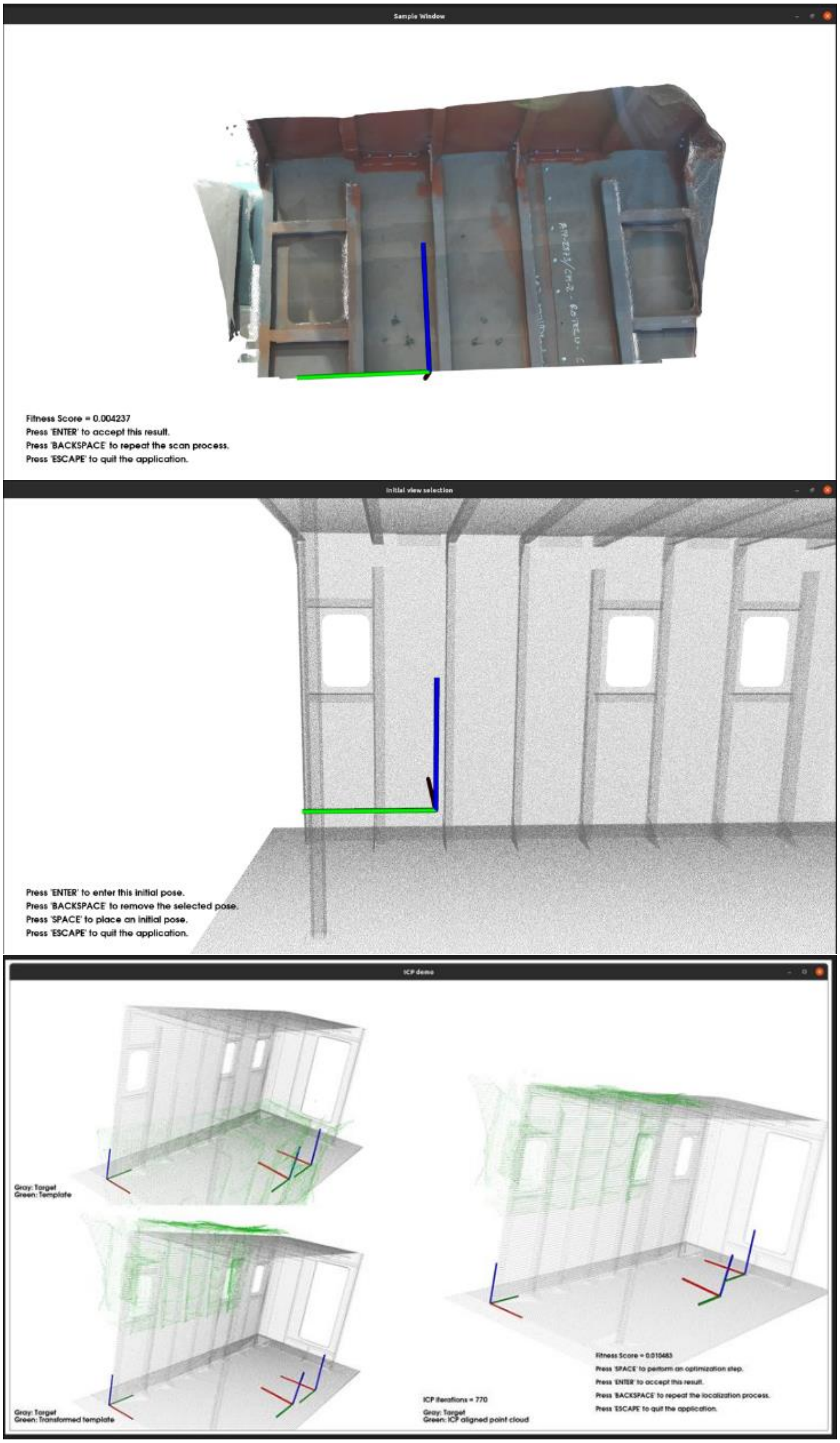


4. Launch the camera.



5. Execute the scan: once started, the scan of the selected area begins automatically. Several screens will appear: the first displays the obtained scan, the second provides an initial approximate localization of the system in the environment, and the third runs the localization algorithm.




Sample Window
Fitness Score = 0.004237
Press 'ENTER' to accept this result.
Press 'BACKSPACE' to repeat the scan process.
Press 'ESCAPE' to quit the application.
Initial view selection
Press 'ENTER' to enter this initial pose.
Press 'BACKSPACE' to remove the selected pose.
Press 'SPACE' to place an initial pose.
Press 'ESCAPE' to quit the application.
ICP demo
Gray: Target
Green: Template
Gray: Target
Green: Transformed template
ICP iterations = 770
Gray: Target
Green: ICP aligned point cloud
Fitness Score = 0.010483
Press 'SPACE' to perform an optimization step.
Press 'ENTER' to accept this result.
Press 'BACKSPACE' to repeat the localization process.
Press 'ESCAPE' to quit the application.

6. Finally, the projection is shown on the selected structure.

The following screenshots show the graphical user interface (GUI) of the system. It has 2 tabs, the main control tab and the configuration window, which contains various parameters for the operation of the system.

