Open-Digital-Industrial and Networking pilot lines using modular components for scalable production

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Summary:
The purpose of this document is to describe the refined version of the ODIN Industrial Large-Scale pilots.

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1. EXECUTIVE SUMMARY

This document shows the intermediate version of Industrial Component of large pilot lines developed in ODIN project. The validation of the software and hardware modules is presented through the pre-industrial demonstrators of LMS and TECNALIA. Special efforts are given in order to have industrial pilots characterized by: Industrial level robustness, industrial grade performance and industrial safety.

This deliverable focuses on presenting the integration of the final version of ODIN modules as these have been developed under D2.4, D2.5, D3.3, D3.4, D4.3 with regards to the following components:

- ODIN Open Component (WP2)
- ODIN Digital Component (WP3)
- ODIN Networked Component (WP4)
- Safety Concept (WP5)

Further information of the ODIN demonstrators are provided in the following sections:

- Section 1: Provides an executive summary of the document.
- Section 2: Provides an introduction of this deliverable.
- Section 3: Provides a description of ODIN Automotive pilot demonstrator.
- Section 4: Provides a description of ODIN Aeronautics pilot demonstrator
- Section 5: Provides a description of ODIN White Goods pilot demonstrator.

LEGAL DISCLAIMER

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2. INTRODUCTION

ODIN WP5 is centralized on the Industrial Component for robust large scale pilot lines. The main objectives for this WP are:

- The deployment of the full-scale demonstrators in different production sectors to serve as a token of the industrial grade performance of the ODIN production systems. A full-scale instance of the pilot, integrating hardware (HW) and software (SW) modules from the Open and Digital components and operating under an actual production environment.
- The validation of demonstrators' performance of the integrated solution and its interoperability.

This deliverable provides evidence on how the core technical Work Packages of ODIN (WP2, WP3, WP4) have been successfully integrated in the pilot lines of M36 combined also with the ongoing safety concept implementation.

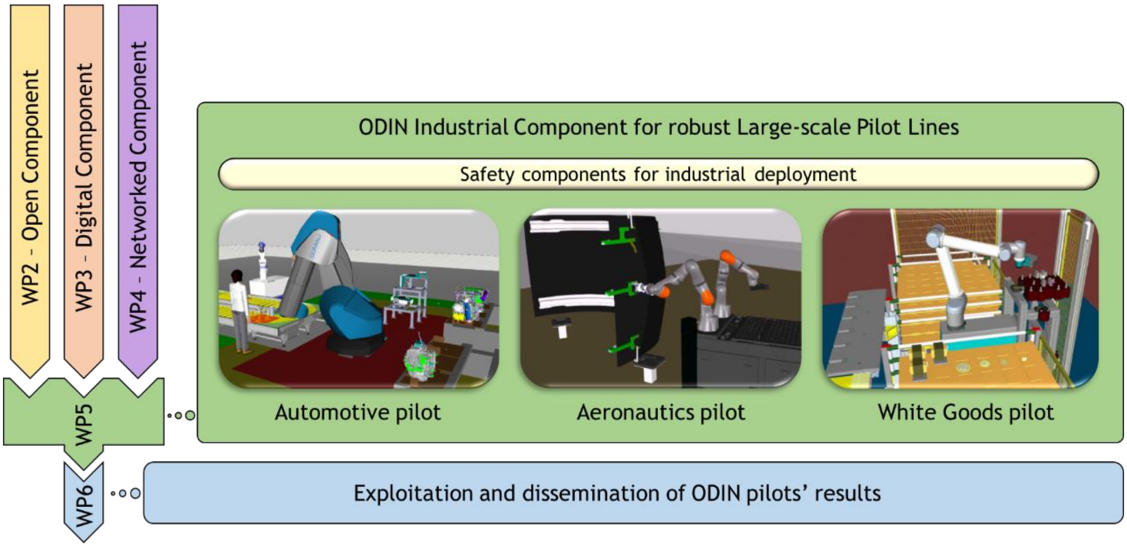


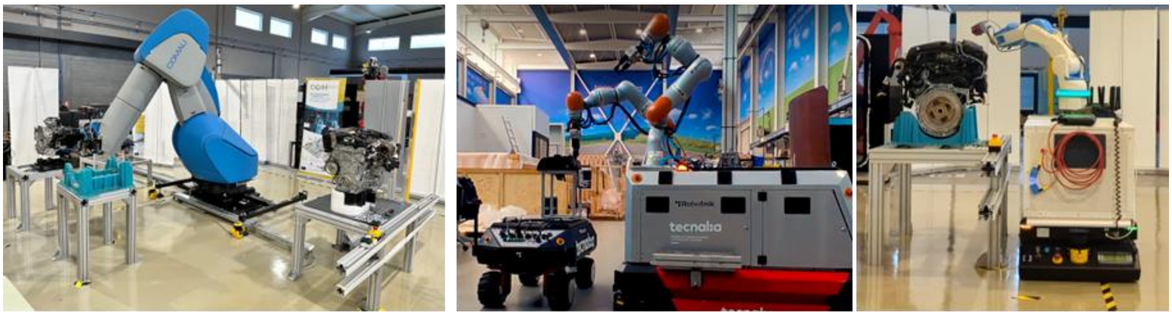
Figure 1: **Large-scale Pilot Lines of Industrial Component – connection with other ODIN Components**

3. ODIN AUTOMOTIVE PILOT DEMONSTRATOR

3.1. Overview

The Automotive pilot demonstrator targets to increase the productivity of the real industrial process at STELLANTIS premises, by utilizing ODIN key technologies. This demonstrator consists of modules from all ODIN components. As presented in D5.2, the final demonstrator of the automotive pilot as consists of three operations:

- Operation 1: Motor & gearbox assembly.
- Operation 2: Additional parts assembly on the motor and gearbox assembly.
- Operation 3: Quality check of installed parts on the motor and gearbox assembly.



a) b) c)

Figure 2: a) Operation 1 at LMS premises, Operation 2 at TECNALIA premises and c) Operation 3 at LMS premises

In its final version, the automotive pilot's operations will take place in a common working area. The COMAU AURA robot [1] will perform the connection of the motor and the gearbox parts on a conveyor which will be utilized also for motor and gearbox assembly transportation to the next working area of the assembly line. The screwing while moving but also the quality inspection operations will take place during the transportation of the motor. Up to M36 of the project, this conveyor has been prepared at DGH premises and its installation and validation at STELLANTIS premises will be presented in D5.5 scheduled for submission on M48.

Automotive Use Case Conveyor on DGH premises

The designing and building of the conveyor at DGH premises have been completed. This conveyor design is based on the required space for all operations' execution. Its design has been validated thanks to the digital simulation of the pilot line.

Figure 3: Automotive use case conveyor

In its final version the conveyor will be connected with the OpenFlow in order to achieve the required start and stop actions of the conveyor belt during the assembly process. The hardware components required for conveyor's functionality but also software connection in the final demonstrator layout is included in its main cabinet presented in the following figure.

Figure 4: Conveyor Electric and communication cabinet

Based on the safety analysis, the conveyor consists of a safety PLC for its controlling and connection with OpenFlow but also several emergency stop and reset buttons in case of emergency during the execution of the assembly process.

Figure 5: Conveyor's emergency buttons

3.2. Automotive demonstrator at LMS premises

The Automotive pre-industrial demonstrator at LMS premises focuses on the first and the third operations of the investigated production line. As previously mentioned, the first operation is centralized on the assmebly of a motor and a gearbox part by a COMAU AURA collaborative robot with the support of a human operator for the final connection. This operation's layout consists of the collaborative robot, the assembled products (gearbox and motor) but also a set of alluminum tables for product's storage. Additionaly, a tool stand has been constructed by LMS for the execution of the tool exchange process by the AURA robot.

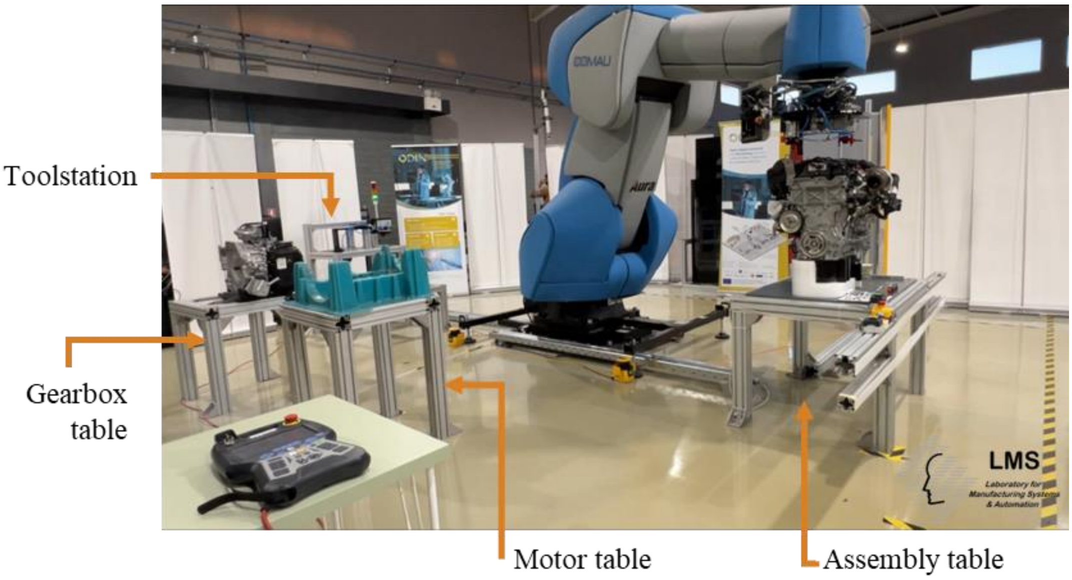


Figure 6: LMS Demonstrator – Operation 1 layout

The third operation of the Automotive pilot is focused on the quality check of the installed parts on the motor and gearbox assembly. This operation is based on the automated inspection of parts on the motor and gearbox assembly by the mobile robot of COMAU. Human operator’s intervation is required only in case of faulty inspected parts. This opearation takes place on the assembly table built for the operation 1 as presented in the previous sub section of this document. The COMAU mobile robot approaches the assembly table and using a RC_Visard 65 camera sensor executes the required quality inspection tasks.

Figure 7: LMS Demonstrator – Operation 3 layout

3.2.1. Integration of Open Component with automotive initial industrial pilot

3.2.1.1 Autonomous mobile manipulators

The mobile robot of COMAU has been shipped to LMS and its integration in the Automotive preliminary demonstrator in Greece has been completed until M36 of the project. This robot focuses on the realization of the quality inspection process of the automotive pilot’s motor and gearbox assembly. As presented in D2.4, COMAU mobile robot [2,3] is able to autonomously navigate in the automotive demonstrator layout and dock in the required positions using feedback from its laser sensors.

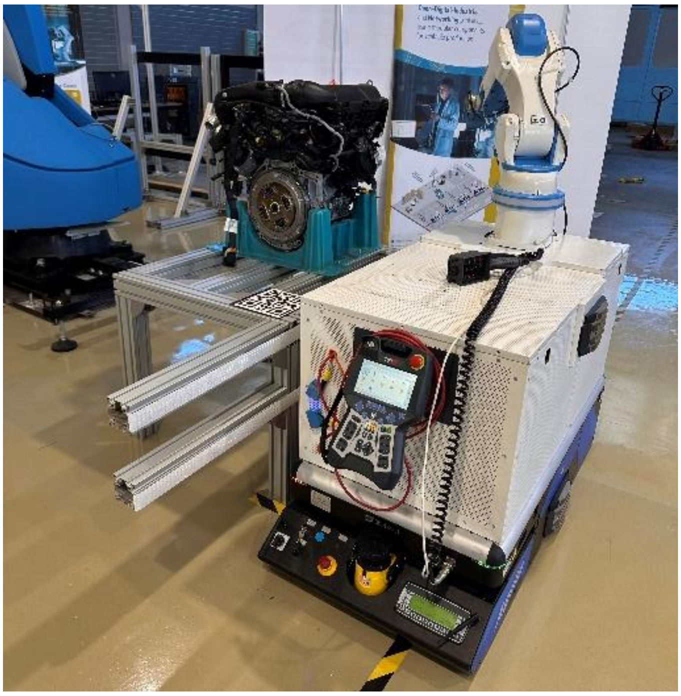


Figure 8: COMAU mobile robot sensor-based docking

The docking of the mobile robot is based on a set of reflective tapes installed on the assembly table of the operation 1 layout.

3.2.1.2 Reconfigurable robot tooling

As previously mentioned, the automotive pilot demonstrator consists of the AURA high-payload collaborative robot which is utilized for motor's and gearbox's parts manipulation. The AURA robot is able to manipulate the required components using the motor and gearbox grippers which have been designed and manufactured by LMS. As presented in deliverable D2.4, the motor gripper consists of a main steel flange, two sets of pneumatic actuators and couple of steel pins to distribute the weight. From the other hand the gearbox gripper is made up from multiple steel flanges and one set of pneumatic actuators with steel pins to distribute the weight of the manipulated part. The final stage of assembly between motor-gearbox parts is achieved using the hand guidance module.

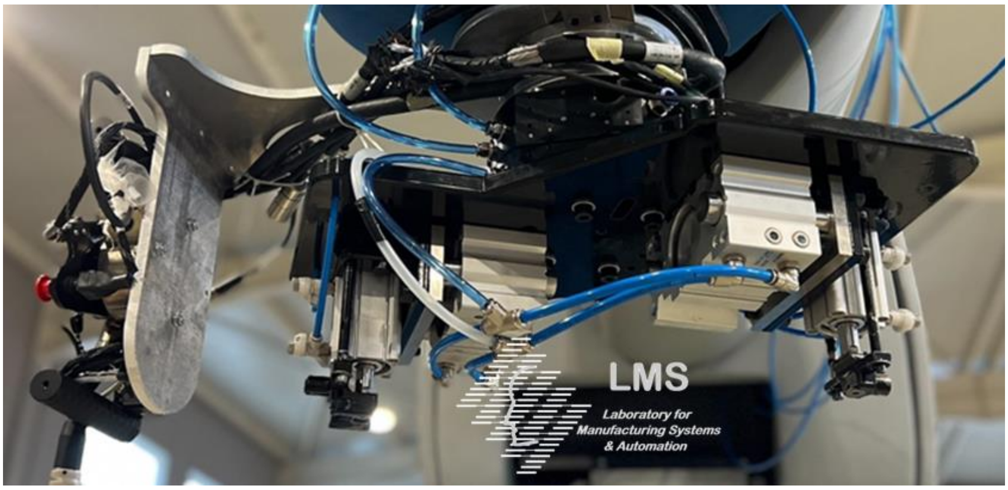


Figure 9: Motor gripper

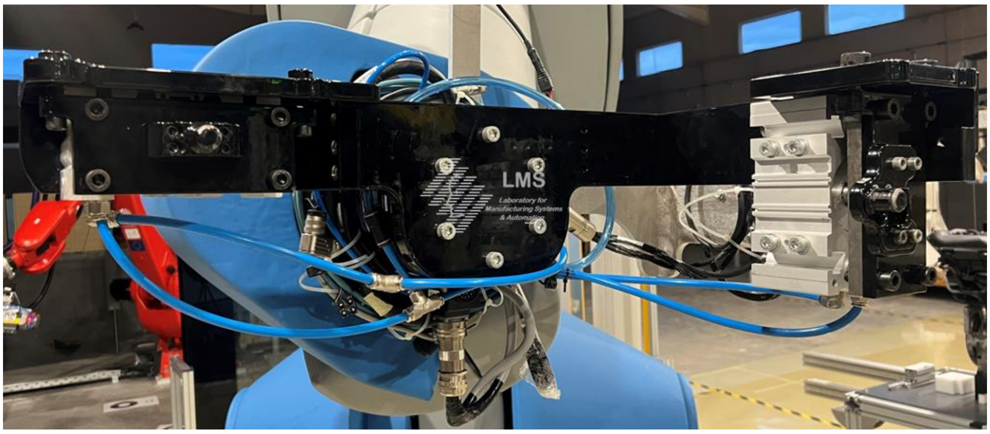


Figure 10: Gearbox gripper

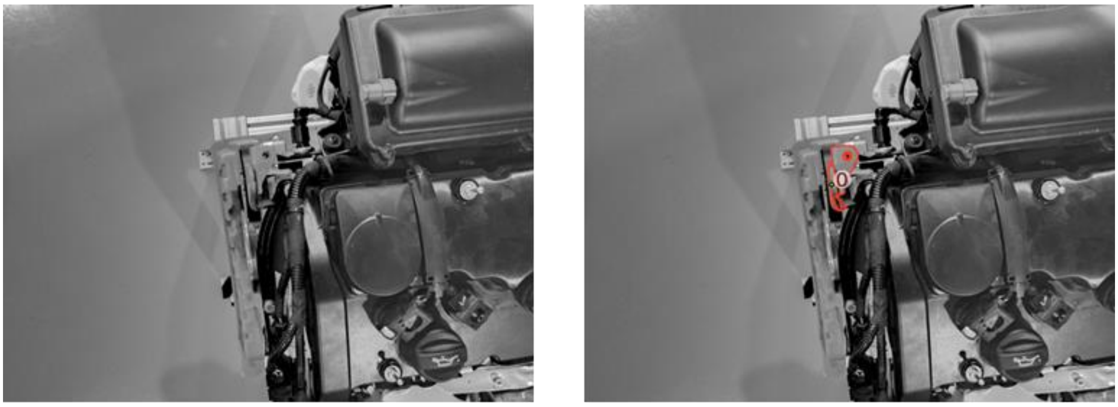
3.2.1.3 Robotic perception for the process, the human and the environment

The automotive demonstrator utilizes a set of robotic perception solutions for the successful execution of the required robot operations. These solutions' contribution in the pre-industrial demonstrator of LMS are:

- Object pose estimation

Thanks to the detection module of ROBOCEPTION, the AURA robot is able to grasp successfully the motor and gearbox parts. As presented in D2.4, the object pose estimation module within the automotive pilot is based on a CAD template for each part to be detected.

Due to motor's complex geometry, the detection of the motor part is based on the detection of one lifting point of the motor using an RC_Visard 160 [4] camera. The detection of this lifting points is based on the pose estimation functionality of the CADMatch detection technique [5]. The integration of this pose estimation operation into the Automotive pre-industrial demonstrator is illustrated in the figure below.



a) b)

Figure 11: a) Motor lifting point, b) Motor lifting point pose estimation using CADMatch

Regarding the detection of the gearbox part, the CADMatch technique is used to identify the whole part and provide the desired grasping point. This module incorporates the same camera sensor used for motor's detection. This camera sensor is connected with an rc_cube S [6], which is responsible for the provision of the required detection template and the execution of the detection process.