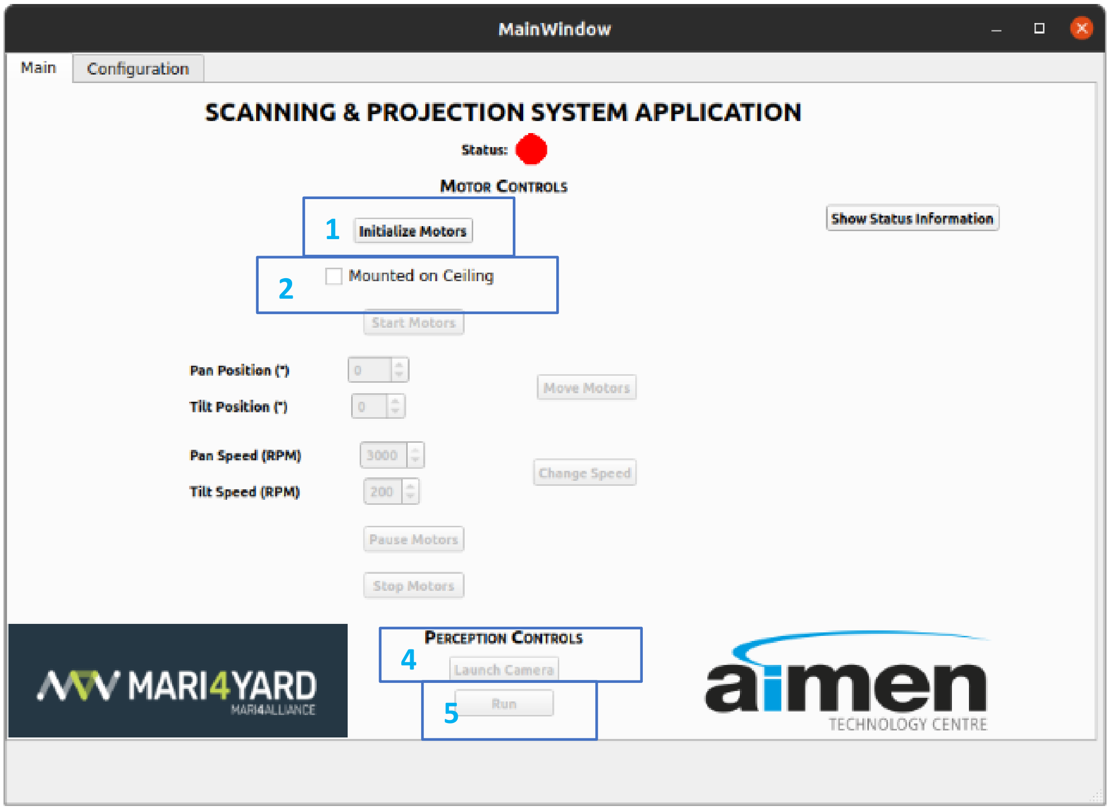
In the main control tab you can, in addition to the steps described previously, stop the system or monitor the system, using its coloured LED or its information subwindow.

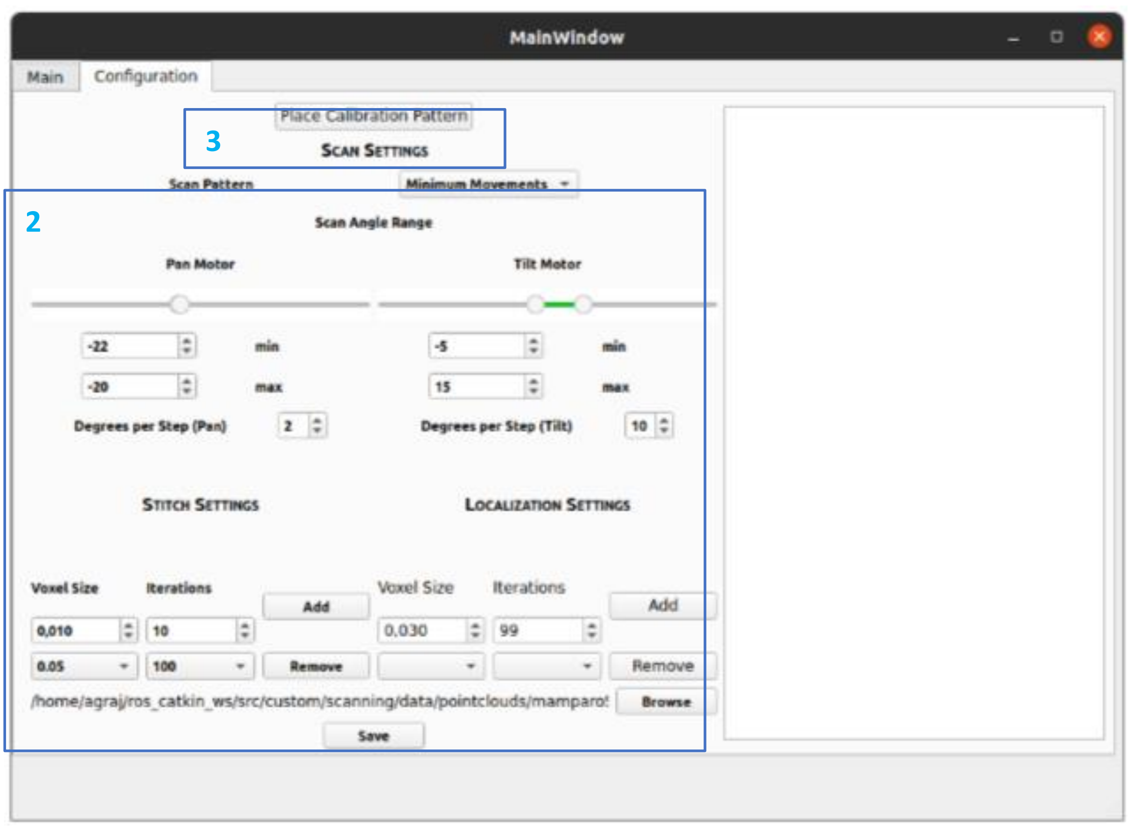
In the configuration window, under scan settings, the following parameters can be modified:

- Scan Pattern. Modifies the path to follow to reach the desired scan locations.
- Scan Angle Range. Defines the limits to the motor movements during scanning.
- Degrees per Step. Configures how many angles the unit should move between scan locations.

In the configuration window, under stitch and localization settings, the following parameters can be changed:

- Voxel Size. Defines the voxel size for the ICP algorithm.
- Iterations. Defines the number of iterations for the ICP algorithm.


MainWindow
Main
Configuration
SCANNING & PROJECTION SYSTEM APPLICATION
Status:
MOTOR CONTROLS
1
Initialize Motors
Show Status Information
2
Mounted on Ceiling
Start Motors
Pan Position (°)
Tilt Position (°)
Move Motors
Pan Speed (RPM)
3000
Tilt Speed (RPM)
200
Change Speed
Pause Motors
Stop Motors
MARI4YARD
MARI4ALLIANCE
PERCEPTION CONTROLS
4
Launch Camera
5
Run
aimen
TECHNOLOGY CENTRE


MainWindow
Main
Configuration
Place Calibration Pattern
3
SCAN SETTINGS
Scan Pattern
Minimum Movements
2
Scan Angle Range
Pan Motor
Tilt Motor
-22
min
-20
max
-5
min
15
max
Degrees per Step (Pan)
2
Degrees per Step (Tilt)
10
STITCH SETTINGS
LOCALIZATION SETTINGS
Voxel Size
Iterations
Add
0,010
10
0.05
100
Remove
Voxel Size
Iterations
Add
0,030
99
Remove
/home/agraj/ros_catkin_ws/src/custom/scanning/data/pointclouds/mamparo!
Browse
Save

2.8.5 Potential disadvantages

- The system needs to be transported by the human operator. It is heavier when compared with other AR approaches based on hand/head-held devices.
- It could be difficult to be used in very confined spaces. This might happen with hull openings, because sometimes they will not be defined until the associated equipment is contracted, and it could be after the hull and block assembly phase.
- The physical state of the ship has small deviations in relation to the 3D CAD model due to construction and assembly errors and structures bending due to welding. These errors are typically below 10 mm. If these errors are much higher, they will influence the precision of the projected information, since the 3D perception system uses the ship's stiffeners to perform relative 6 DoF alignment and projection.

2.8.6 Potential risks/barriers

Technical

- Issues that may be overcome and possible mitigation measures. Sometimes the problem with hull openings is that they are not defined until equipment is contracted, and it could be after hull and block assembly phase. Sometimes the actual state on field does not correlate with 3d model (from which we take positions of openings). correlation of model and reality must be kept at high levels, along with equipment contracting which should be known before hull assembly.
- It requires a 3D model of the structure of interest, where the information to be projected is already represented.
- Requires a relatively flat surface for the tripod to be mounted.
- Projection should be done on relatively flat surfaces. Surfaces that have a large depth range may cause the projected information to be out of focus due to the limited depth of focus of the lens of the projector.

Economic

- The return of investment will be faster if there are a lot of cutting operations in which the projector can be used without the need to be moved a lot. For very few operations and in hard to move ship zones, it might be faster to rely on the traditional methods.

Social

- Generating the CAD models and PLY point clouds requires knowledge of software capable of manipulating CAD, mesh and point cloud models. It might require the upskilling of the workforce.

Legal (Rules, regulations)

- Not foreseen.

2.9 Technology: AR with head-mounted device

2.9.1 Description

Shipyard workers are equipped with ruggedized HMD (head-mounted devices) that are attached to safety helmets and having connectivity, monocular camera, microphones, noise cancellation algorithms and TTPSC SkillWorx system leveraging computer vision and remote SLAM. That setup gives the workers full hands-free experience to check, record and document construction progress, completion, and quality of delivered work and follow digital work instructions.

The system serves as a source of information for field workers during on-the-job activities.

Main benefits:

- Act as fast as possible during real-time supervision, troubleshooting, inspections, repairs, reviews.
- Access to the right information without sacrificing worker safety nor comfort.
- Streamlined communication and collaboration during field work with increased transparency and situational awareness.

Figure 42. Operator using the AR Head mounted device

2.9.2 Potential Applications

HMD App: Navigate workers within physical environment using spatial intelligence – application streams video feed to remote SLAM server to build in real-time 3D map that allows onsite and remote workers to tag and overlay information on the real 3D world while also maintaining safety, situational awareness, low eyestrain, hands-free use, and full-shift battery life.

Web App: Collaboration endpoint for over- the-shoulder help during construction, inspection, repair, trouble-shooting, review etc. as remote assistance enriched with real-time AR (when onsite worker and remote supporters can collaborate and place sticky, pervasive AR annotations on a live video). AR is placed on video from ultra-low bandwidth low resolution up to 4K and is stored in the form of reusable 3D maps.

2.9.3 Replicability

Remote knowledge sharing solutions can be replicated in every shipyard as long as there is some connectivity provided between workers and remote mentor (GSM, Wifi). Digitalization of step-by-step procedures can be applied to any standard operating procedures (including training/maintenance/quality).

Overall solutions can be replicated to any industry (for instance automotive, machine producers, inspection services, maintenance etc.)

2.9.4 Expected benefits

Digitalisation of learning material should greatly improve the speed and repeatability of learning courses. One AR headset can contain a whole library of user manuals, regardless of the type of work (electrician, welder, maintenance, even project engineer).

Economic benefits

Solution boosts performance of worker thanks to providing contextual information.

It also reduces the time to perform duties and the need to travel.

Sustainability

Solutions can reduce human errors and scrap. It can also reduce the need to travel.

Societal benefits

It can increase worker's self-confidence if they know that they can reach digitalized knowledge and/or have access to remote expert. In general, the solution should increase comfort of work for human operators.

2.9.5 Guidelines for the application of the solution

For sure a dedicated training should be conducted for both technicians wearing monocular device and remote operators working on web browser tool.

Most important is to train technicians to reduce their barrier of using a wearable device and train them how to interact with it by voice commands. Dedicated training for Skillworx applications is needed to teach end users how to scan environments and how to place digital markers to improve communication with remote experts.

Video tutorials recorded during the final workshop demonstrations, explaining step by step how to use the solutions and its capabilities can be found following the links:

Part 1. Creation of an AR handbook. https://bit.ly/skillworx-aimen

Part 2. Use of AR handbook. https://bit.ly/skillworx-aimen-2

2.9.6 Potential disadvantages

At the current stage there are no disadvantages identified.

2.9.7 Potential risks/barriers

Technical

Network coverage is required (GSM/Wifi).

Economic

Device cost is around 2500 Euro. The additional cost for licence is around 200 Euro per user monthly (cost licence includes also infrastructure cost).

Social

Using wearable device may be a mental barrier for some people.

Legal (Rules, regulations)

There may be concerns on transmitting video stream and usage of such data.

2.9.8 Usage introduction

As long as connectivity is established and technicians are trained, the system is ready for use. Remote mentor should be accessible for incoming calls or there should be a calendar scheduling remote calls.

Best practice for digitalisation of procedures is to organize knowledge in a well-defined structure (for instance group procedures for specific welding machine).

2.10 Technology: AR with handheld device

2.10.1 Description

The technology is a user-centric tablet application for easy checking of construction progress in a designated construction area. In addition to this, a web application was developed to prepare and provide the data for the tablets and also serve as a user interface for clear evaluation of the progress recording.

The system serves as an additional source of information for the workers, while no special skills are required. Three main benefits that are to be expected:

- Faster recording of construction progress
- More precise recording of the progress
- Faster and more transparent communication of the actual progress