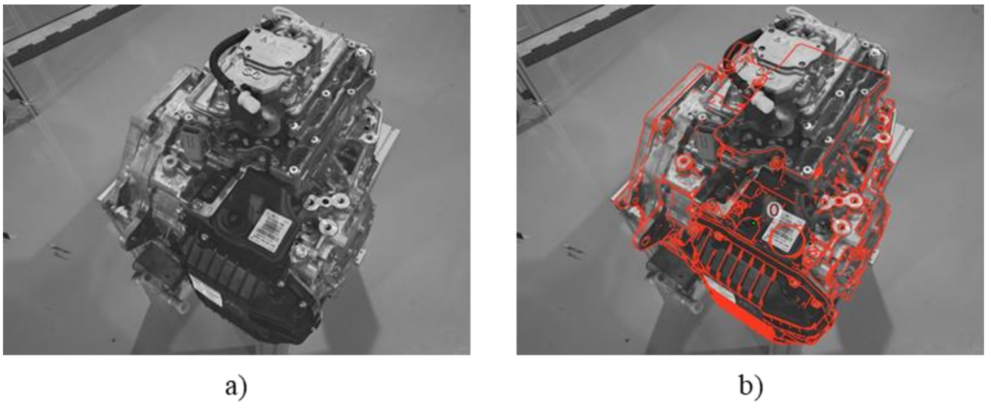


Figure 12: a) Gearbox part, b) Gearbox pose estimation using CADMatch

The integration of the pose priors feature was implemented to optimize the process. In the figure below, the camera point cloud at the moment of pose prior determination is depicted in gray, while the CAD template of the gearbox part is represented with blue color. This user defined process for establishing the pose priors of the parts was performed before the integration of the pose estimation module in the Automotive pilot demonstrator as presented in the following figure.

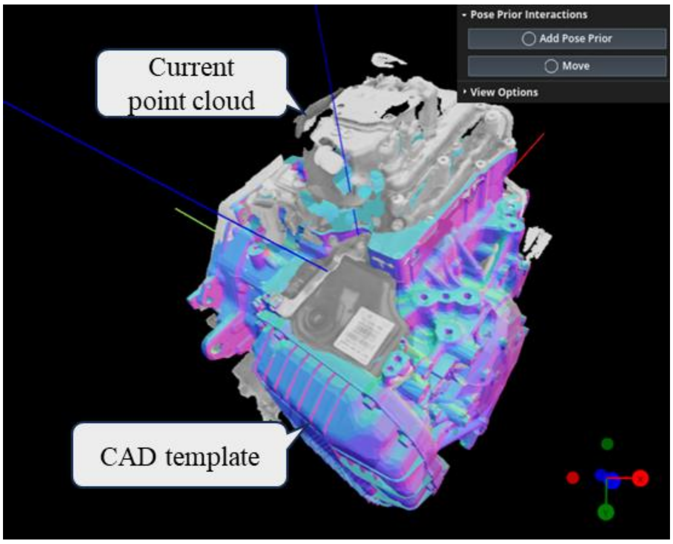


Figure 13: Setting of gearbox pose prior

The results of the CADMatch module are provided to OpenFlow for the creation of the corresponding grasping points as frames inside the transformation tree of ROS environment. These frames are used to define the final poses for the AURA robot towards the grasping of the desired parts.

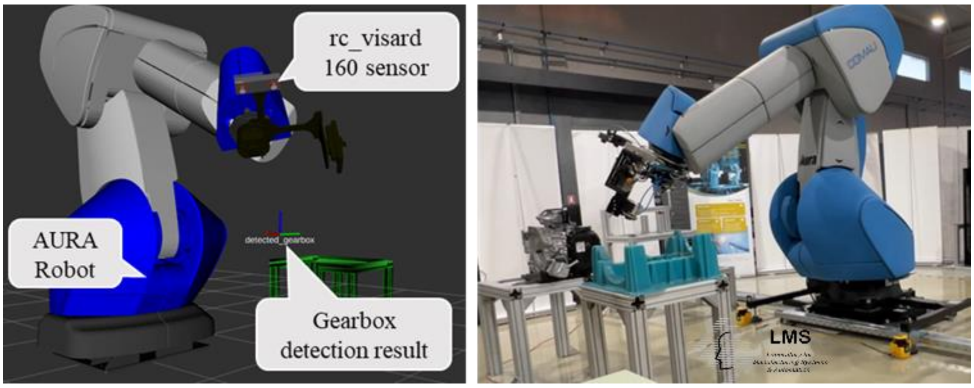


Figure 14: CADMatch Gearbox Detection Result in Robot simulation

The spatial object detection module developed by LMS is critical for the final connection of the motor and gearbox parts under Automotive pilot Operation 1. Utilizing this module, the final position of the motor placement on the assembly table is detected. Similar to the previously presented object detection process, the result of the spatial object detection is sent back to OpenFlow for the definition of the final gearbox's connection point. Using this data, the robot can go to the desired pose for gearbox and motor alignment. The CNN-based approach of this spatial object module is detailly presented in D2.4.

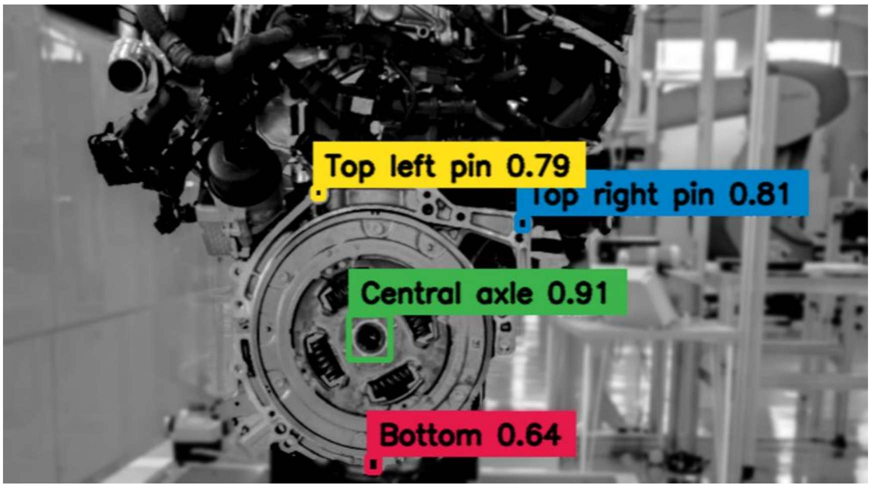


Figure 15: Alignment positions by spatial object detection module

- Quality inspection

The primary emphasis in Automotive Operation 3 revolves around the quality inspection of the assembled parts on the motor and gearbox assembly. This operation involves the usage of COMAU mobile robot's RC_Visard 65 camera sensor [7] and the corresponding software module of ROBOCEPTION. The COMAU mobile robot is capable of inspecting faulty installation of connectors, strap holders, screws and valve pipes on the assembled component.

In accordance with the specifications in D2.4, the module sequentially identifies Regions of Interest (ROIs) for each part to be inspected. The classification of the inspected parts as either 'OK' or 'NOK' is established through the quality check service, a deep learning approach developed by ROBOCEPTION. The implemented quality check service, which incorporates updated models for these objects inspection (i.e., electrical connectors, strap holders, screws and valve pipes) has been integrated into the pre-industrial pilot of LMS. The results of this module's integration in the Automotive demonstrator of LMS are presented in the following figure.

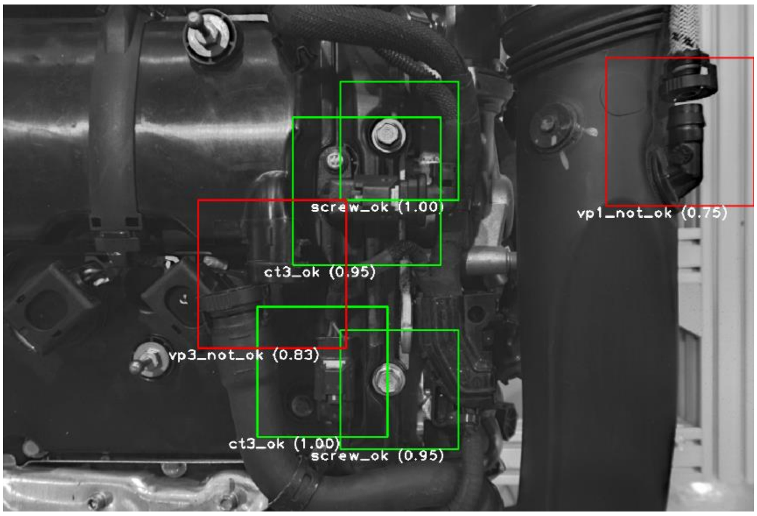


Figure 16: Quality inspection on the assembly

3.2.1.4 Smart human side interfaces

The operators of the automotive demonstrator use the AR application of ODIN in order to successfully execute their assembly actions. As presented also in D2.5 and D2.6, the AR application of ODIN developed by LMS consists of several features assisting human operators of the Automotive pilot in a multi-pillar way in terms of:

- Assembly guidance provision,
- Controlling of mobile and static robots,
- Production system security breach notifications provision,
- Assembled products quality inspection results provision,
- Resilience of the production system in case of unexpected events,
- Safety awareness for the operators,
- Production schedule hologram-based visualization.

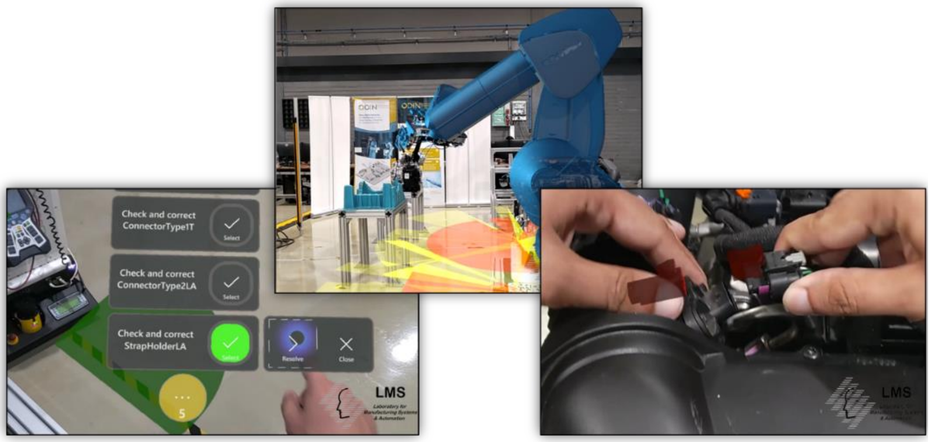


Figure 17: AR application usage in Automotive demonstrator

3.2.2. Integration of Digital Component with automotive initial industrial pilot

Until M36 of ODIN, all the Digital Components have been integrated and tested in the pre-industrial demonstrator of the Automotive use case at LMS premises with the support of individual developer partners.

3.2.2.1 Digital Simulation

The digital simulation of the automotive pilot is focused on the assembly, screwing and quality check of a motor engine. The digital simulation has been built based on the process modelling methodology of Visual Components software.

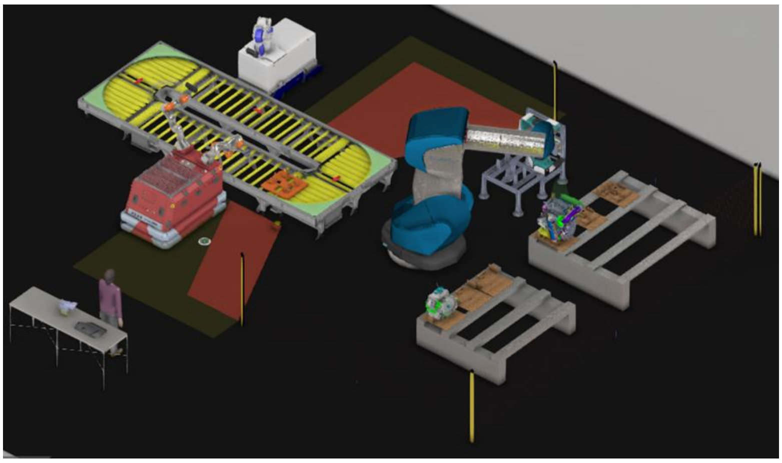


Figure 18: Automotive demonstrator simulation layout

The digital simulation of the automotive demonstrator is used for the preliminary validation of ODIN components before their integration in the physical layout but also for demonstrator's layout finalization in terms of components installation and robots' reachability in the layout.

In its final version, the digital simulation of the automotive demonstrator consists of ODIN grippers required for motor and gearbox parts' manipulation but also the safety components towards the validation of the safety concept before physical demonstrator's setup. The validation of the safety concept was based on the modeling of PILZ safety laser scanner PSENscan but also PILZ safety curtains by PILZ, VISUAL COMPONENTS and LMS partners collaboration.

- Integration of PILZ safety laser scanner

The digital model of PILZ safety laser scanner is directly connected with the digital controller of AURA robot in order to receive the speed of the robot and update the protective zone's dimensions based on the safety formula delivered by PILZ. The laser scanner device is directly connected with the robot's digital controller in order to reduce robot's speed or pause robot's motion depending on detected human operators' location.

- Integration of PILZ safety curtains

The digital model of PILZ safety curtains includes the corresponding safety feature for measuring the minimum distance between the plane of the curtains and the total robot envelop after the execution of the assembly process. Based on the minimum distance allowed by the safety standards, the digital simulation informs the user whether the installation point of the barriers meets the safety standards or not.

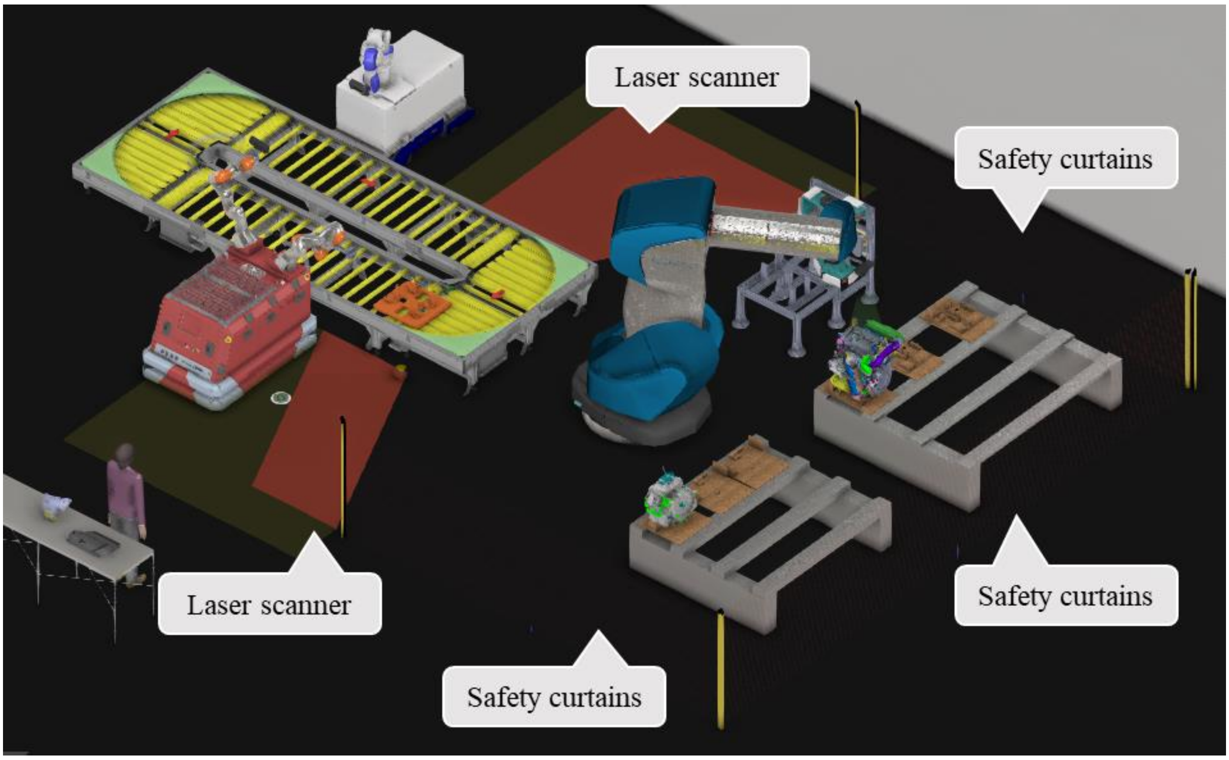
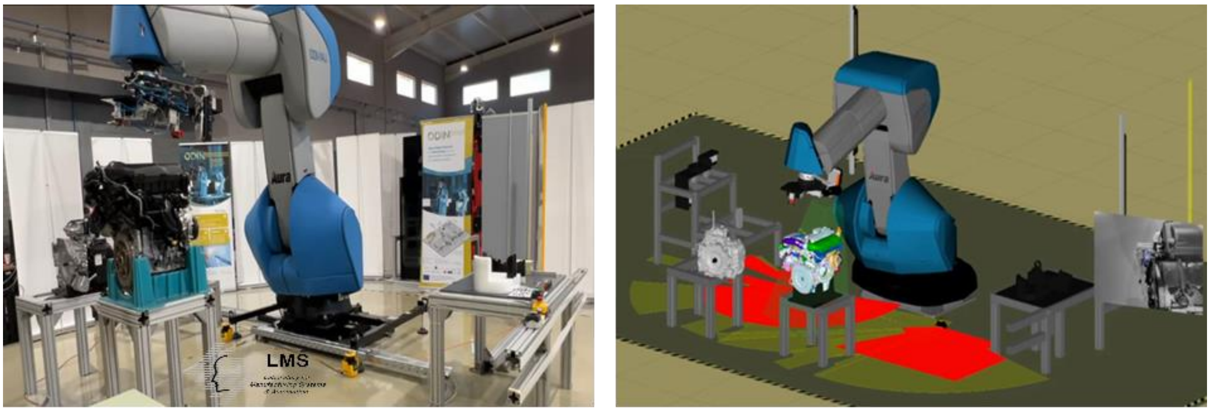


Figure 19: Safety components validation in Automotive simulation

3.2.2.2 Digital Twin

The Digital Twin (DT) of ODIN utilizes the visualization and connectivity functionalities of the Visual Components software. The final version of the Automotive demonstrator DT includes the COMAU robots but also laser scanner and vision sensors' real-time data.



Physical workstation Digital Twin

Figure 20: Digital Twin of Automotive pre-industrial demonstrator

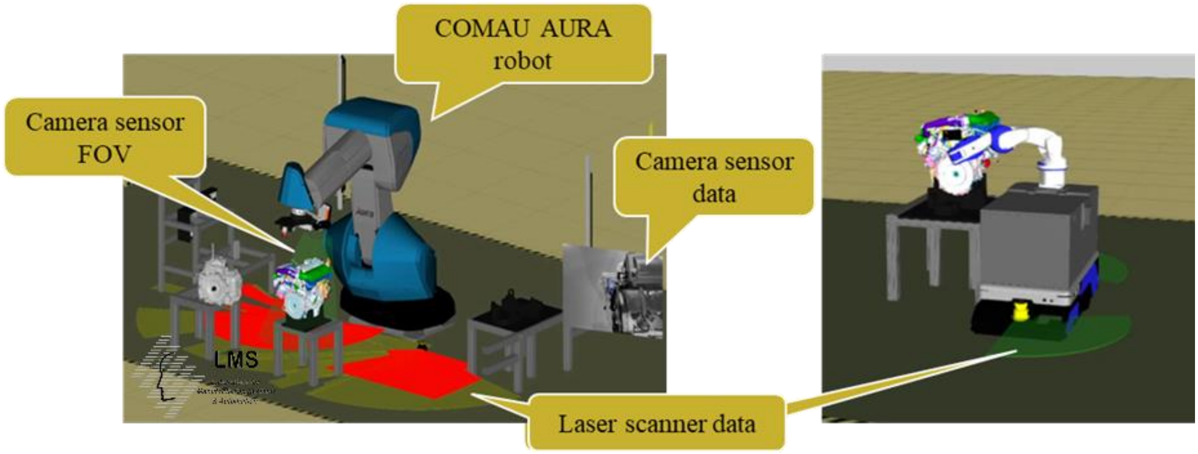


Figure 21: ODIN Digital Twin data

The Digital Twin module of the Automotive demonstrator seamlessly interfaces with the Robot Operating System (ROS) to receive real-time data of robots and sensors crucial for creating an accurate digital replication of the physical workstation. This module captures a diverse set of information derived from ROS, including robots' joint states, enable/disable signals for grippers' actuation, precise cues for pick and-place of gearbox and motor parts but also the result of the object detection and quality inspection modules. Additionally, it incorporates data derived from PILZ safety scanner sensors, ensuring the faithful visualization of safety zones' shape.