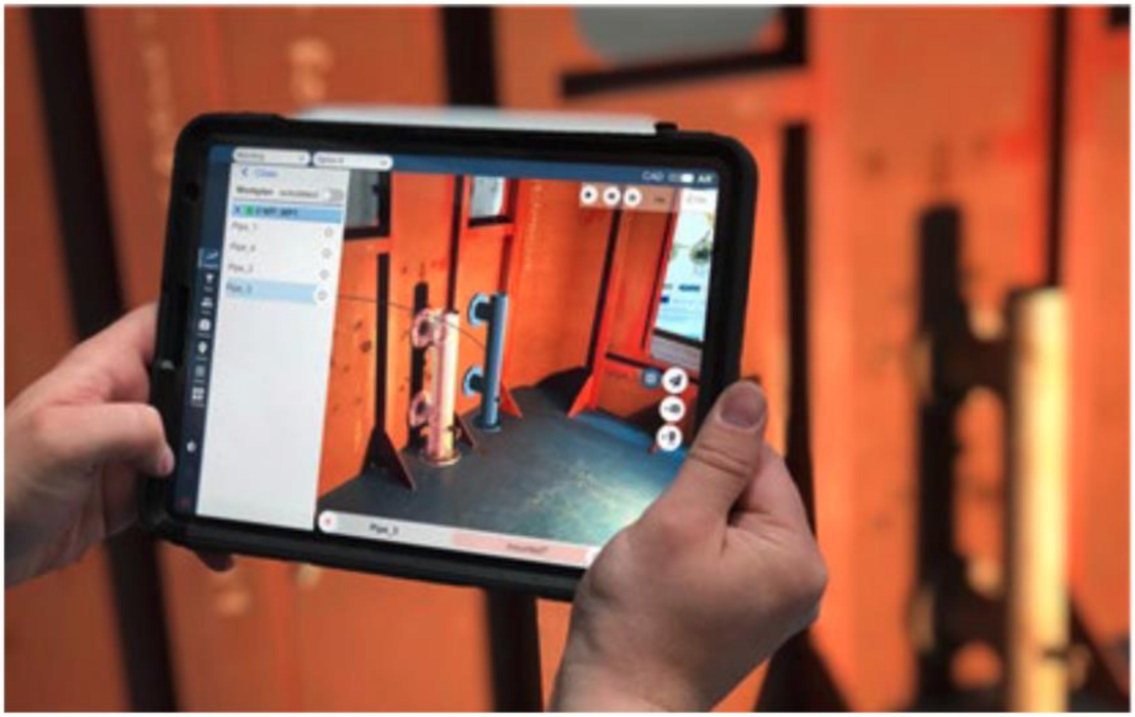


Figure 43. AR with handheld device. Operator using the table.

2.10.2 Potential Applications

The Web App can be filled manually or automatically by third party systems, e.g. shipyards PLM systems. It serves as an endpoint for the Tablet App.

The Tablet App can be used to navigate the working environment in CAD or AR mode and is therefore used to carry out described work processes and check their current status. After that, the progress can be monitored by the supervisors in the web Application.

2.10.3 Expected benefits

Economic benefits

It is expected that the system will lower the time consumption of searching for information and fulfilling tasks by around 10-25%, which translates to an economic benefit. This is especially true when the transparent tracking of the current status prevents unnecessary travel times to and from the working sites.

Sustainability

On the one hand side, digitalisation and reduction of paper-based work will have a positive influence on natural resource demands. On the other hand, energy consumption will slightly increase due to the use of a handheld device.

Societal benefits

It is expected that the workers' satisfaction will increase by preventing repetition of tasks that were faulty. Also, frustrating elements by handling a lot of paperwork will be reduced.

2.10.4 Guidelines for the application of the solution

Before the system can be integrated into a shipyard, there are preconditions. The main challenge would be a minimal level of digitalisation of the shipyard. Using 3D information (3D models of the working spaces and/or worked-on parts) is highly recommended when using this system. If this information is only available as technical drawing without the digital CAD counterpart, this is to be overcome.

Another point to consider is the shipyards' PLM-systems. Evaluation amongst the consortium made clear that most companies and especially shipyards use different file formats and information structure. Interfaces on the import and export side of the solution system need to be configured to be able to communicate with the shipyards' systems. A "one for all companies" solution is therefore not realistic due to a lack of digital standardization in industry.

2.10.5 Potential disadvantages

At the current state, there are no disadvantages visible.

2.10.6 Potential risks/barriers

Technical

As for most technologies, a proper handling of such has a strong influence of the benefit it provides. Some people will need time to learn and adapt, if they are not already used to such applications. Due to the high amount if digitalisation in European societies, a proper level of comprehension is expected from most users.

When it comes to digital systems, data security is a topic to be addressed. This is, not only, but especially the case, when it comes to systems that are open to external networks. Security measurements need to be fulfilled, while also security updates need to be done ongoing.

If the shipyard ERP is not up to date, plans, tasks, and resources cannot be used effectively as input for this application. The 3dD models should represent the reality as much as possible

Economic

Regarding hardware, there will be a small investment needed at the beginning for the handheld devices, around 1000-1500 € per device.

The costs of a full system are not precisely calculatable at this stage, since it is in prototype stage. The costs will be highly dependent on how established such solutions are already in industry, when a shipyard decides to implement it. Big shipyards will most likely be forerunner there.

Social

In the past, tests with the application that involved workers showed a fear of some that such technologies could be used to supervise their productivity. Also, every new technology face resistance of people that need to adapt to something need. Clear communication and transparency can help with both.

Legal (Rules, regulations)

Regarding the already mentioned technical and social aspects, the legal requirements regarding data security and data privacy need to be fulfilled when implementing such a system. There could also be new safety rules when it comes to working with handheld devices in a technical surrounding in the future.

2.10.7 Usage introduction

To use the system properly it needs to be included as part of the production processes. The web application can be used right away. Depending on the companies' level of digitization, authoring processes for either construction or supervision instructions need to be imported via the web application or made there instead of the paper-based approaches. Once a number of tasks have been created, they can be assigned to a person or group, which can then load those onto their mobile device. A visual instruction can be seen in the training material for the external training in April 2024, available here.

Workers bring their mobile device on site, using it as an instruction manual, as well as a reporting tool. They can either report a task as done, which meaning is dependent on the definition of the task. If a task cannot be fulfilled, workers have the chance to report an issue. They can choose from a list of often issues, write about the occurrence and/or attach screenshots and photos made with their mobile device's camera. They can connect their device with a local or global network at all times to synchronize their reporting with other mobile devices, as well as with the web application. A visual instruction to the mobile application can be seen in this video.

Other players, e.g. supervisors, can see the progress and reported issues in their web application and react to it accordingly.

For example, a worker is assigned to check the assembly status of some pipes in a section. They approach the section, checking that most of the pipes are correctly assembled. Some of them are not yet, which needs to be reported to have a clear view on the current progress. Another one is assembled but broken which they report with a photo of said object. The supervisor can act, collect a new pipe and send people to replace it. Then the worker in the section tries to approach the last pipe system, but it is not accessible since there is some other work going on right now. They report this, others will know that the area is not accessible today, which prevents a lot of walking back and forth and a waste of time.

2.11 Technology: Exoskeleton for shoulder support and lumbar support

2.11.1 Description

Exoskeletons are wearable mechanical devices designed to provide support to workers by reducing their physical effort. Two occupational exoskeletons, namely a shoulder-support exoskeleton and a lumbar- support exoskeleton, were developed within Mari4_YARD project. Their ultimate goal will be to reduce physical strain of workers in those production stages characterized by the presence of wearing job movements for the shoulder girdle and the spine, respectively. The shoulder-support exoskeleton is designed to provide antigravitational support to the user's arms for those job activities requiring static or repetitive shoulder flexion.

Thanks to an embedded battery-operated control unit, the exoskeleton is capable of adjusting the provided support depending on the inherent effort of the working activity though effort- based and perception-based adaptive algorithms. The lumbar-support exoskeleton is designed to support the user's trunk erector muscles through an assistive action delivered at the level of the lumbo-sacral joint in those job activities requiring repetitive load lifting actions or static flexion trunk poses. The intensity of the assistance level can be manually tuned over five levels.

As "wearable" tools, both exoskeletons are designed to provide a comfortable human- machine interaction thanks to a light-weight structure, high kinematic compatibility ensuring for complete freedom of movement and high adaptability thanks to a set of adjustments mechanisms that allow to tailor the size of the devices to fit on specific users. Both exoskeletons are also endowed with a control unit that is devoted to acquiring kinematics information from an integrated sensory apparatus and implementing wireless MQTT protocol to share information with IoT networks.

Figure 44. Workers using exoskeletons in welding activities (Vertical and Overhead welding positions)

2.11.2 Potential Applications

Exoskeletons have gained attention in recent years as a potential solution for reducing workplace injuries and improving productivity in physically demanding jobs. While automation is often heralded as a solution in industries that require repetitive or heavy manual labour, many shipbuilding working activities require flexibility, adaptability, or sensitivity to navigate and operate in complex environments. This is where exoskeletons result useful advanced tools for supporting workers improving ergonomics in those activities that require prolonged static postures or repetitive movements that can cause musculoskeletal discomfort. Specific examples in shipbuilding scenario are assembly tasks such as welding and other related workshop activities. Welding or grinding, especially under the keel of the ship, requires keeping postures with flexed shoulders for several minutes and a shoulder-support exoskeleton can be considered a viable solution to reduce strain of workers and consequently reduce operation time. Assembly activities in workshop are often performed on large tables requiring operators to keep bent trunk postures while manipulating heavy objects; a device designed to reduce the strain at the level of the spine can be relevant for reducing back pain or keeping more ergonomic working postures.

2.11.3 Replicability

Once the benefit brought by the utilization of the exoskeletons are demonstrated, their replicability in the maritime industry or in other sectors can be easily achieved given the low investment with respect to other strategies such as redefining a production process.

2.11.4 Expected benefits

Manual working processes that require flexibility and adaptivity cannot be easily targeted by automation, nevertheless the physical strain of operators cannot be reduced to a certain extent by reorganizing geometry of workspaces to improve ergonomics. When all the measures taken to minimize the strain are already pursued, still the biomechanical overload represents a huge risk factor in the long-term development of work-related musculoskeletal disorders. Exoskeletons are advanced tools that, by providing mechanical support in synergy with the human articulations, are effective in further reducing the physical strain of workers, still allowing for flexibility and dexterity of their operations. In this sense, exoskeletons can be seamlessly integrated in the working routine without requiring reconditioning of the working environment or operations. In the next sub-sections, more details are provided on the expected benefits under economic, sustainability and societal perspectives.

Economic benefits

From an economic viewpoint, exoskeletons are a cost-effective solution that can have short-term and long-term impacts:

On the short term, exoskeletons can have potential to significantly enhance workforce productivity and efficiency. Reduced biomechanical overload can contribute to:

- reduce fatigue-induced errors enabling cost saving in terms of repetition of operations and materials.
- reducing the number of discomfort event requiring to stop operations and rest to recover from fatigue
- increasing precision and speed in the operations.

Exoskeletons could potentially reduce ergonomic risk indexes. Biomechanical overload risk indexes are predictors of incidence of injuries and development of work-related musculoskeletal disorders. Reducing the biomechanical overload risk indexes may be indicative of long-term economic gains in terms of reduction of health costs, turnover and injuries as well as of insurance costs.

Sustainability

From a sustainability viewpoint, the investment on exoskeletons is limited to the purchase and training. The investment goes in favour of enabling safer operations of the current workforce with minimum to null reconditioning of the working place.

Societal benefits

From a societal viewpoint, by investing in preserving human factor through the provision of advanced tools to improve the working condition of operators, the company or shipyard will contribute to increased quality of life of workers, thus increasing their motivation, well-being and safety. Investing in well-being will promote a clear message of attention towards human factors that can have positive impact in attracting competitive young workforce, improve engagement and satisfaction of workers.

2.11.5 Guidelines for the application of the solution

Two main recommendations can apply to the introduction of exoskeletons. Firstly, as an innovative tool, despite ease of use, structured user training can significantly boost acceptability and usability of the device. Training sessions on how to wear and operate the exoskeletons can be strategic not only to drive technical aspects but also to educate users about the benefits of exoskeletons This approach ensures that employees are well-prepared to integrate exoskeletons into their daily routines effectively. Secondly, setting up a dedicated area for stock and user preparation can significantly amplify the success of their deployment among workers. Setting-up a specific area (a locker room or even a corner close to the production stage) dedicated to exoskeleton stock, donning and doffing, makes the "tool" easily accessible to the users.

2.11.6 Potential disadvantages

As advanced tools the learning curve of the devices is fast, yet it may require an initial effort that may slow down operations in the first place (less than one week).

2.11.7 Potential risks/barriers

Main risks and barriers in the introduction of exoskeletons are represented by the actual usability and acceptability in the workplace.

Technical

From a technical viewpoint, the main risks or barriers can be represented by the difficulty of performing working activities in narrow spaces hardly accessible by the operators themselves in their regular working equipment. In this case, it is suggested to encourage use of exoskeletons only in operations that are compatible with their use.

Economic

Introduction of exoskeletons have minimum to null economic risk if accompanied by proper training of workforce to the use of the device.

Social

From a social viewpoint, being an advanced tool, it is possible that not all the workers may be open to accept learning how to use and take benefit of innovative tools. Forcing an operator to use the device may taint the attitude towards the use of the device with the risk of spreading prejudice. To mitigate the risk, the company should invest in training people that are well-disposed toward the technology and that are able to clearly identify pros and cons of using the exoskeletons. Their experience will then be the main driver to attract other workers in spreading the use of the device.