The Digital Twin module leverages UDP clients that function as ROS subscribers for data exchange with OpenFlow. This communication mechanism allows the module to subscribe to OpenFlow ROS topics. Concurrently, within Visual Components, the module employs UDP servers to receive, process, and dynamically alter the properties of the involved components based on the transmitted data. With the implemented UDP communication, the Digital Twin module establishes a real-time connection between ROS and Visual Components, ensuring the accurate synchronization of the virtual environment with dynamic events of the physical Automotive demonstrator.

3.2.2.3 AI Task Planner

The integration of the AI Task Planner module in the Automotive demonstrator has been completed up to M36 of the project. All the required assembly tasks and resources have been successfully modelled inside the database of ODIN including information about the nature of each task.

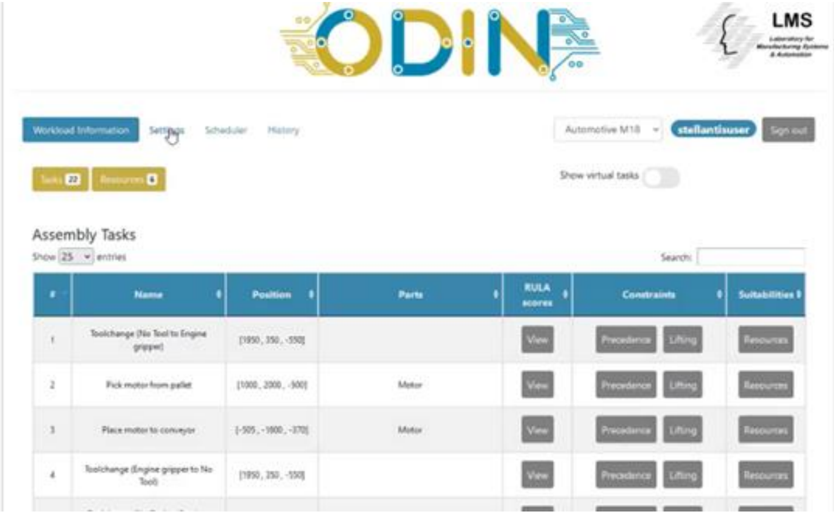


Figure 22: Integration of ODIN AI Task Planner with the Automotive demonstrator

The final version of the AI Task Planner consists of online re-planning features which are utilized under the automotive pilot demonstrator. The effect of planner's reconfiguration capabilities is centralized on operation 3. In case of faulty assembled parts' detection, after the execution of the quality inspection operation by the mobile robot, a human operator is informed to approach the motor assembly and perform the required corrective action on the motor. This extra action of the human is an update on the initial production plan and the AI Task Planner is triggered in order to handle the re-configuration request and generate the new task plan.

3.2.2.4 Virtual Commissioning

The Virtual Commissioning module integration under the Automotive pilot has been validated by designing new robot poses for the COMAU AURA robot in the case of updated initial position of gearbox table. After the change of the gearbox table's location inside the demonstrator layout, the robot is not able to pick the desired part since the gearbox is outside of detection camera's field of view when the robot is at its detection pose. In this case, the robot program needs to be updated in order to define a new detection pose for the AURA robot.

The production designer is responsible to update the layout of the Digital Simulation in order to install the gearbox table at its new position in the cell and using the VC model of the COMAU AURA robot he/she is able to program a new robot trajectory for the robot. After the validation of the robot movement in the Digital Simulation in terms of robot reachability and singularities, the production designer is able to export the corresponding robot program from the Visual Component software. Then he/she is able to upload the generated PDL and LSV file in robot program and update robot's trajectory.

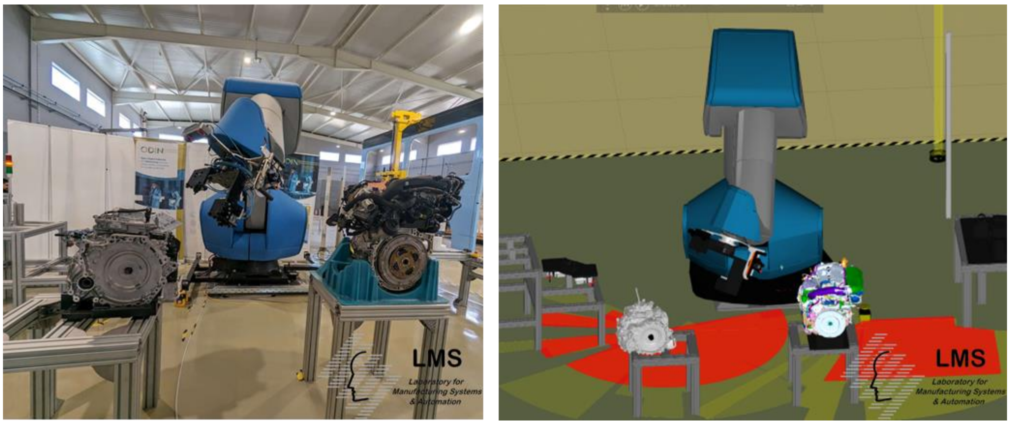


Figure 23: Virtual commissioning validation in the Automotive pre-industrial demonstrator

3.2.3. Integration of Networked Component with automotive initial industrial pilot

3.2.3.1 OpenFlow

The final version of ODIN OpenFlow has been integrated in the Automotive demonstrator at LMS premises. In its final form, the OpenFlow orchestrator is connected with all the other modules of ODIN which are required for the realization of the assembly process. The final version of OpenFlow and its integration with other ODIN modules is presented in D4.4.

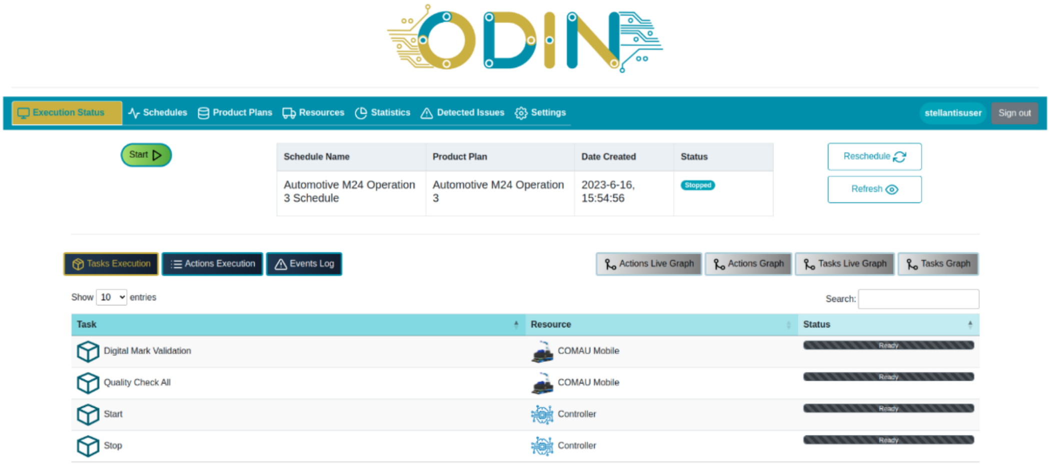


Figure 24: Integration of OpenFlow in the automotive pilot demonstrator

The execution schedule of the Automotive pilot has been updated in order to include all operations' tasks assigned to robots and human operators. A dockerized version of OpenFlow has been prepared by INTRA and is running in a high-performance PC at LMS premises.

The required actions execution by the robotic and human resources is based on a set of ROS Action and Services servers (Table 1) connected with the different hardware and software components of the Automotive demonstrator.

Table 1: ROS action servers for final Automotive pilot execution

ROS Action Servers	Description
Move Cartesian Action Server	Action server for the planning and execution of robot motions using Cartesian space goals.
Move Joint Action Server	Action server for the planning and execution of robot motions using Joint space goals.
Configure Payload Execution Service Server	Service server for robot's payload reconfiguration based on the payload of grasped parts (motor/gearbox/grippers).
Configure TCP Action Server	Action server for updating the robot's end effector when robot carries parts (motor/gearbox/grippers).
Detection Action Server	Action server for the detection of parts to be manipulated by the robot using CADMatch with pose estimation technique.
Assembly Detection Action Server	Action server for the execution of the assembly detection process.
Safety Action Server	Action server to communicate the safety status of the cell with OpenFlow module.
Execute Human Task Action Server	Action server for the connection of AR operator support application with OpenFlow.

Control Gripper Action Server	Action server for enabling / disabling robot’s grippers.
Mobile Control Action Server	Action server for mobile robot’s navigation.
Quality Inspection Action Server	Action server for the execution of the quality inspection algorithm.

The connection of OpenFlow module with the previously mentioned ROS Action and Service servers, along with the necessary ROS Controllers and hardware/software components is presented in the following figure.

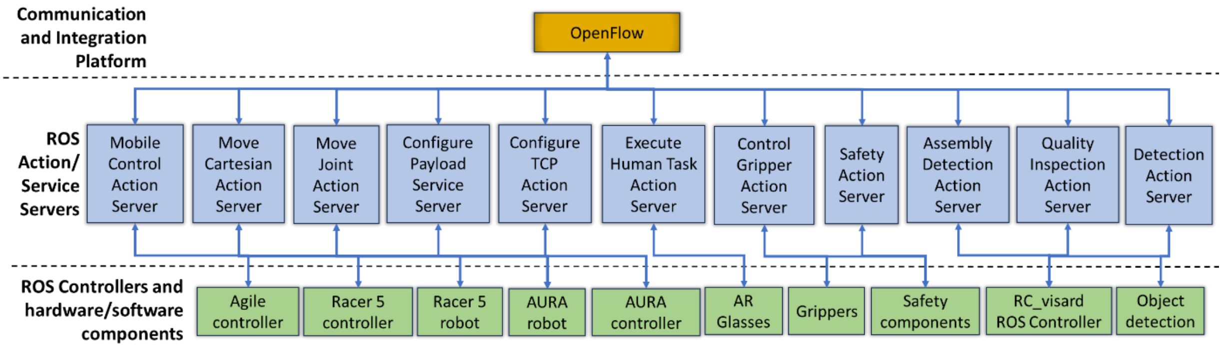


Figure 25: OpenFlow connection with ROS action servers for Automotive pre-industrial demonstrator at LMS premises

3.2.3.2 Cyber Security

The cybersecurity module of ODIN is integrated in the pre-industrial demonstrator at LMS facilities. This module has the overview of ODIN network for potential threats detection and inform the OpenFlow in order to accordingly adapt the execution of the assembly process if required. This module’s integration with the OpenFlow and the Automotive pre-industrial demonstrator is similar to the approach presented in subsection 0.

3.2.4. Automotive pilot safety concept integration at LMS premises

With the support of PILZ, the safety concept of the Automotive demonstrator has been integrated into the pre-industrial demonstrator of LMS.

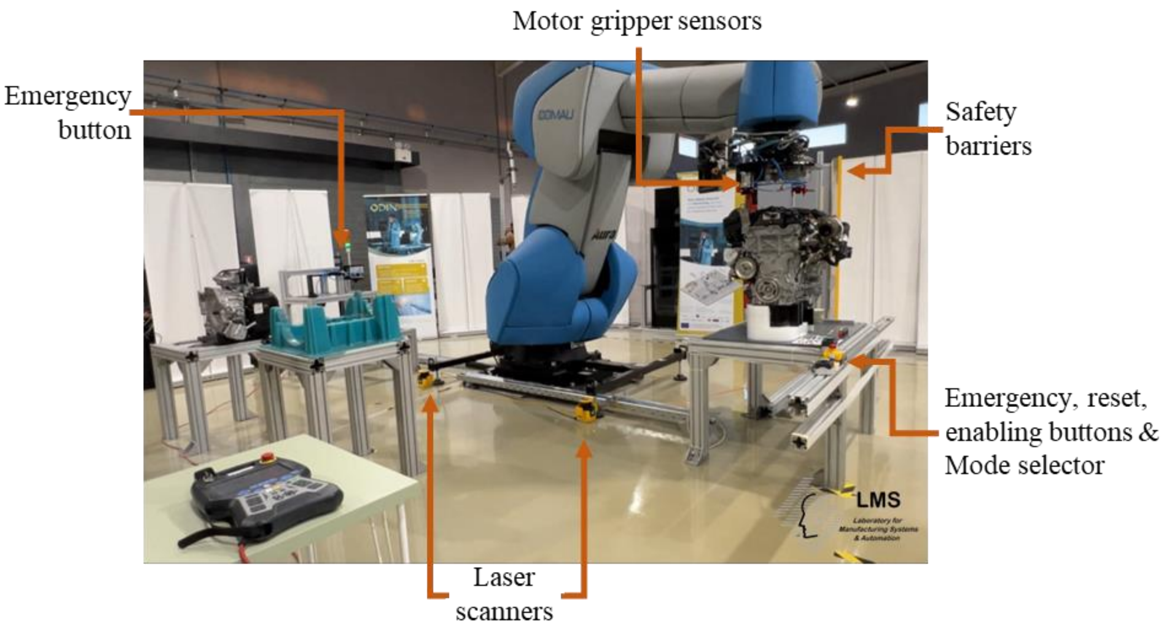


Figure 26: Safety components installed in the demonstrator layout at LMS premises

The safety concept of the Automotive demonstrator consists of the following safety component's installation in the investigated demonstrator:

- Safety PLC

The safety PLC of the automotive pilot is connected with all the safety hardware devices of the robotic cell. The main safety logic is implemented within this PLC to increase the performance and ensure reliable and consistent operation of the process. The safety PLC of the Automotive pre-industrial demonstrator is installed in the main cabinet of ODIN cell.

- Motor gripper sensors

A set of position and inductive sensors have been installed on the motor gripper to detect the actuation of the gripper and confirm that the grasping process has been completed successfully and then trigger the OpenFlow about the continuation of the assembly.

- Laser scanners and barriers

Installation of laser scanners and barriers inside the layout of the automotive demonstrator to detect human operators presence and stop the assembly in case that an operator has infringed a safety zone. The use of laser scanners gives the opportunity to system to change the speed of the robot in case of obstacle detected inside the warning area of the layout.

- Emergency button

Two emergency buttons are installed inside the automotive layout in order for the operator to stop the assembly process if it is required. The first emergency button is installed on the assembly table of the automotive demonstrator where human operator approaches for the realization of motor and gearbox connection during the first operation of the investigated pilot line. The second button is placed on the back side of the tool stand. These buttons are connected with the safety PLC of the demonstrator.

- Reset and enabling buttons

One reset button is installed next to each emergency button of the demonstrator layout in order for the operator to restart the system if required. One more button is installed on the assembly table in order to enable the actuation system of gearbox gripper when the placement of the gearbox is completed.

- Mode selector

Based on D5.2, the operator of the automotive pilot is responsible to manually guide the AURA robot when it is equipped with the gearbox, near the motor part in order to align the two components and perform the screwing tasks. For the realization of the manual guidance operation, a mode selector component is integrated with the safety PLC of the demonstrator. In order for the operator to enable the manual guidance mode of the AURA robot, a specific configuration of the mode selector is required.

3.3. Automotive demonstrator at TECNALIA premises

The operation 2 of the automotive demonstrator has been carried out at TECNALIA premises. This operation starts after the motor and gearbox connection under Operation 1 and consist on the installation and screwing of additional parts in the motor/gearbox assembly (Figure 27). The disruptive innovation consists of doing the screwing operation in motion, improving the efficiency of the automated solution. The operation 2 can be subdivided in the following steps:

1. TECNALIA mobile robot approaches the conveyor belt.
2. When the motor passes in front of the robot, the mobile platform starts tracking and following it along the conveyor.
3. Then, the screwing while moving operation starts. This step allows assembling of additional parts that the operator have been installed manually.
4. When the screwing operation is finished, the TECNALIA mobile robot goes away from the conveyor belt leaving the motor moving to the next station.

Figure 27: TECNALIA demonstrator - Operation 2 layout

ODIN components' integration in the TECNALIA pre industrial demonstrator are presented below.

3.3.1. Integration of Open Component with automotive initial industrial pilot

3.3.1.1 Autonomous mobile manipulators

Despite the main advantages of the developments regarding the 3D Navigation are exploited at the aeronautics demonstrator (details are presented at Section 4.2.1.1), these capabilities have been also integrated in the automotive demonstrator at TECNALIA premises.

The usage of a 3D LiDAR provides much more robust robot localization than with the 2D approach, since the obtained point cloud contains data of the walls and ceilings. With this information the localization algorithms are less sensible to eventual changes in the workshop such as boxes, pallets, equipment re-organization, or any obstacle that can appear over the reference map that the robot has.

3.3.1.2 Robotic perception for the process, the human and the environment

One of the features that might be of great importance is the robot's ability to adapt the tool's movements in real time. This feature is crucial, especially for the Automotive Pilot where the motor is continuously moving along the conveyor belt (or an AGV in similar scenarios). Therefore, it is mandatory to develop a Mobile Visual Servoing module able to carry out tasks on non-stationary parts. This module adds the capability to carry out real-time control of the robot arms based on visual feedback received by vision systems. The current development has been integrated at TECNALIA's pre industrial demonstrator and includes the following features:

- Low-level robot control based on the Direct Servo and Smart Servo libraries provided by KUKA. The KUKA LBR IIWA [8] arms are directly connected to ROS nodes which commands the manipulators in joint space with a frequency of up to 350Hz.
- Cartesian twist controller developed by TECNALIA and implemented as ROS controllers (plugin). This controller accepts twist commands which can be referenced to any arbitrary tool and reference frame.

- Control framework to enable/disable low-level control of both KUKA LBR IIWA arms. This framework allows to mix of high-level movements (joint trajectories) with control operations in any application in a seamless way.
- Mobile Visual Servoing application able to control both the mobile platform and robot arm based on the visual feedback, relying on an eye-to-hand configuration where the camera is placed on the front of the mobile platform. This module generates twist commands which are sent to the Cartesian twist controller and the mobile platform with a frequency of 25Hz.

The presented architecture is depicted in Figure 28.