Legal (Rules, regulations)

No legal limitations are identified.

2.11.8 Manual

Detailed user's manuals for the safe and effective use of the devices have been edited in the framework of the WP7. In this section, the main actions that a novel user of the technology should follow are reported:

- Comprehension of the intended use and unintended use of the devices

Unintended use

NOTE

The Mari4S_Exo device should not be considered a medical device.

- The product cannot be used by:
  - Pregnant women;
  - Individuals under the legal age;
  - Individuals with:
    - skin conditions, inflammations, scars in areas of the body in contact with the device (shoulders, chest, back, hips, and thighs);
    - Hernia;
    - Breast prostheses;
    - Hip prostheses;
    - Knee prostheses;
    - Recent surgical interventions;
- Any condition deemed potentially incompatible with the use of the device.
- The device cannot be used in an unsuitable workstation or environment. Experienced and qualified individuals must assess the workplace to identify any risks that could pose a danger to the user. The following risks are possible:
  - Risk of unintentional collisions with external objects or people;
  - Risk of unintentionally getting entangled in fixed or movable objects;
  - Risk of obstruction during the evacuation of a room;
  - Any other risk related to safety and ergonomics during use.
- The Mari4S_Exo should be stored in a dry place, preferably hung on a coat rack or placed on a flat surface of adequate size.
- Remove the device if skin irritations occur.
- Use the device correctly and do not make modifications to it.
- Use the device with care and only for its intended purpose.
- Check the integrity of the device (through visual inspection) before each use and in case it has been exposed to extreme stress (e.g., after falls).
- Be careful not to accidentally hit the assistance enablement mechanism during use.
- Dry the device after use if wet or damp.
- Clean the device with a damp cloth to remove any sand, dust, and debris.
- Be cautious that clothing or tools do not get caught in the device or between the device and the body.
- Wear appropriate clothing.
- Improper use of the device can cause cutting or crushing injuries (see Section 3.3).
- Keep the device away from children and pets.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006798

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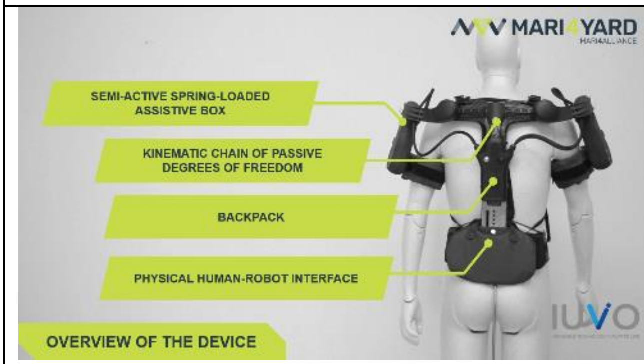
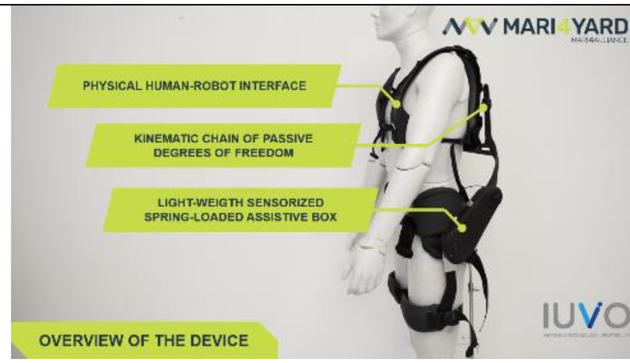
- Comprehension of the main components of the devices

Mari4S_Exo	Mari4L_Exo
	

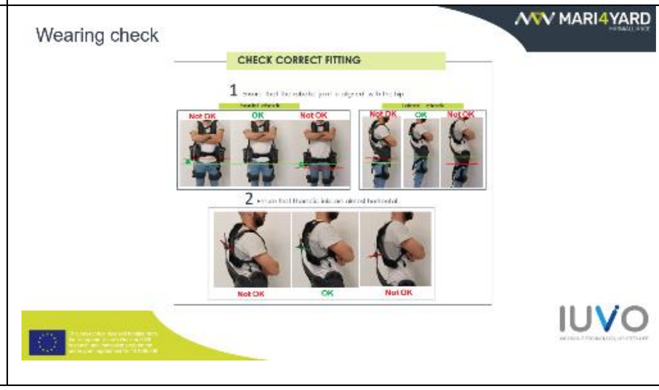
- Comprehension of the proper personal configuration of the sizing and tailoring of the devices

Mari4S_Exo	Mari4L_Exo
	

- Comprehension of the autonomous wearing and unwearing procedure

Mari4S_Exo	Mari4L_Exo
	

- Comprehension of the procedures to recognize a proper tailoring and wearing of the devices

Mari4S_Exo	Mari4L_Exo
	

Detailed explanations of this actions are reported in the user's manuals. Moreover, for each exoskeleton, a Quick Reference Guide was developed for easy access to all the relevant information in the form of a A4 sheet.

Mari4S_Exo	
	 ç

Mari4L_Exo

3 Life Cycle Performance Assessment

3.1 Method

Life Cycle Performance Assessment is a methodology initially developed in the FP7 projects BESST and JOULES to combine a Life Cycle Assessment (LCA) with an economic assessment in terms of Life Cycle Costing (LCC) over the lifetime of a product. It encompasses a number of environmental KPIs as well as KPIs for the economic aspects. Figure 45 shows the LCPA methodology in a nutshell. The following explanations are not results of the Mari4_YARD project, but just describe the method and tool for reference and as explanation how to apply them for the sustainability analysis later in the WP.

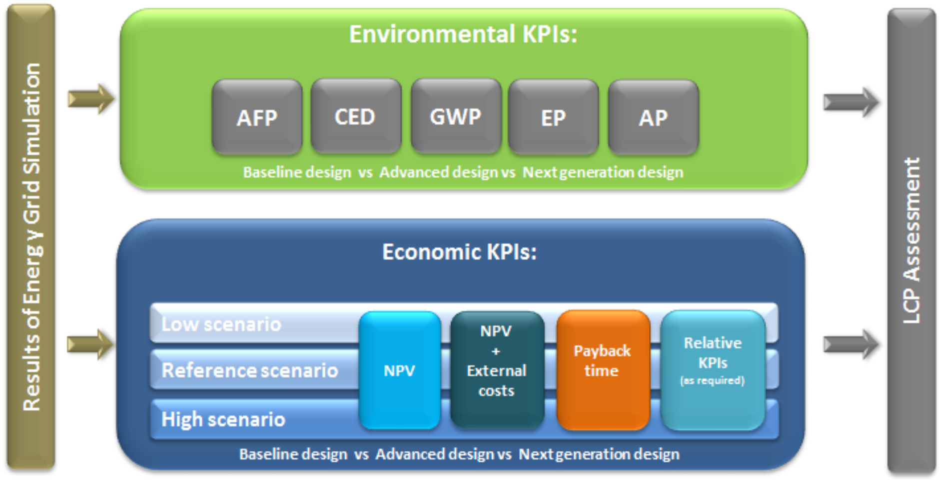


Figure 45: Assessment Methodology

With this methodology, the advantages of future technology used in the advanced or next generation products can be made transparent and relevant interactions or trade-offs between the different KPIs can be identified.

3.2 Screening LCA Methodology

In the projecting stage of a new product, all relevant decisions regarding use of materials, costs and energy efficiency of components are made until contract signing.

Thus, all relevant issues need to be discussed in the early design stage and any assessment for the comparison of different design options has to be done in this stage. Although items may be changed after contract signing, the incurred costs for these changes will be high.

On the other hand, projecting a product is a very complex process involving already information from many stakeholders in the early design stage, basically from the owner, operator, supplier, sub-suppliers, regulators, financial investors etc. In this respect, information might be difficult to achieve, not finally binding or time constraints is a typical problem to overcome. Due to the complexity of a whole product with potentially thousands of individual components and processes, a detailed Life Cycle Assessment (LCA) is far too much work. Thus, the LCA as developed in the earlier projects had to deal with these restrictions and consequently, the methodology of a Screening LCA has been introduced.

A Screening LCA uses a limited number of input variables and calculation results to address KPIs (environmental impact categories) as follows:

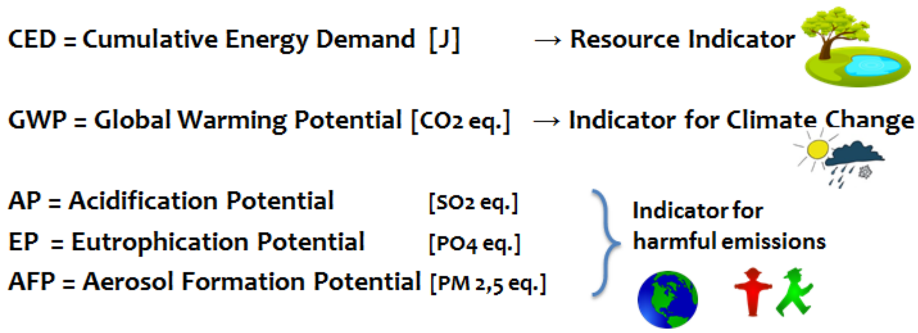


Figure 46: KPIs (Environmental Impact Categories)

Since the demonstrators are showing the use of the different technologies on a generic level and not related to dedicated processes in the shipyard, LCPA in the Mair4_YARD context was carried out on a general level, concentrating on life cycle costing and additionally on the Global Warming Potential as environmental KPI. The approach used was:

- Generic processes were defined that could be supported by the innovative technologies
- Innovative variants of these processes were derived that would perform the same activity but with prior installation of the new tools and using them during the operation phase
- Since in all cases the technologies would replace manual activities that were not using specific tools and technologies to be replaced by the new ones, the effort for setting up the new systems and for running them would be higher than for the original processes. Therefore, the savings could only be realised by reducing the personnel effort when using the new technologies. This means that in the next step the scenarios were adjusted in a way that would lead to similar costs over the defined time. The approach was to increase the personnel effort in the original process until the cost was equal for both scenarios. The result of this activity was the reduction of personnel effort that was required until the new technology would be beneficial for the shipyard. By following this approach, it was not described to what extent the shipyard could save costs when using a technology but to what extent the technology needs to be introduced before the additional effort pays off. It was assumed that the break-even point of the innovative solution should be reached after 5 years at the latest under the assumption that especially smaller companies will not take the risk of investments that take much longer to generate benefits. Personnel costs are set to 45.000€ per year and Full Time Equivalent (FTE) which is according to Eurostat 2022 figures for workers in the maritime industry the average for workers in the major EU shipbuilding countries (Finland, Germany, The Netherlands, France, Spain, Italy, etc.).
- The environmental impact of the new technologies was not analysed in detail. Since none of the new technologies will replace energy intensive technologies bit mainly manual activities, the energy consumption of the new technologies is actually higher than for the current processes. Therefore, the environmental impact will never be lower with the new systems but equal in the best case (when using sustainable energy to operate them). Therefore, additional operation energy was taken into account in terms of fuel and externals costs, leading to additional effort to be compensated by the innovative processes.

The outcome of this analysis gives a direction for the shipyards how many processes they have to support with the innovations in order to benefit from them. Since smaller shipyards typically do not have large amounts of money available to introduce innovations, a second analysis has been carried out. In an LCPA model that contains all innovative technologies, a comparison was run that shows the benefits of the different technologies in relation to the investment. By analysing these results, the shipyard could decide which technology would be the best choice when a certain investment capacity is available. The results of this second analysis are public and therefore shown in the following section.

3.3 Results

The first chart shows the life cycle costs of the innovative solution over an estimated time of 15 years. Since the expected investment costs (purchase of equipment, installation, user training) for each of the technologies lies between 50.000€ and 120.000€, the starting point of the graphs is slightly different. The operating costs vary depending on the complexity of the devices and the energy consumption, leading to an overall end value of the NPV (not considering revenues) of -400.000€ to -900.000€. Distributed over the years, this leads to the conclusion that each of the technologies will pay off within 5 years if in the processes supported one Full Time Equivalent can be saved. By this approach, either the productivity of the workforce would be enhanced, or the problem of finding qualified personnel could be reduced significantly.