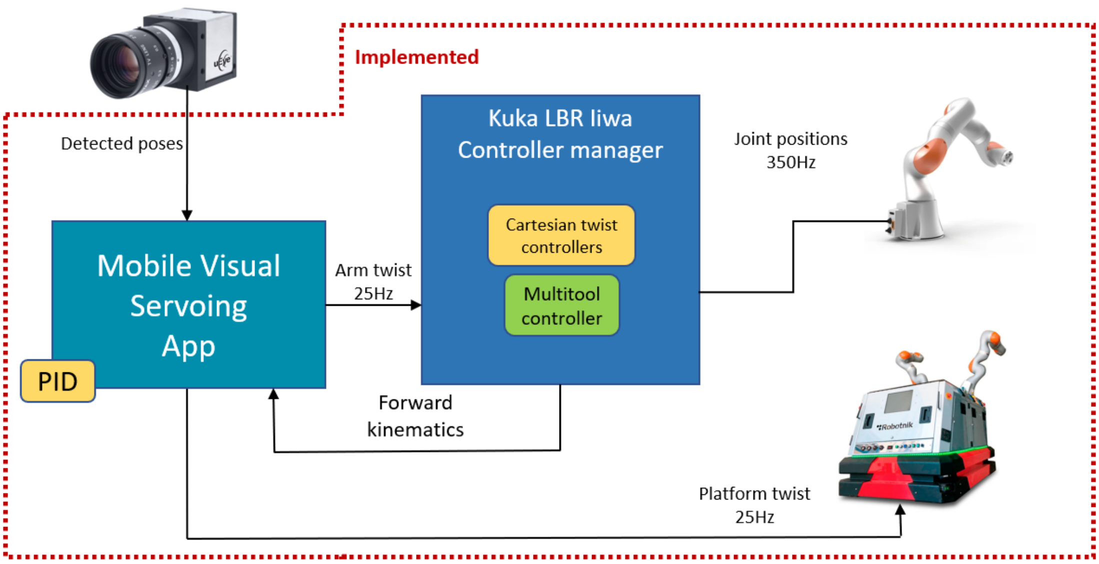


Figure 28: General architecture for screw while moving

Regarding the Mobile Visual Servoing application, several features have been added, which are listed below:

- Based on the initial tests, a straightforward approach where the control loop manages both the mobile platform and robot arm from the beginning did not fit the posed problem. From the operational point of view, to accomplish the screwing task while the engine moves, in an initial phase the platform should approach the engine and once it is nearby, the arm should start moving towards the screws. Additionally, to insert and remove the screwdriver it is necessary to approach the screws perpendicularly, adding some intermediate points in the arm destinations. Therefore, it was decided to add a state machine to guide the control loop among the different steps of the screwing task, as illustrated in Figure 29:
  - **Initial platform approach:** The mobile platform approaches the desired marker pose to place the robot in a position where the arm can reach the screws. At this initial phase, the arm is still, only the platform receives twist commands.
  - **Initial arm approach:** As the mobile platform is placed near the desired position, the arm tries to reach a pose perpendicular to the screw plane and at a parametrizable distance. The platform receives twist commands to adjust its position to the desired marker position while the arm receives twist commands to the approach pose.
  - **Destination arm approach:** The robot arm tires to reach the screw position. At this phase, the platform receives twist commands to adjust its position to the desired marker position while the arm receives twist commands to the screwing pose.
  - **Gripper activation:** As the gripper can take some time until its activation, the screwing task in this specific case, the mobile platform and arm must maintain the position while the target (engine) is moving. The gripper is activated asynchronously using a thread to call a defined ROS service. In this case, both the mobile platform and its robotic arm receive twist commands to compensate the target's movement.

- **Operation:** In this state, the platform and the robotic arm maintain the desired position for a defined amount of time. This state is used to leave some security time to perform the task (screwing in this case) and carry out the task without any unexpected event. In this case, both the mobile platform and arm receive twist commands to compensate the target's movement.
- **Arm retract:** In this last state the mobile platform maintains the defined marker position while the arm moves backwards to a safe position perpendicular to the screw, ensuring a safe removal of the screwdriver.
- After this last state, if more screws are defined, the state machine goes back to the ***initial arm approach*** state to work on the next screw.

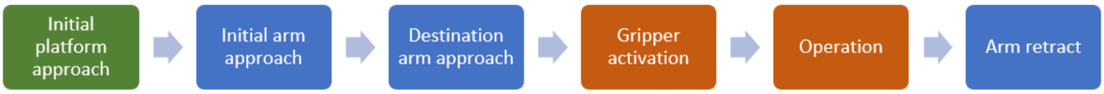


Figure 29: States of the screwing task

- The control law manages several homogeneous transformations to calculate the desired twist vectors for both the mobile platform and the arm. Initially, from the setup calibration process the module includes the homogeneous matrix

$$ {}_{platform}H^{camera}, $$

defining the pose of the camera in the mobile platform's frame, as well as matrix

$$ {}_{arm}H^{camera}, $$

defining the camera pose in the arm's base frame. For each execution, the user can parametrize the process defining the pose between the camera and marker (target pose of the platform) and the pose between the marker and the arm target (pose where the arm will carry out the screwing) using matrices

$$ {}_{camera}H^{marker*}, $$
$$ {}_{marker}H^{dest}. $$

In each control loop, the system receives the last marker detection pose and arm's pose

$$ {}_{camera}H^{marker}, $$

which are used to calculate the error of the mobile platform and arm using equations

$$ E^{platform} = \left({}_{platform}H^{camera} \cdot {}_{camera}H^{marker}\right)^{-1} \cdot {}_{platform}H^{camera} \cdot {}_{camera}H^{marker*}, $$
$$ E^{arm} = \left({}_{arm}H^{tool}\right)^{-1} \cdot {}_{arm}H^{camera} \cdot {}_{camera}H^{marker} \cdot {}_{marker}H^{dest}. $$

Finally, these errors generate the twist vectors of the platform and arm through a PID module included in the control framework

$$V^{platform} = PID\left(E^{platform}\right),$$
$$V^{arm} = PID\left(E^{arm}\right).$$

These two twist vectors are sent to the low-level twist controllers of the mobile platform and robot arm for their execution.

The presented architecture allows a vision-based control of both the mobile platform and robotic arm, as well as the asynchronous activation of the screwdriver during the control process.

In the demonstrator developed at TECNALIA premises until M36, some screws have been selected on the top of the motor provided by STELLANTIS for being tightened. In the current phase an OnRobot screwdriver is being used instead of ESTIC (Figure 30), due to different reasons:

- Size: ESTIC screwdriver [9] is very elongated due its mechanism for reducing the effort suffered by the operator, the OnRobot [10] is more compact. A compact shape reduces the possibility of configuration changes when a tracking is performed. The handicap is the obviously the torque provided by the OnRobot, which does not provide enough strength for automotive standards.
- Adaptability: OnRobot screwdriver is a robotic-oriented tool, i.e., provides specific features for screwing through a robot in an automated manner. This includes eccentric screw search, error detection and handling strategies, feeding, etc. ESTIC screwdriver is an operator-oriented tool that does not provide those features, even though mechanical accessories could facilitate the process.

Figure 30: ESTIC screwdriver (left) and OnRobot screwdriver (right)

The main objective is validating the concept and base technology, integrating a more appropriate screwdriver for reaching production times.

Regarding the obtained results, Figure 32 shows the sequence of a screwing test. The marker located in the motor fixture is detected by the robot for start following it: on the one hand the robot platform is navigating along the conveyor, and on the other hand, the robot arm is trying to reach the target (the screw). When the tracking error is low enough the screwing process can be triggered. At Figure 27 the limited length of the conveyor belt can be perceived, thus, in this set-up the current demonstrator only allows doing a unique screw operation.

With this set-up the required timing for performing a screw has been measured. The screwing tests produced the following results (Figure 31 and Table 2):

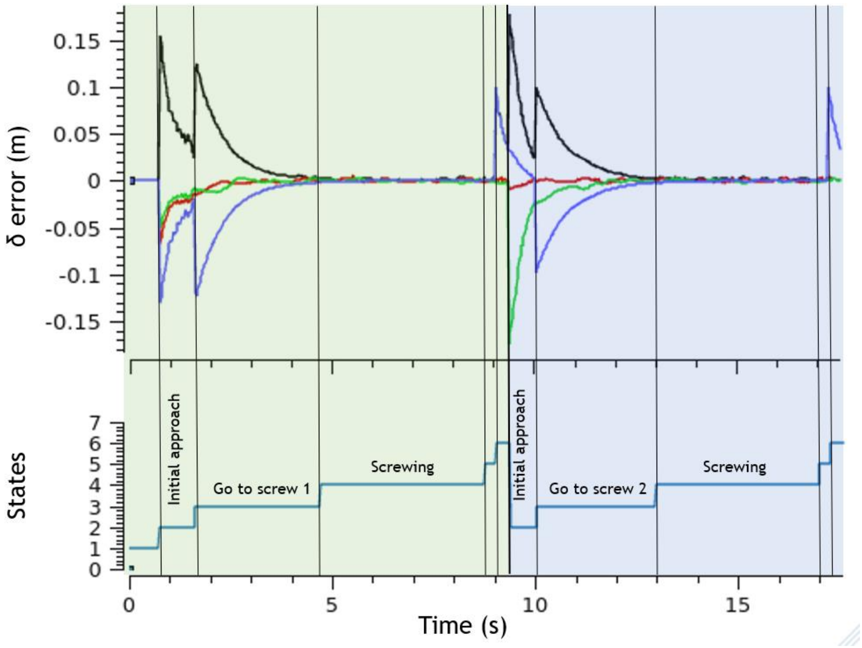


Figure 31: Error plotting and state sequence

Table 2: Summary of the time measurement of the screwing tests

Step	Time
Init + approach	2 secs
Go to screw	3 secs
Screwing	3-5 secs
Total	8-10 secs

These time results are preliminary: the approach and retract are not optimal, the screwing time depends on the screw length, the screwdriver is not as powerful as ESTIC, etc. The approach time required considerably additional time due to the required time for converging to a reasonable error of positioning for starting the screwing. These times are being improved at each iteration and is expected to be reduced in the next integration activities.

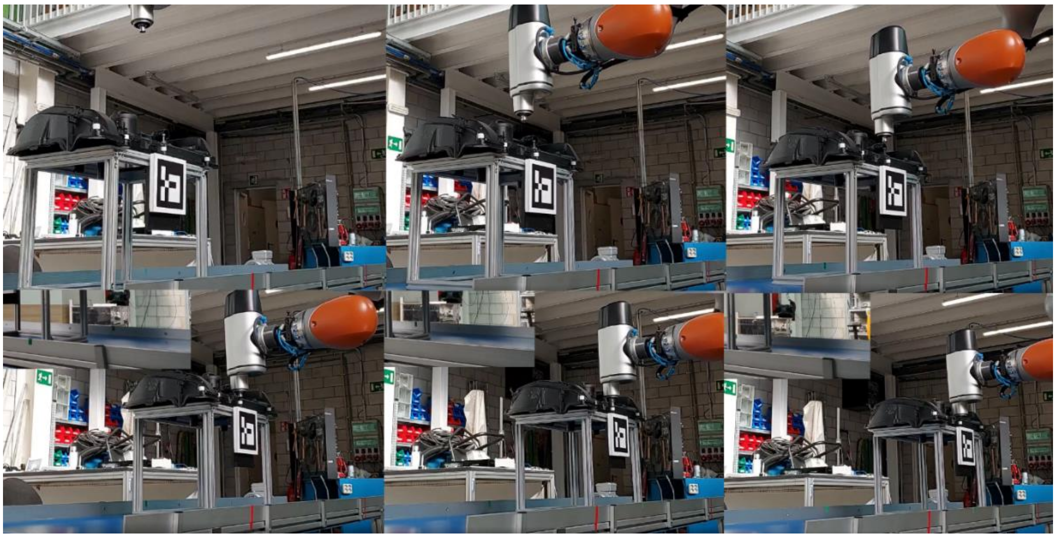


Figure 32: First demonstration of successful screwing in motion

3.3.1.3 User friendly robot programming interfaces

As well as with Section 3.3.1.3 (3D navigation for autonomous mobile manipulators), the aeronautics demonstrator takes greater advantage of user-friendly robot programming interfaces. But as mentioned in the D5.2, this module has been integrated in the automotive demonstrator. Figure 33 shows how through Blocky based GUI the required skills for performing a screwing while moving operation can be sequenced easily.

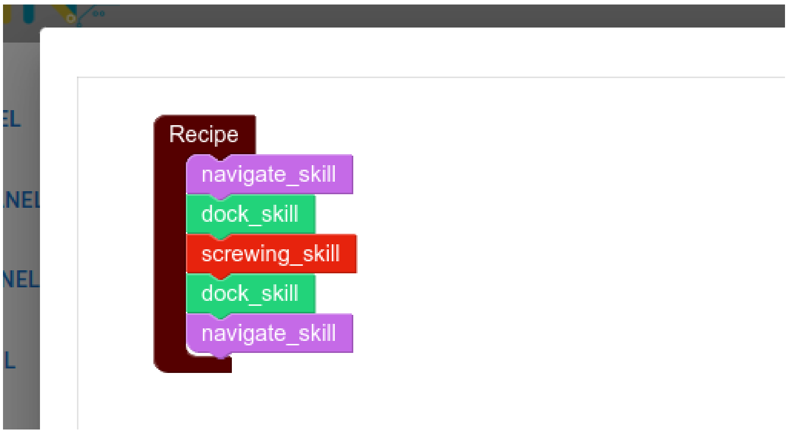


Figure 33: Blockly based screwing while moving operation sequence

3.3.2. Integration of Digital Component with automotive initial industrial pilot

As for the digital component, the demonstrator integrates the developments made up to M36 that allow representing a digital version of the pilot.

3.3.2.1 Digital Simulation

Up to the M36, the Digital Simulation of the automotive demonstrator (Figure 34) has been used for various purposes, namely:

- Planning the demonstrator's sequence of operations, making it possible to discuss the limits of the previous and subsequent operations.
- Analysing the feasibility of the concept, validating the reachability of the robot arms and determining the relative position of the platform with respect to the conveyor belt.
- Validation of the Safety Concept, identifying the critical steps in which additional actions are required.

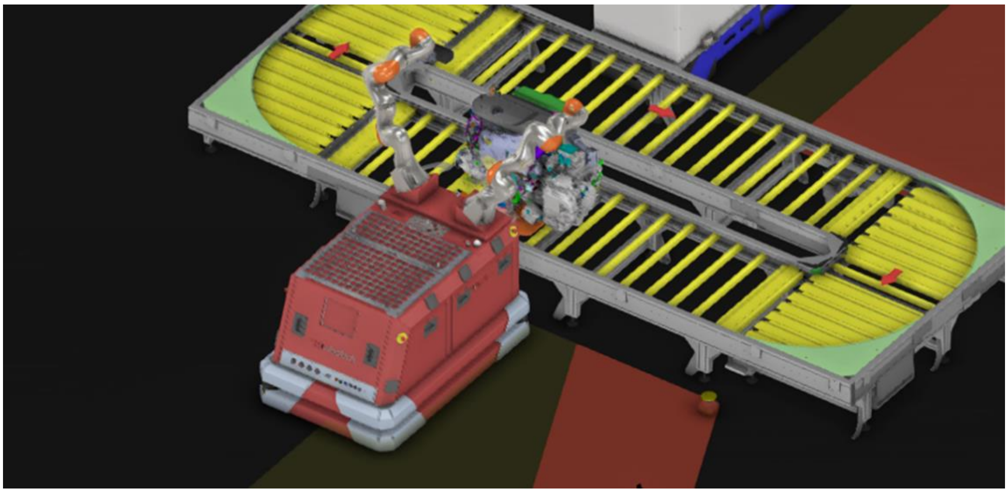


Figure 34: Digital Simulation of the automotive industrial pilot Operation 2

3.3.3. Integration of Networked Component with automotive initial industrial pilot

Up to M36, the integration interfaces proposed in the previous period have been updated and implemented enabling OpenFlow interaction with the TECNALIA's robot programming framework.

3.3.3.1 OpenFlow

In the previous period an interface based on ROS actions was proposed. Each skill was intended to offer an action server for being requested by OpenFlow. After some integration tests, the concept has been generalized, centralizing all skill execution through a unique action client.

Instead of requiring an action server per step of the operation 2, or at the end, per skill, the Execution Engine introduced at D5.2 implements an action server which can execute any kind of skill through an "execute_skill" ROS action server, providing the skill name as parameter. It manages the requests from OpenFlow, provides feedback at each sub-step of the skill, and returning the result when the skill finishes. This approach increases flexibility of the system, avoiding the need of programming new action servers when new skills are added to the framework.

At M36, after the refinement of the OpenFlow integration into the TECNALIA's robot programming framework, the workflow is as follow:

1. Through user friendly robot programming interfaces (CAD Programming, Blockly or Onsite-interactive skill programming), which will be presented in more detail at D2.5 and Section 4.2.1.3 of this document, skills can be parametrized, sequenced and grouped for performing different task or operations.
2. OpenFlow receives production orders (from different sources depending of the end-user) and after processing them, creates and schedule a succession of tasks which are mapped to available skills at TECNALIA's robot framework.
3. OpenFlow request TECNALIA's Execution Engine the sequential execution of each scheduled task. The Execution Engine provides feedback of the status of each task, and the result after completion.

Regarding the Operation 2 of the automotive pilot, the involved tasks are the following: navigate to conveyor, dock, start screwing, undock, navigate to start. As presented in Figure 35, OpenFlow generates the schedule for accomplishing the Operation 2, and on the other hand, the Execution Engine contains the implementation of all corresponding skills.

Task	Resource	Status
Docking	TECNALIA mobile	Ready
Go To Home Station	TECNALIA mobile	Ready
Go To Screwing Station	TECNALIA mobile	Ready
Screwing in Motion	TECNALIA mobile	Ready
Start	Controller	Ready
Stop	Controller	Ready
Undocking	TECNALIA mobile	Ready

Figure 35: Schedule of task generated by OpenFlow

3.3.4. Automotive pilot safety concept integration at TECNALIA premises

The Automotive pilot safety concept presented by PILZ at D5.1 is being integrated at TECNALIA's demonstrators.

The TECNALIA's mobile robot used in the Automotive pilot has a SICK safety PLC that runs the safety logic to achieve the requirements of the safety concept (at Figure 36 the FlexySoft project [11] with the initial hardware can be seen). Because of this it was decided that all the safety logic will run on the SICK safety PLC and the PILZ Safety PLC will only be used for the communication with the main PILZ Safety PLC of the pilot (located in the main cabinet).

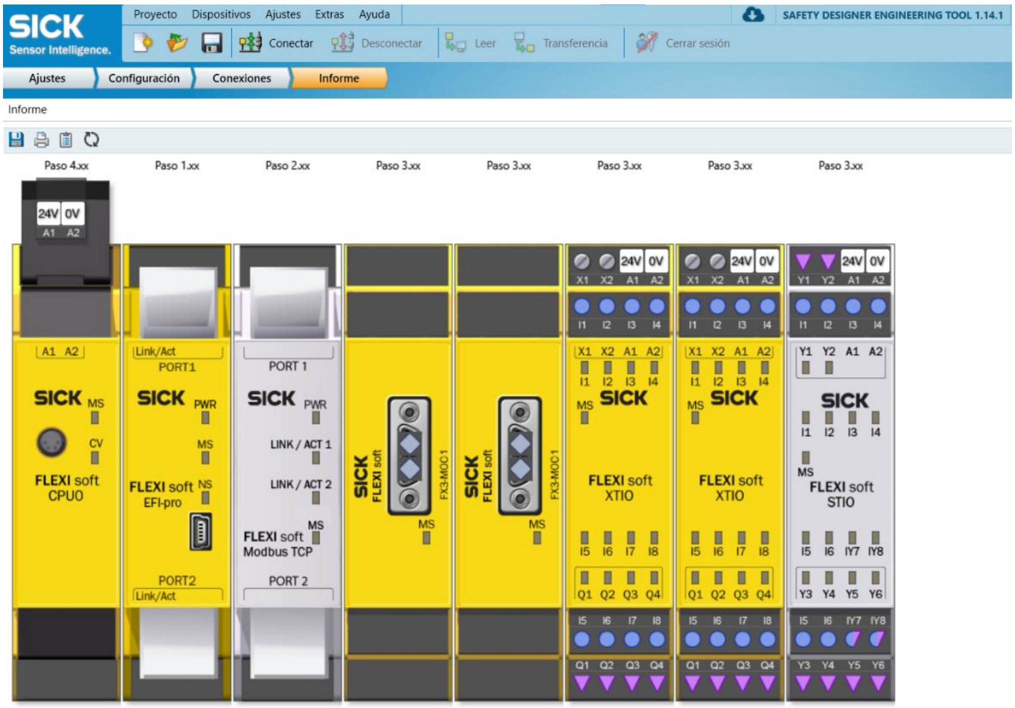


Figure 36: FlexiSoft project with the current hardware

The safety concept has been developed at a higher level and adapted for aeronautics and automotive use cases. In addition to changing the PLC Safety logic, bellow is a list of other interventions needed to implement the security concept and their status up to M36:

- **Adding 3 SICK IO modules:** The previous safety set-up does not have enough IO modules for integrating the required sensors and safety modules. Thus, three additional safety IO modules have been mounted in the ODIN robotic platform up to M36.
- **Adapting safety configuration for IIWA arms:** Fine-tuning of the safety settings for the IIWA arms is required for accurately determining their position within safe zones, mitigating risks during operations. This configuration is carried out inside the KUKA IIWA robot cabinets. Not yet tested the integration with FlexiSoft at M36.
- **Transfer emergency signals from IIWA arms:** In the previous set-up the emergency of the IIWA robots was not connected with the platform, i.e., if the robot arm enters in emergency the platform could continue moving without being aware of the issue. Enabling the IIWA arms to promptly escalate emergencies to the platform enhances overall safety measures, addressing critical situations when screwing operation is being performed. At this stage of the project, the robots are already wired with the safety PLC, but the integration with FlexiSoft has not yet been tested on M36.
- **Contour detection for safety zone switching:** Implementing this module facilitates a seamless transition between navigation and working safety zones, allowing a safe approach of the robot to the conveyor belt. Not yet implemented or tested at M36.

- **Retroreflective sensors on the robotic platform:** These sensors serve as a crucial checkpoint, ensuring the robot's proximity to the conveyor. The Retroreflective sensors have been tested on the COMAU mobile platform but have not been implemented in the TECNALA mobile platform at M36.
- **Integration of PILZ safety PLC:** Integrating this PLC allows communication between subsystems, and thanks to the R3 EchoRing device the TECNALIA's platform can communicate with the main PLC of the automotive pilot case. Not yet implemented or tested at M36.

3.4. Safety Related Parts of Control System

The components and functions described herein represent an update of the safety functions described in sections 5.5 of deliverable D2.1. These components and functions are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 4.1 and 5.2 of deliverable D5.1 (M18), respectively. Each analysis represents the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9, providing a higher level of detail.

Below are the updates of the safety architecture and safety concept for each Business Use Case.

a. Motor and gearbox manipulation and assembly operation (AUTO-BUC-1):

Figure 37 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

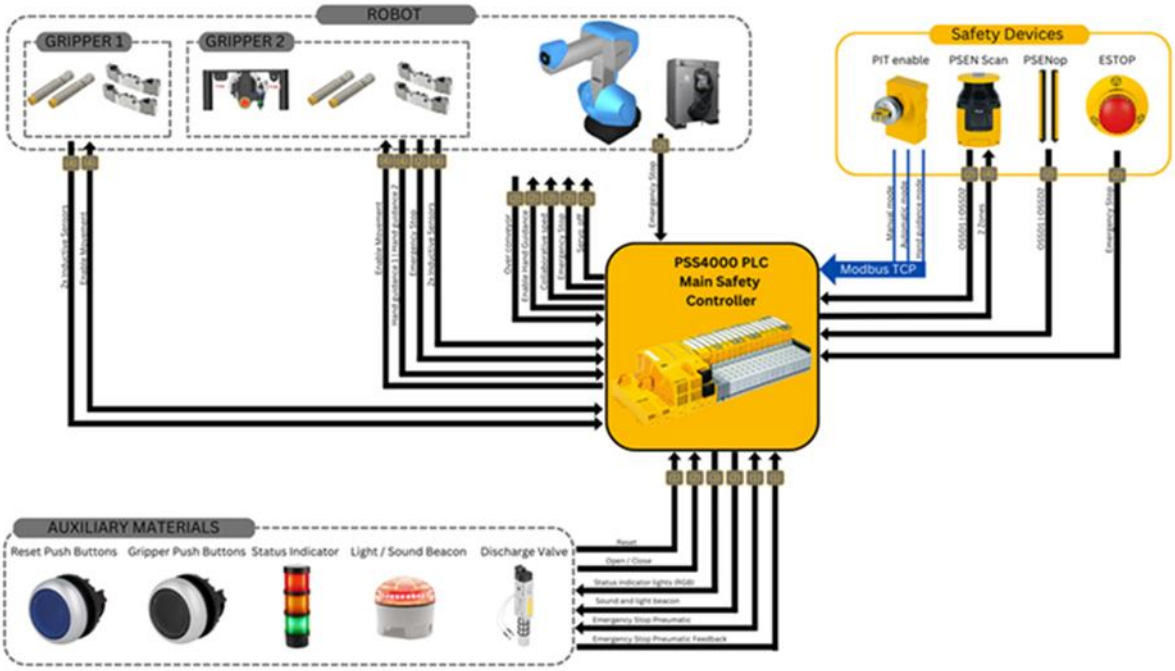


Figure 37: Safety Architecture for AUTO-BUC-1

For AUTO-BUC-1 no modification to the safety functions listed in D5.1 have been made.

b. Kitting operation (AUTO-BUC-2)

Figure 38 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

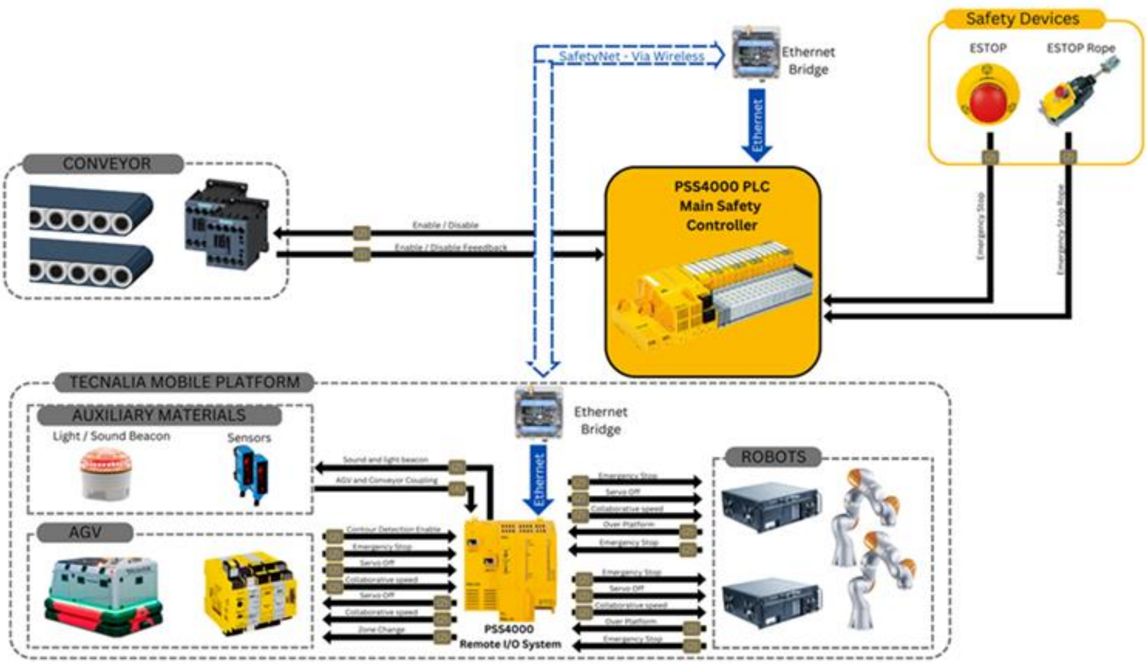


Figure 38: Safety Architecture for AUTO-BUC-2

For AUTO-BUC-2 no modification to the safety functions listed in D5.1 have been made.

c. Inspection operation (AUTO-BUC-3)

Figure 39 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions addressed to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

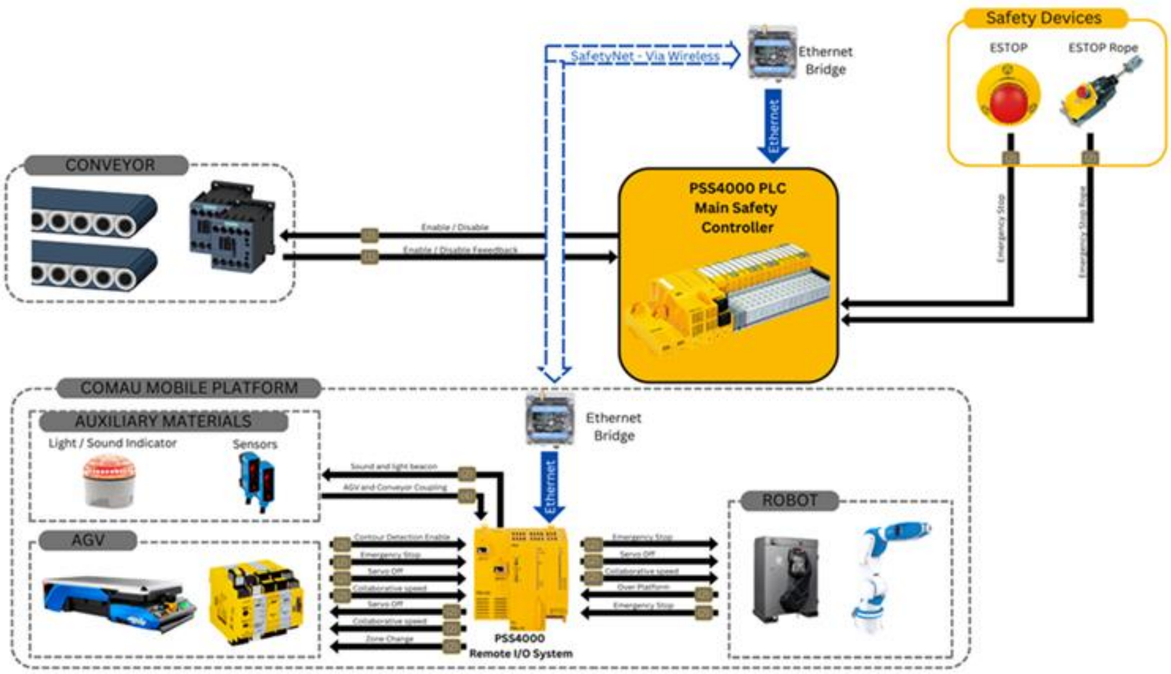


Figure 39: Safety Architecture for AUTO-BUC-3

For AUTO-BUC-3 no modification to the safety functions listed in D5.1 have been made. The coupling mechanism used to ensure a safe coupling between the conveyor and the AGV will be the same as in AUTO-BUC-2.

As mentioned in D5.1, the required performance level for the safety-related control system above described is PL "d" category "3" according to EN ISO 13849-1 [12]. This level is stipulated by standard type C EN ISO 10218-1 [13] for robots and robotic systems.

3.4.1. Safety Concept Update

The modifications described herein represent an update of the safety concept described in sections 6.2 of deliverable D5.1

AURA Robot autonomous operation – SSM

The laser scanner safety zones will not be static. They will change in shape depending on the speed and position of the AURA robot in accordance with the ISO 10218 -2 [14]. A safe signal based on the AURA robot Cartesian Safe limited Position and Safety-Rated monitored Speed will be used to enable the different safety zones.

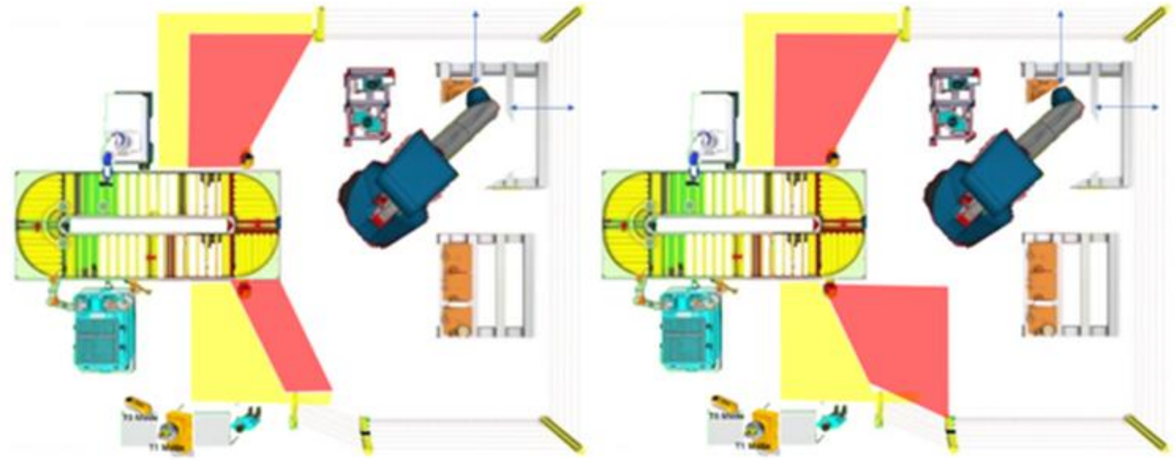


Figure 40: AUTO-BUC-1 laser scanner safety zones

*Mobile Platform operation operations linked to conveyo*r

During the screwing (AUTO-BUC-2) and inspection operations (AUTO-BUC-3) of the automotive demonstrator, a safe coupling of the AGVs with the conveyor will take place.

The AGV from TECNALIA and COMAU will be equipped with two retroreflective sensors. In the conveyor, reflective tape will be installed in two different positions/angles and adjusted with a different range. Using contour detection, the AGV will detect if it is in the coupling position with the conveyor and will activate the muting of the safety scanner in the direction of the conveyor.

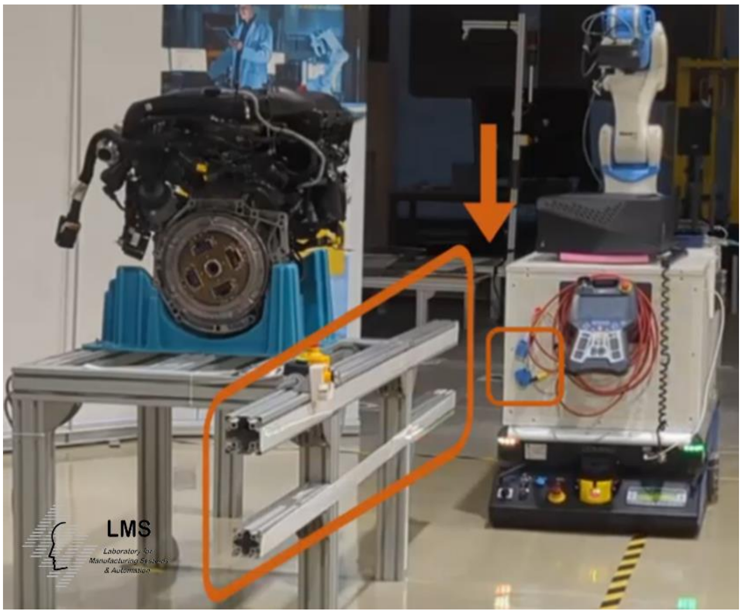


Figure 41: COMAU mobile robot coupling action at LMS pre-industrial demonstrator

Once in position, the retroreflective sensors are used to detect the reflective tape installed in the conveyor. The AGV is able to operate as long as the sensors are detecting the reflective tape. Once the operation is complete the decoupling process can begin.

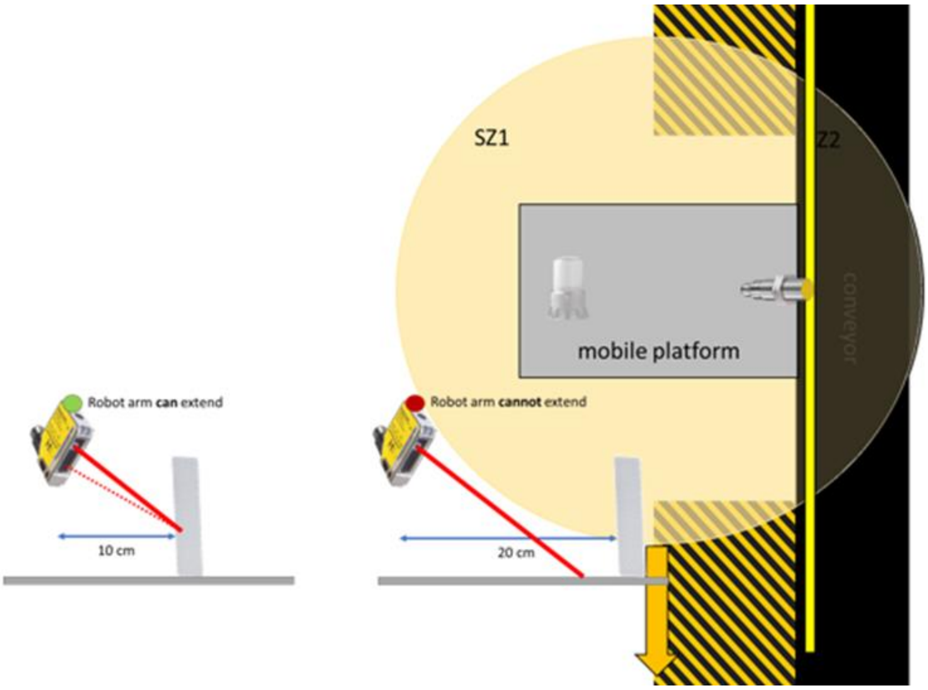


Figure 42: AUTO-BUC-2 & AUTO-BUC-3 coupling mechanism

The rest of safety functions required remain the same as the ones explained in D5.1.

4. ODIN AERONAUTICS PILOT DEMONSTRATOR

4.1. Overview

The aeronautics pilot demonstrator is focused on the automation of a set of operations that currently are performed manually at AEROTECNIC facilities. Through the ODIN key enabling technologies, the productivity of the investigated pilot line will be improved. The Aeronautic demonstrator consists of the following operations:

- Template-based drilling of the Fan-Cowl (FC), for the assembly components (Figure 43.a).
- FCs handling and transportation of the parts between different workstations (Figure 43.b).
- Inspection of the parts for several purposes: detection of presence/absence of components, checking the right assembly of components, detection of defects, etc. (Figure 43.c).