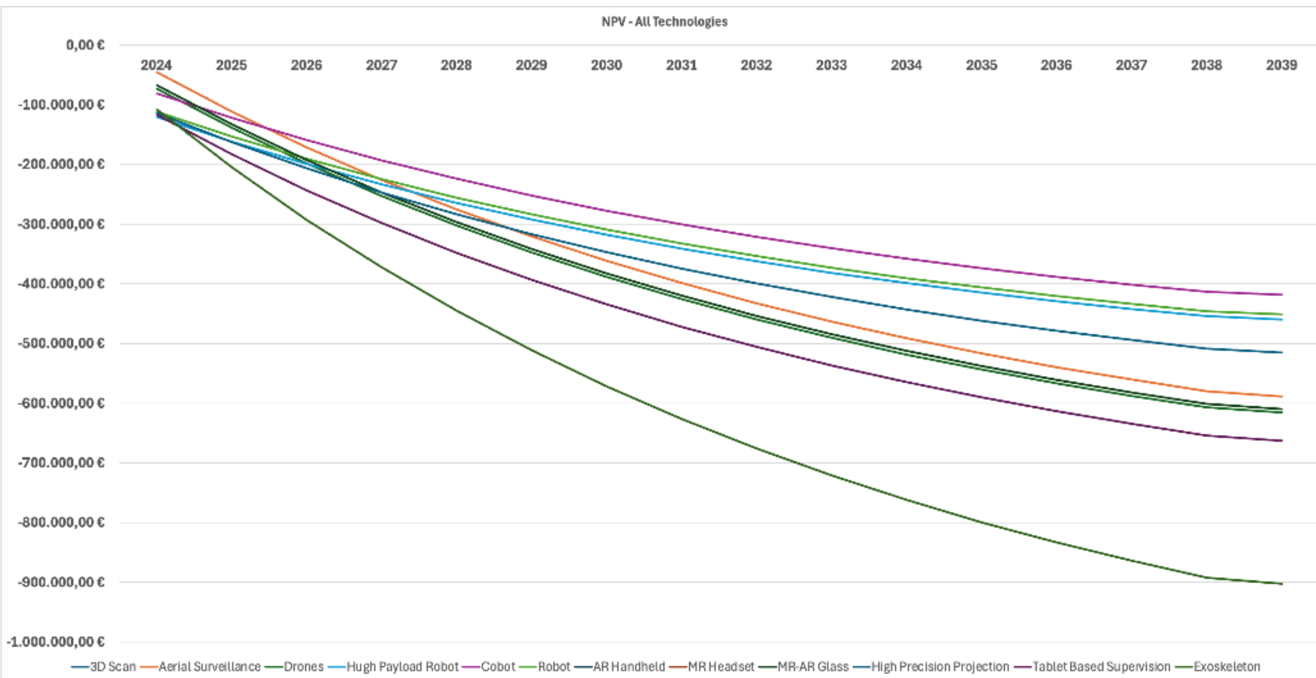


Figure 47: Lifecycle costs of the innovative solutions

Although the environmental impact of the different technologies is not zero, none of the technologies will produce large amounts of greenhouse gases. As shown in the chart below, nearly all technologies will emit less than one ton within the 15 years, assuming that the electricity required will originate from sustainable sources. Only exception are the high payload robots that have a slightly higher but still negligible additional environmental footprint. Production of the devices has not been considered due to missing data.

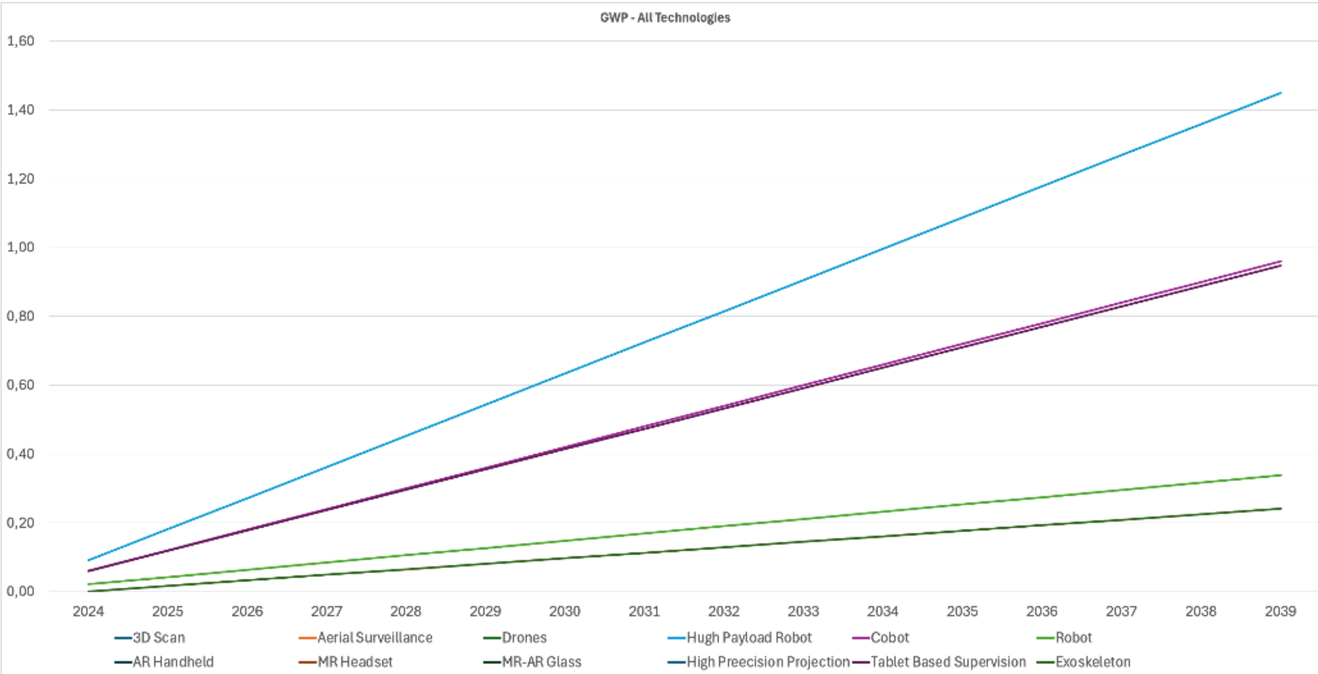


Figure 48: Environmental impact (GWP) of the innovative solutions

The results of both the financial as well as the environmental impact of all technologies covered by the Mari4_YARD project are low enough to not block the introduction to even smaller shipyards. Therefore, the decision for one or more of the innovations can solely be taken by identifying the most promising processes that should be supported. The different technologies can therefore be seen as a catalogue for small and medium-sized shipyards of which one or more solutions can be selected independent of each other to reduce costs or to increase the productivity.

4 Conclusion And Outlook

This document is the final version of the Mari4_YARD best practice handbook which gives a first overview of the different solutions, their possible applications and the conditions under which they may be introduced. The enclosed findings are mainly related to the demonstrators at the shipyards, tests in the lab and user training that took place inside and outside of the yards. The outcome was gaining comprehensive knowledge about benefits as well as potential issues. Furthermore, it provided input data for the Life Cycle Performance Assessment that shows the viability of the solutions in terms of KPIS covering the economic and environmental impact. The public subset of these results has been included in this public deliverable.