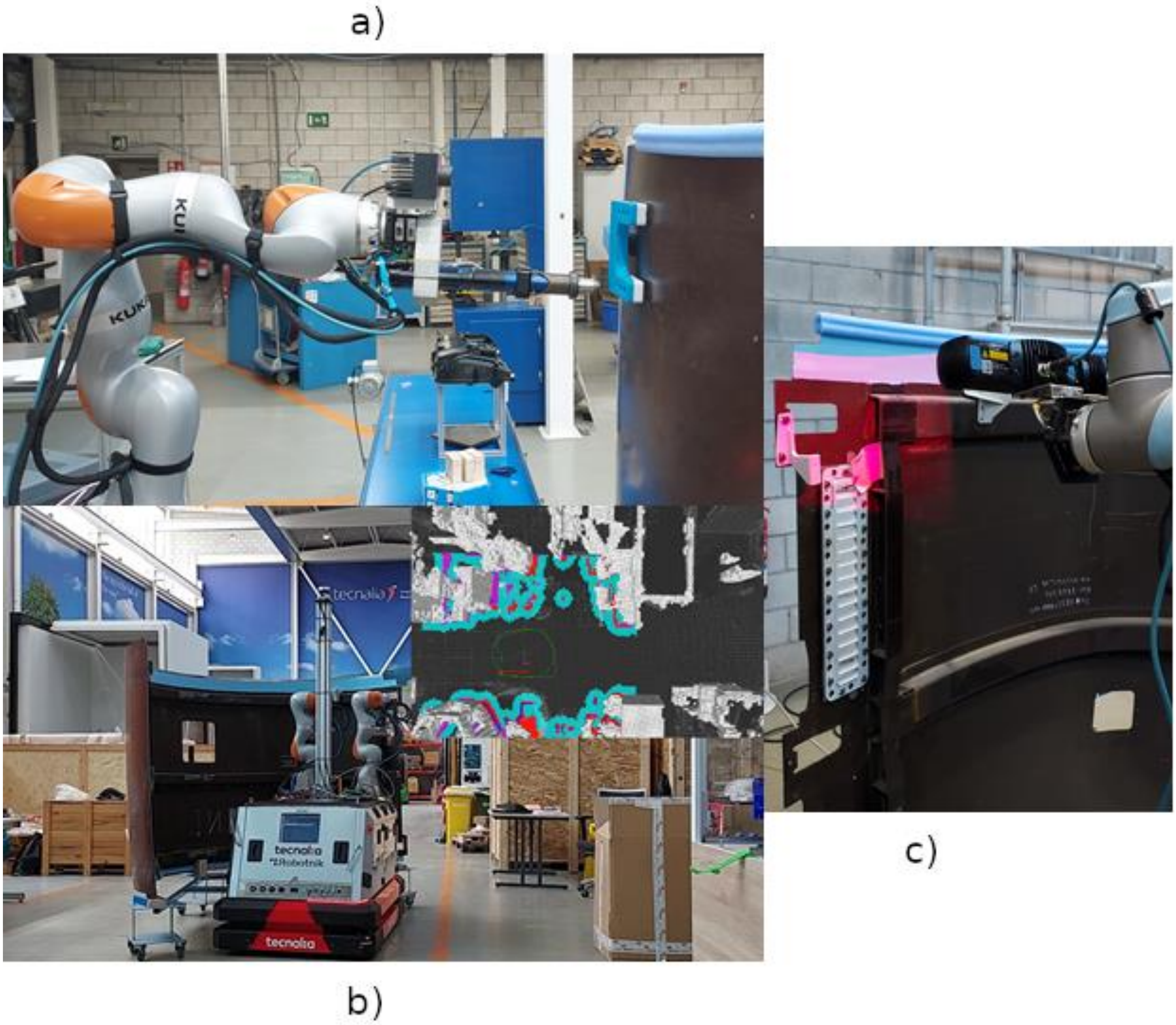


Figure 43: a) Template-based drilling. b) FC transportation. c) Part inspection

4.2. Aeronautics demonstrator at TECNALIA premises

Throughout the project, once the key enabling technologies have been validated in the small scale pilots, they have been evolved with the intention of looking as much closer to the physical demonstrator at AEROTECNIC premises. Up to M36, TECNALIA demonstrator consists of two main cells that are in different locations in the workshop. AEROTECNIC has provided two FCs for the demonstrators and each of them is used for different operations' execution.

One FC has been mounted on specifically designed cart ready for transportation operation (Figure 44). This part is transported along the workshop to a target position, which will simulate the involved logistics for transporting one Fan Cowl from one station to another, as presented in Figure 45.

Figure 44: FC on the transporting cart

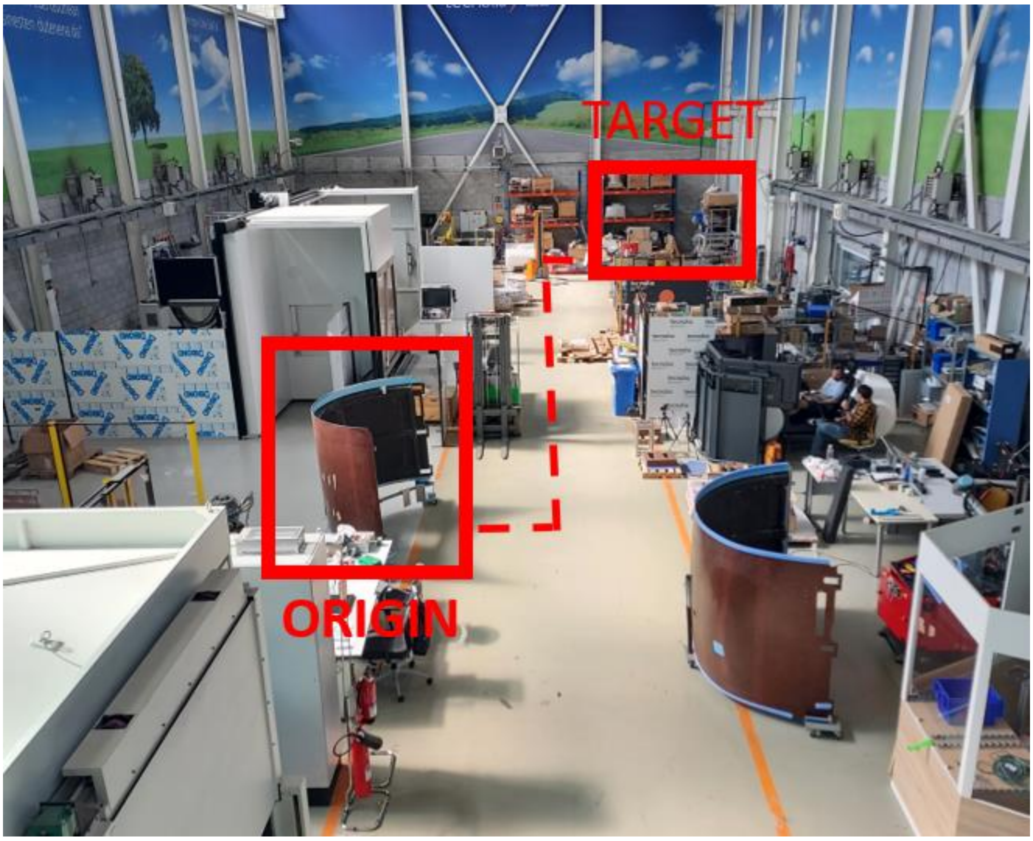


Figure 45: Transporting origin and target stations in the workshop

The second FC is used for demonstrating the template-based drilling and quality inspection (Figure 46). As presented in Figure 47, the element has been equipped with a dummy drilling template (will be replaced for an actual one in the future) and some of parts provided by AEROTECNIC to be inspected. On one of the sides of the FC the drilling operation is performed, while on the other side the quality inspection operation is carried out (Figure 48).

Figure 46: Drilling and inspection cell location in the workshop

Figure 47: Drilling cell

Figure 48: Inspection cell

4.2.1. Integration of Open Component with Aeronautics initial industrial pilot

4.2.1.1 Autonomous mobile manipulators

Regarding the Autonomous mobile manipulators, the focus during the latest period of the project was on properly configure the navigation suite so the robotic manipulator could safely navigate attached to the FC.

The dynamic configuration of the planning/control part of the navigation suite had several constraints to consider:

- Large protection area ("footprint") to consider due the large size of the FC.
- Slow speeds on lineal and, specially, angular movements to prevent stress on the docking system.
- Lack of 3D perception on close distances, where collision risk is higher, due the high position of the 3D LiDAR.
- Prioritise backwards motion so the FC is "protected" by the advancing robot and not the other way around.
- Avoid self-perception of the dolly and FC due the "non-rigid" nature of the system (due torsions in the dolly/docking or inaccuracies in the FC mounting).

The combined manipulator-FC footprint was defined using the CAD models, using the system profile with an added padding for safety. This padding can be adjusted depending on the characteristics of the operational environment. In cladded environments, the padding can be reduced to allow the robot to pass through narrower spaces. In more open environments, the padding can be bigger for increased safety. Figure 49 shows the footprint defined with a padding of 0.5m. In the tests done in TECNALIA the padding was reduced to 0.2m due space constraints in the workshop.

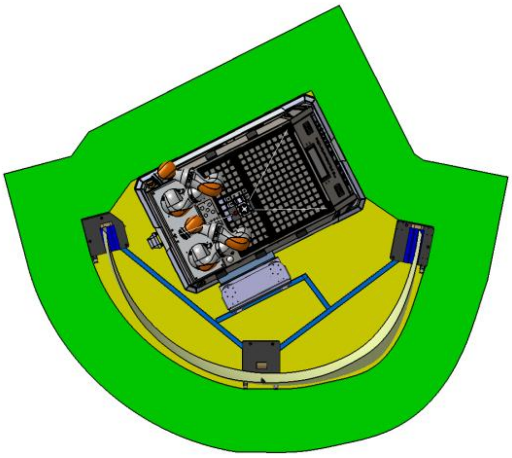


Figure 49: Navigation planner's safety "footprint" of the combined manipulator-FC system.

For the 3D obstacle perception, a "voxel" 3D grid layer was added to the costmap, fed with the cloud point from the 3D LiDAR. Akin to the 2D costmaps, this voxel grid records the occupancy probability, but in 3D space. Due the higher dimensionality of the data, voxel grid resolution is much lower than in 2D maps, using 0.1m voxels. The 3D voxel grid is projected to the 2D costmap so the detected 3D obstacles can be used by the 2D planner of the navigation suite.

However, as mentioned in the constraints, the high position of the LiDAR to avoid the FC causes that there is no 3D perception in the proximity of the manipulator. To solve this, the voxel grid is configured to "remember" occupied voxels for a certain amount of time, so obstacles will remain in the costmap even if they are not perceived by the sensors anymore and the planner will consider far away detected obstacles when the manipulator gets close to them.

The main drawback of this method is the "ghost" obstacles coming from elements that are not actually there anymore. The best example are the dynamic obstacles: they leave a trail of occupied space as they move, that remain occupied for some time even if the obstacle has move far from there. Figure 50 show an example of a person walking by the manipulator, leaving a trail behind. Note also how, even being a high obstacle, it is not perceived when closer to the manipulator. Even if the trail will eventually be deleted from the map when it times out, it can still impact the performance of the navigation. Thus, to achieve a good compromise between safety and performance, the timeout must be adapted to the operational speed and the presence of dynamic obstacles in the environment.

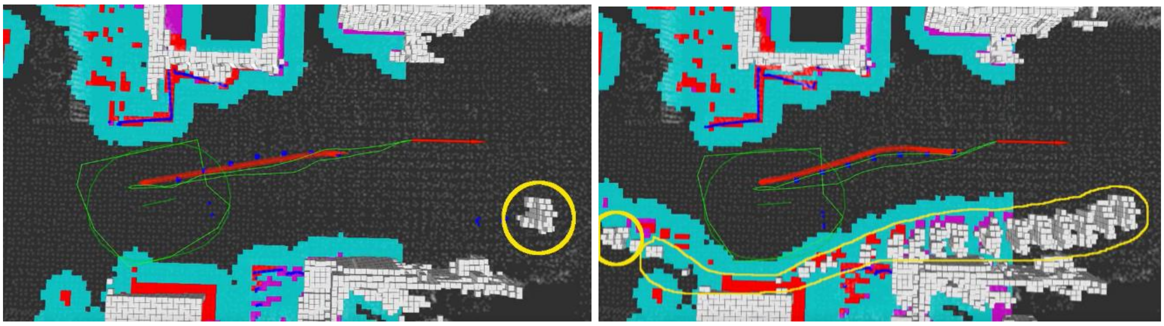


Figure 50: Trail left by a dynamic obstacle

To avoid self-perception, both the inputs from the 3D and 2D LiDARs are filtered using a space-based filter. In the case of the 3D laser, a bounding box for the manipulator-FC system is estimated. The LiDAR's 3D point cloud is filtered discarding all the points that fall inside the bounding box. In the case of the 2D LiDAR, the scan is filtered by defining three 2D zones in the approximate locations of the dolly's wheels. A margin is added to the size of the zones to account for the bouncing of the structure (Figure 51). Artifacts caused by reflection in the edges of the dolly's pillars are also filtered using the available shadow and speckle filters on the ROS's laser_filters [15] package.

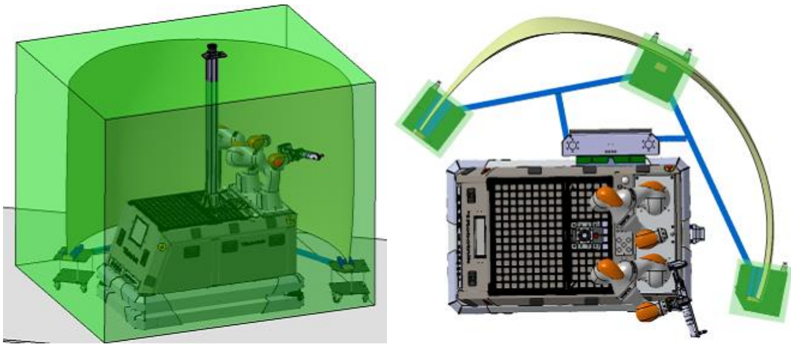


Figure 51: 3D LiDAR pointcloud filtering bounding box and 2D LiDAR filtering zones.

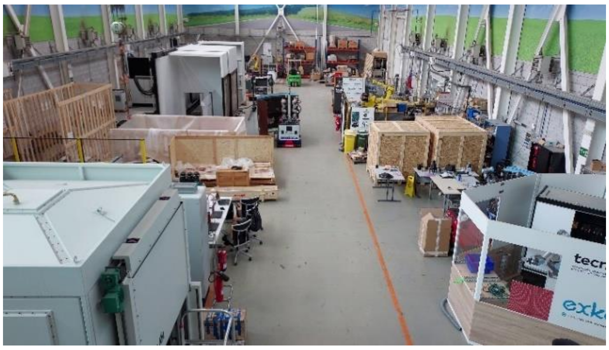
The navigation with the FC has been tested at TECNALIA's workshop in Donostia-San Sebastián. Figure 52 shows a sequence of stills from a test where from the starting point (a) the robot turns so it drives backwards (b) as defined in the constraints, passes through a narrow space (c) and finally rotates again (d) to arrive to the goal in the requested orientation (e).

(a)

(b)

(c)

(d)



(e)

Figure 52: Manipulator-FC navigation test

4.2.1.2 Robotic perception for the process, the human and the environment

The technologies developed for quality inspection have been compiled into skills (as explained in D2.5). At this stage of the project the inspection skills have been integrated within a context involving more modules, i.e. to perform the inspection the mobile platform navigates to the cell, positions itself correctly and finally performs the inspection tasks.

On the one hand, Figure 53 shows the robot approaching to the inspection cell and start scanning the FC from trajectories pre-recorded via the OISP module (more details in D2.5) by the operator. Figure 54 shows the result of the scanning process.

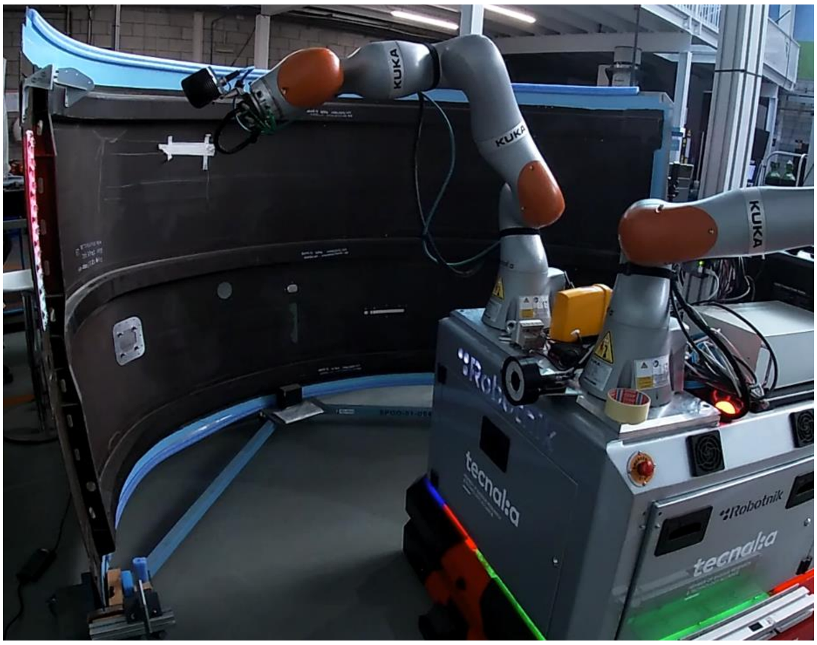


Figure 53: Inspection process using TECNALIA robot platform and Photoneo sensor

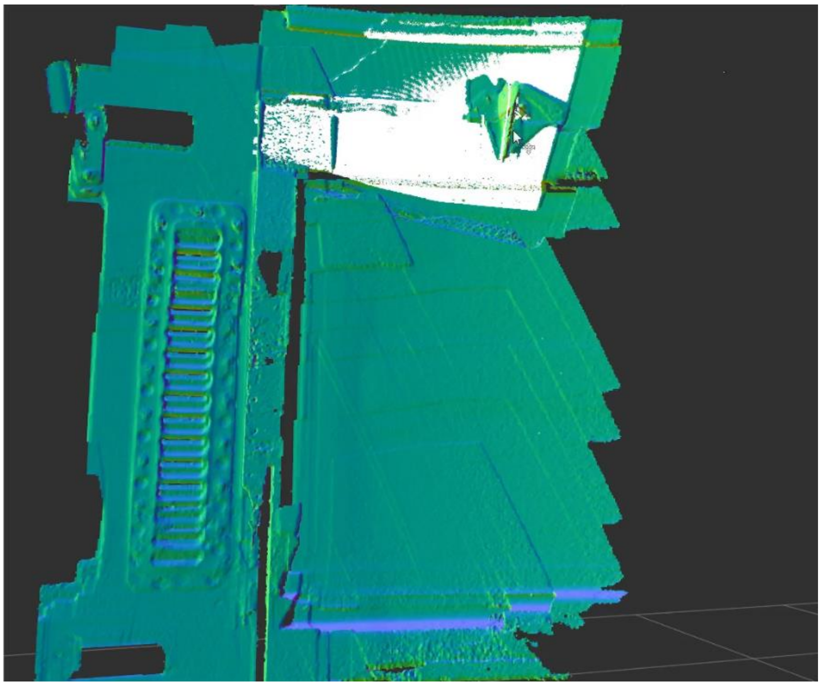


Figure 54: Scanning and reconstruction result

On the other hand, using a synthetic 3D dataset a model has been trained for detecting the parts that have to be inspected. Figure 55 shows first results of pose estimation of the part using the synthetic dataset. The integration of the technology in the actual 3D reconstructions is still a work in progress, being the expected result something similar than the result obtained with SAM [16] in the previous tests (Figure 56)

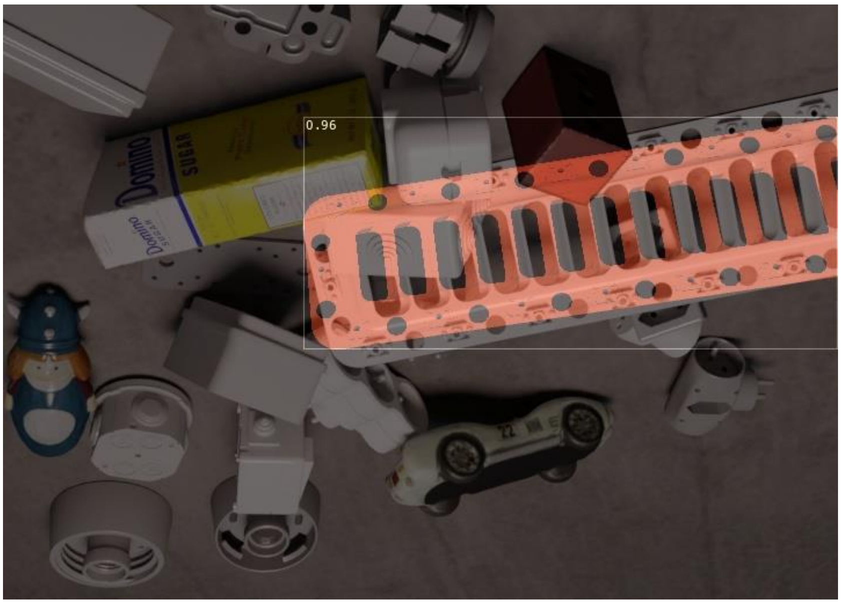


Figure 55: Pose estimation result over synthetic data

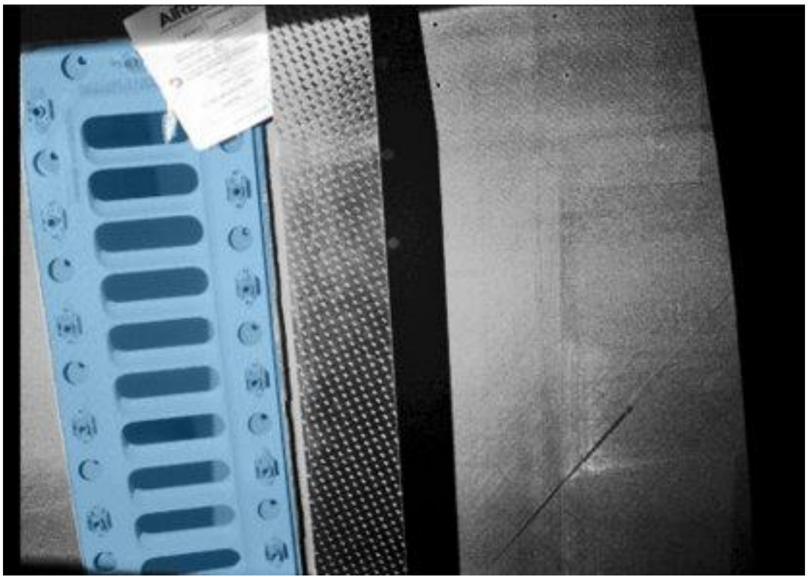


Figure 56: Expected result of part pose estimation

4.2.1.3 User friendly robot programming interfaces

At M36 of the project, the user friendly robot programming interfaces have been integrated into the demonstrations being carried out at TECNALIA's facilities.

For each of the demonstrators the necessary skills have been sequenced using the Blockly interface (more details can be found in D2.5). In addition, for operations that require complex trajectories, the OISP (On-site Interactive Skill Programming) module has been used, which allows interacting directly with the robot while the interface guides you through the steps have to be followed in order to store a trajectory and associate to it the necessary I/O at the characteristic points where they are needed (more details on this can also be found in D2.5).

Different sequences generated for each of the demonstrators are visualized in Figure 57. Each *"execute_traj_*"* block corresponds to an OISP taught trajectory.

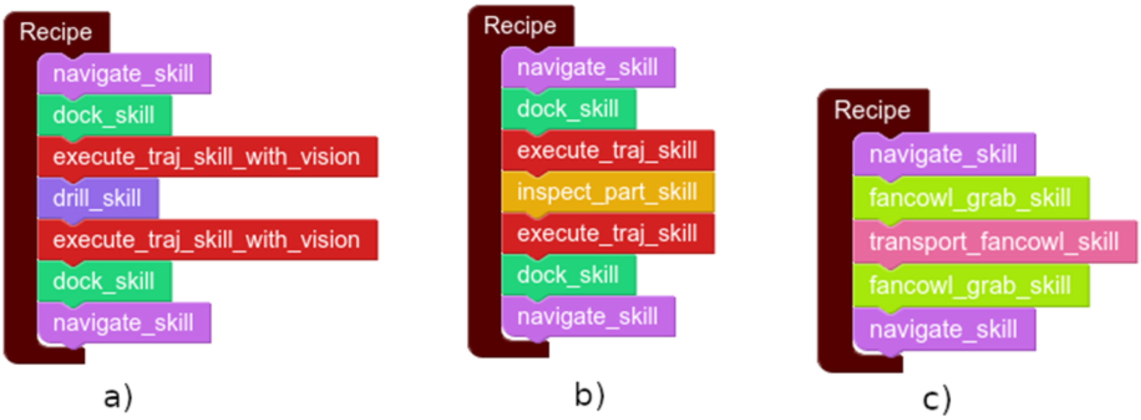


Figure 57: Blockly based skill sequences for each operation of the demonstrator. a) Drilling. b) Inspection. c) Transporting

4.2.2. Integration of Digital Component with Aeronautics initial industrial pilot

The integration of Digital Component in the Aeronautics demonstrator, analogously to the Automotive pilot, allow representing a digital version of the pilot.

4.2.2.1 Digital Simulation

As indicated in D5.2, the Aeronautics industrial pilot has been modelled using Visual Components software. At this stage of the project, the focus has been on using simulation to determine the actions to be taken in order to implement the ODIN safety concept. Figure 58 presents the different operations simulated in the aeronautics pilot case.

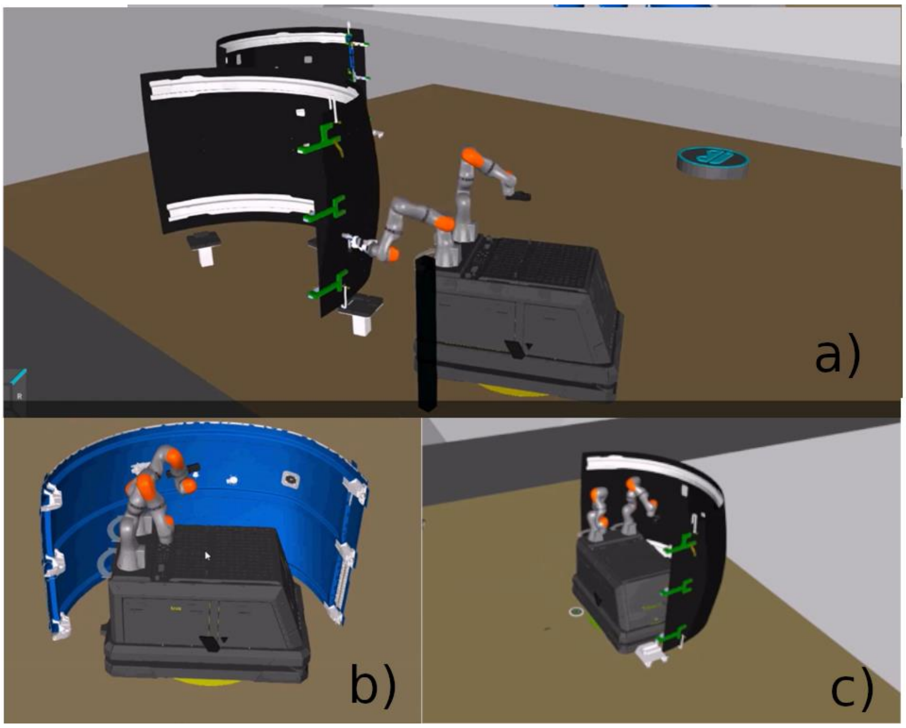


Figure 58: Aeronautics pilot simulation using Visual Components. a) Drilling operation. b) Inspection operation. c) Transporting operation

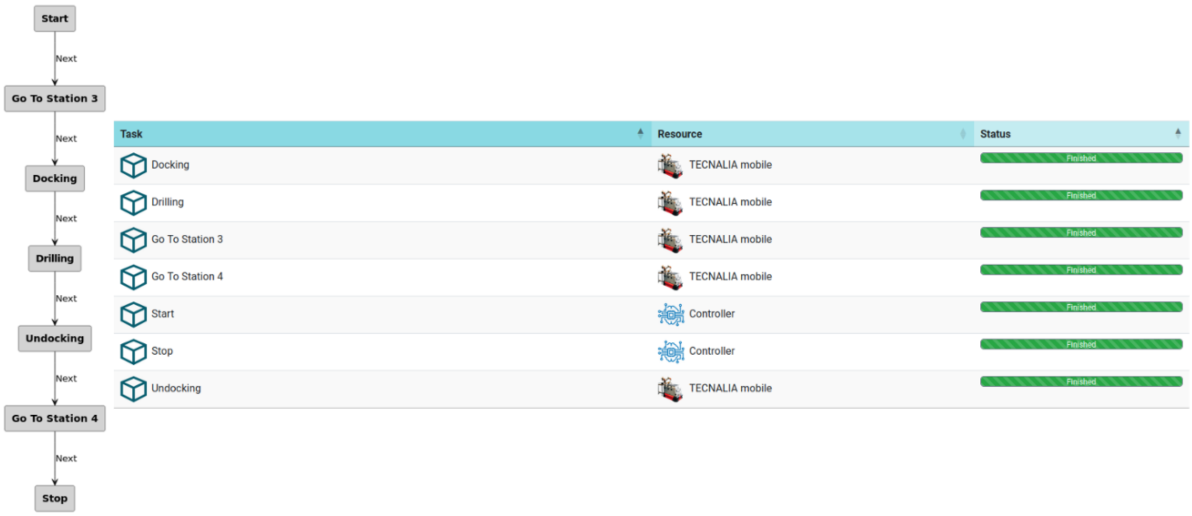
4.2.3. Integration of Networked Component with Aeronautics initial industrial pilot

The integration of the OpenFlow modules developed by INTRA for the Aeronautics industrial pilot has been approached following the same concept as mentioned in the previous section (Section 3.3.3).

Regarding the integration of the Cyber Security modules developed by S21SEC, as TECNALIA is responsible for the integration of the Aeronautics industrial pilot, an ongoing process of deployment has been initiated accordingly.

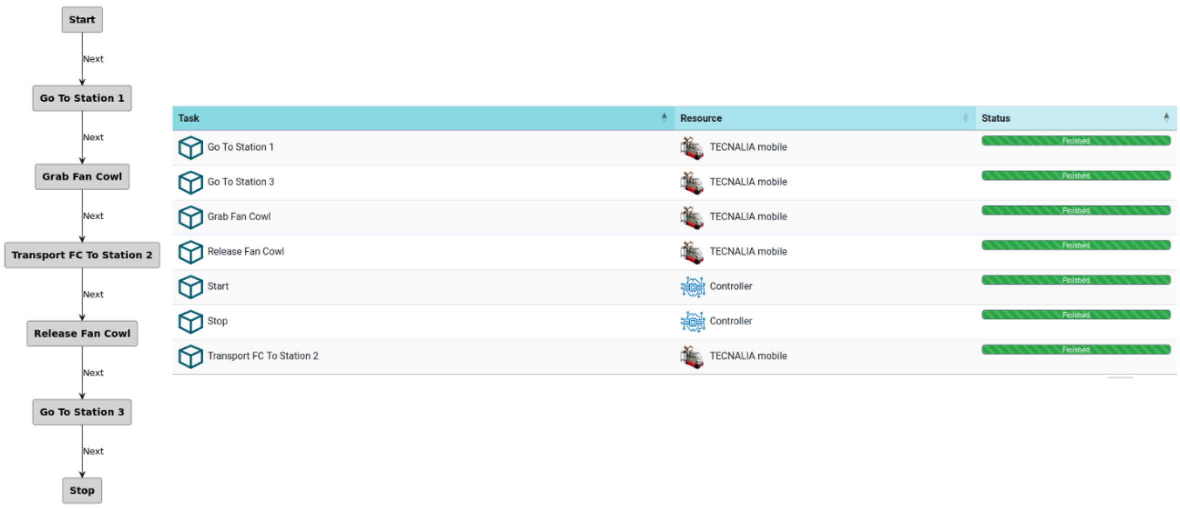
4.2.3.1 OpenFlow

The integration of OpenFlow in the Aeronautics industrial pilot involves various tasks that are composed by corresponding skills per each operation. Some of the skills are common for all the operations: navigate, dock, undock, etc. As can be seen at Figure 59, Figure 60 and Figure 61, OpenFlow generates the schedule for accomplishing the three operations implicates in the pilot.



Task	Resource	Status
Docking	TECNALIA mobile	Finished
Drilling	TECNALIA mobile	Finished
Go To Station 3	TECNALIA mobile	Finished
Go To Station 4	TECNALIA mobile	Finished
Start	Controller	Finished
Stop	Controller	Finished
Undocking	TECNALIA mobile	Finished

Figure 59: OpenFlow integration at the Aeronautics pilot - Drilling operation



Task	Resource	Status
Go To Station 1	TECNALIA mobile	Finished
Go To Station 3	TECNALIA mobile	Finished
Grab Fan Cowl	TECNALIA mobile	Finished
Release Fan Cowl	TECNALIA mobile	Finished
Start	Controller	Finished
Stop	Controller	Finished
Transport FC To Station 2	TECNALIA mobile	Finished

Figure 60: OpenFlow integration at the Aeronautics pilot - Transporting operation

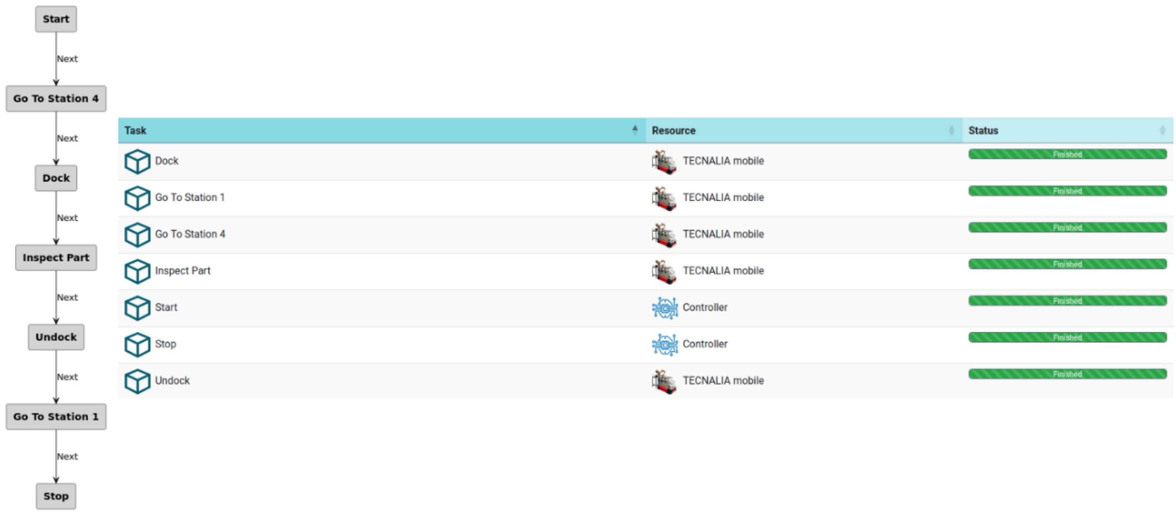


Figure 61: OpenFlow integration at Aeronautics pilot - Inspection operation

4.2.3.2 Cyber Security

The cybersecurity module developed by S21SEC is in the process of being integrated into the pilots developed by TECNALIA. Up to M36, the infrastructure has been prepared to deploy the modules, offering remote access to S21SEC to some machines that will be part of the network of the demonstrators. The integration in a scenario which represent a typical real use case will be validated in the coming months.

4.2.4. Aeronautics pilot safety concept integration at TECNALIA premises

Analogous to what is presented in Section 3.3.4, the ODIN safety concept for the Aeronautics pilot is being integrated into TECNALIA's demonstrators.

The safety logic changes necessary to implement the safety concept are the same as for the Automotive pilot. However, there are some differences with respect to automotive safety concept. Bellow the list of actions needed and their status up to M36 is presented:

- **Adding 3 SICK IO modules:** Same action and status as in the automotive pilot.
- **Adapting safety configuration for IIWA arms:** Same action and status as in the automotive pilot.
- **Transfer emergency signals from IIWA arms:** Same action and status as in the automotive pilot.
- **Contour detection for safety zone switching:** Similar to the automotive pilot the contour Detection function of the safety laser scanner will be used for determining the appropriate location of the robotic platform with respect the operation stations and trigger the different safety zones.
- **Integration of PILZ safety PLC:** Same action and status as in the automotive pilot.

4.3. Safety Related Parts of Control System

The components and functions described herein represent an update of the safety functions described in sections 6.5 of deliverable D2.1.

These components and functions are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 5.1 and 5.2 of deliverable D5.1 (M18), respectively. Each analysis represents the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9, providing a higher level of detail.

Below are the updates of the safety architecture and safety concept for each Business Use Case.

a) Drilling operation (AERO-BUC-1):

Figure 62 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions. These functions are necessary to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

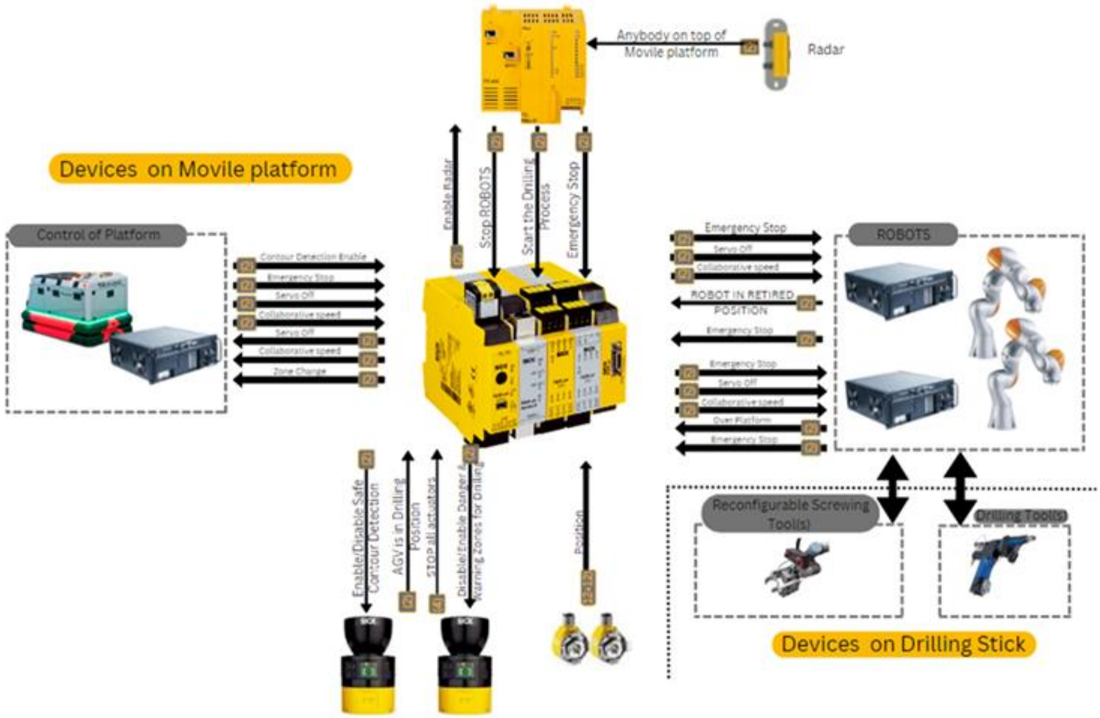


Figure 62: **Safety Architecture for AERO-BUC-1**

For AERO-BUC-1 no modification to the safety functions listed in D5.1 have been made.

A) Transport operation (AERO-BUC-2)

Figure 63 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions. These functions are necessary to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

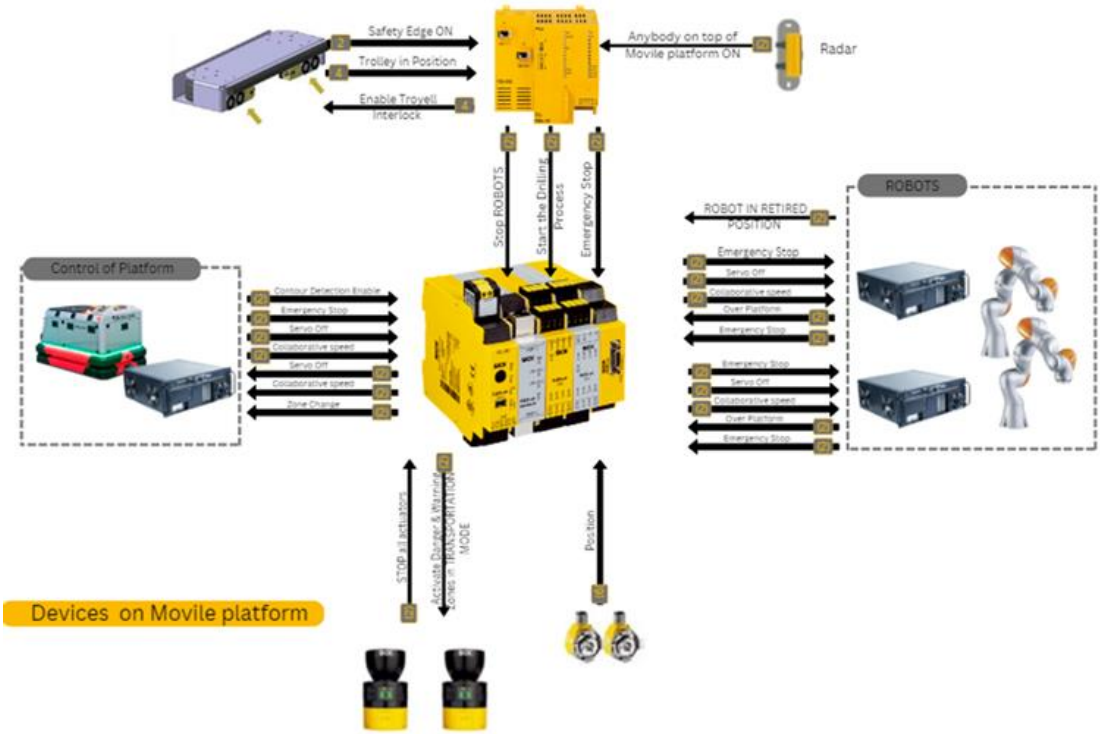


Figure 63: Safety Architecture for AERO-BUC-2

For AERO-BUC-2 no modification to the safety functions listed in D5.1 have been made.

a. Inspection (AERO-BUC-3)

Figure 64 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions. These functions are necessary to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

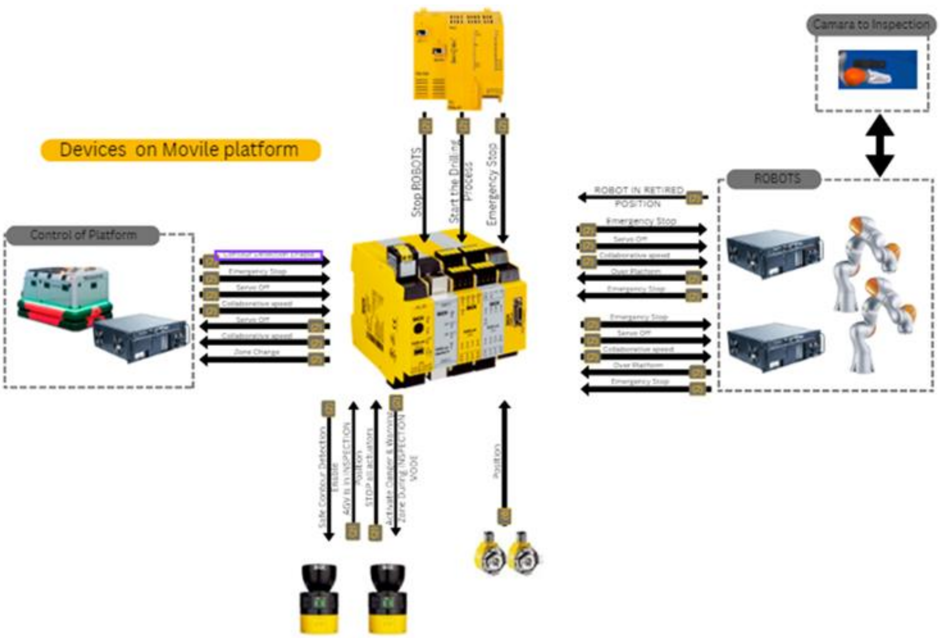


Figure 64: Safety Architecture for AERO-BUC-3

For AERO-BUC-3 no modification to the safety functions listed in D5.1 have been made.

4.3.1. Safety Concept update

The modifications described herein represent an update of the safety concept described in sections 5.2 of deliverable D5.1.

The Fan cowl will be fixed in three supports by two operators. The mobile platform will use the Countour detection function of the laser scanner as a safe signal to switch between the different safety zones to prevent unauthorized access to the operator to dangerous areas and to mute the ESPE fields when approaching the correct positions for drilling and inspection.

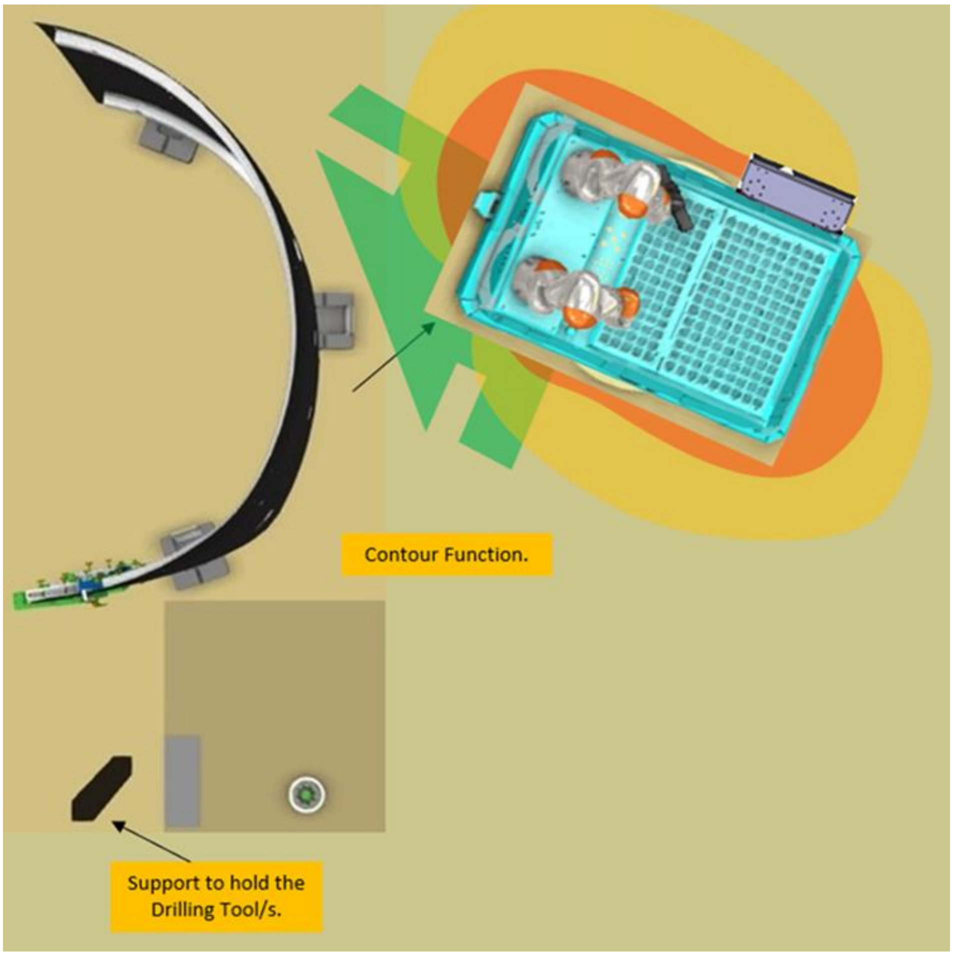


Figure 65. Contour Detection

Also, during the inspection operations the robot arms will be it in method 4 according to ISO 15066. There will be different inspection positions. When the mobile platform is moving from one position to another one the robot arms will be in retired position and the warning & danger zones for navigation will be active.

The rest of safety functions required remain the same as the ones explained in D5.1.

5. ODIN WHITE GOODS PILOT DEMONSTRATOR

5.1. Overview

The White Goods pilot focuses on the demonstration of ODIN technologies and modules in the White Goods industrial sector. This pilot investigates the enhancement of HRC regarding the productivity and safety in an industrial HRC shopfloor. As presented in D5.2, the layout of the White Goods pilot is based on an existing industrial workstation at WHEMAN premises. This workstation is focused on the assembly of electrical ovens, with the operator performing the installation of transformers on the final products, while the robot is feeding transformers to the operator, from the logistics carts. The vision of ODIN is to improve the flexibility of the workstation, in terms of manipulating different White Goods parts (big, medium, small cooktops, knobs and transformers), while also achieving seamless HRC and safety standards.

The White Goods pilot layout consists of one UR10 cobot and one operator for the execution of the required assembly tasks. Additionaly, several mechanical constructions for parts installation and automated tool change by the robot are included in the layout.

5.2. White Goods demonstrator at LMS premises

All the required assembly tasks for the assembly of one oven and one gas cooktop burner are executed in the final version of the White Goods demonstrator at LMS premises.

Figure 66: White Goods pilot pre-industrial demonstrator at LMS premises

In more details, the executed tasks are presented in the following table.

Table 3: M36 White Goods pre-industrial pilot tasks execution

Task_ID	Task title
1	Toolchange (From no_tool to magnetic gripper)
2	Pick transformer from the cart
3	Place transformer on the assembly table
4	Install transformer in “microwave”
5	Pick small cooktops from the cart
6	Provide small cooktops to operator
7	Install small cooktop on the cooktop burner
8	Pick medium cooktops from the cart
9	Provide medium cooktops to operator
10	Install medium cooktop on the cooktop burner
11	Pick big cooktops from the cart
12	Provide big cooktops to operator
13	Install big cooktop on the cooktop burner
14	Toolchange (From magnetic gripper to no_tool)
15	Toolchange (From no_tool to flexible gripper)
16	Pick knob from the cart
17	Provide knob to operator
18	Install knob on the cooktop burner
19	Toolchange (From flexible gripper to no_tool)
20	Toolchange (From no_tool to vacuum gripper)
21	Pick cardboard from the transformer cart
22	Place cardboard on the spare cart
23	Pick separator from the transformer cart
24	Place separator on the spare cart
25	Pick big cooktop blister
26	Place big cooktop blister
27	Pick medium cooktop blister
28	Place medium cooktop blister
29	Pick small cooktop blister
30	Place small cooktop blister
31	Toolchange (From vacuum gripper to no_tool)

5.2.1. Integration of Open Component with White Goods initial industrial pilot

5.2.1.1 Reconfigurable robot tooling

As previously mentioned, in the pre-industrial demonstrator of the White Goods pilot, a UR10 robot is utilized for feeding the required components to the operator to perform the final assembly of the products. Robot's manipulation of knobs, cooktops and transformers is based on a modular framework of robot gripping tools for human robot collaborative production lines. This framework consists of three different types of grippers: a) Magnetic, b) Flexible and c) Vacuum grippers as presented also in deliverable D2.5.

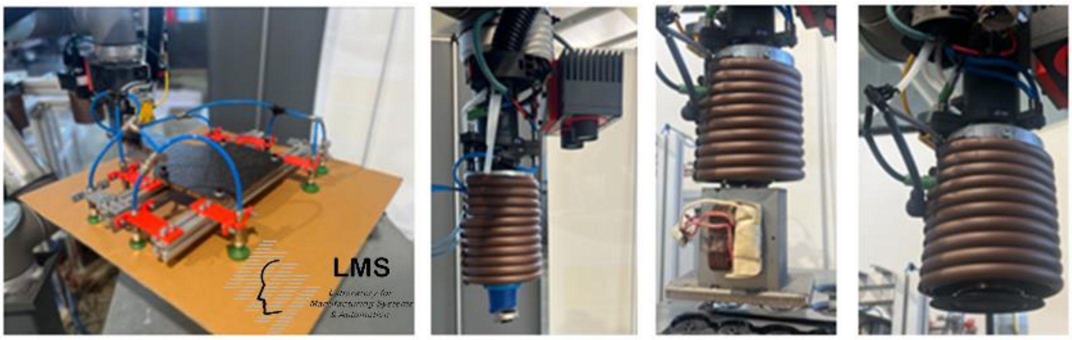


Figure 67: Reconfigurable tools of the White Goods pilot

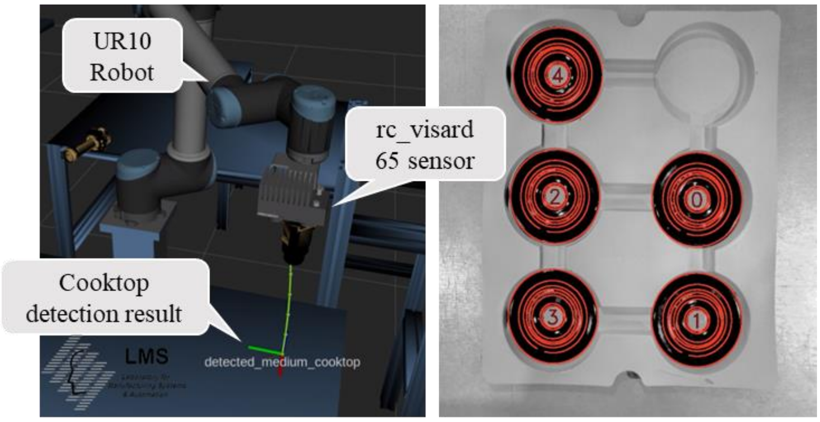
The magnetic gripper is used for the manipulation of the cooktops and the transformers due to their ability to be magnetized. Knobs' manipulation is based on the flexible gripper. Using the vacuum gripper, the robot removes cardboards and separators from the assembly table which are initially used to separate different layers of the transformers. These objects are flat lightweight flexible sheets able to be manipulated with suction grippers.

The UR10 robot is equipped with the low payload tool changer of the framework for the quick exchange of the proposed vacuum, flexible and magnetic grippers. The actuation of the grippers is achieved through the Digital I/O board of the UR10 CB3 controller but also the required ROS action servers. The Digital I/O board is connected with the required pneumatic components (Electro valves and Ejectors) to enable the functionality of the flexible and the vacuum gripper.

5.2.1.2 Robotic perception for the process, the human and the environment

- Object detection

The initial integration of the object detection module inside the White Goods demonstrator at LMS premises has been detailly presented in D5.2. In the final version of this module, the detection of the parts is implemented with two software solutions provided by ROBOCEPTION namely CADMatch and SilhouetteMatch. CADMatch is employed for detecting cooktops and knobs, whereas SilhouetteMatch is utilized for the detection of transformers. These detection operations are executed using custom CAD templates designed for each respective part.



a) b)

Figure 68: a) Module integration in robot simulation, b) Multiple medium cooktops detection

Using an updated version of the cooktops' template, the detection algorithm is able to successfully identified all cooktops using a single shot of the RC_Visard 65 camera, (Figure 68b).

Additionally, LMS demonstrator includes the detection of transformers for electrical ovens' assembly. Transformers' detection is based on SilhouetteMatch algorithm utilization providing accurate detection results for transformers' manipulation. The grasping point generated after the successful detection of a transformer part is denoted by a green dot inside the User Interface of ROBOCEPTION camera used.

An RC_Visard 65 camera sensor is mounted on the robot's end effector for detection module's execution. The detection module runs in a RC_Cube S device providing also the required CAD templates for objects' detection. After the successful execution of the detection module, the results of the detection module are provided to the OpenFlow for the creation of the corresponding grasping points as frames inside the transformation tree of ROS environment. These frames are used to define the final poses for the UR10 collaborative robot towards the grasping of the desired parts.

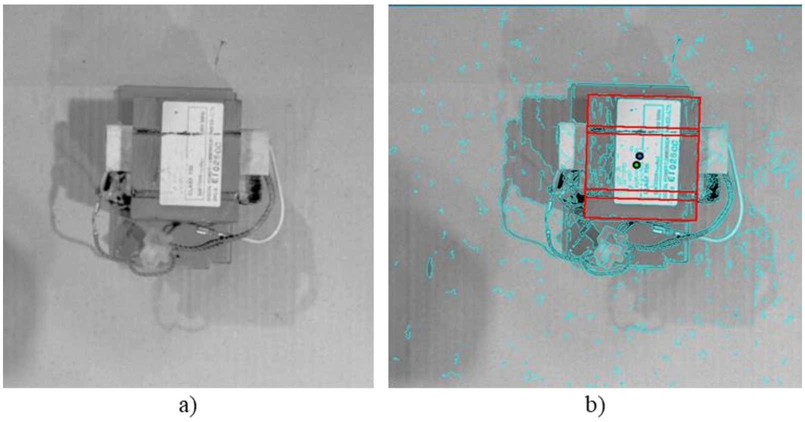


Figure 69: Transformer detection: a) Image acquisition; b) SilhouetteMatch result

- Human motion intention

The human motion intention module has been integrated in the pre-industrial demonstrator of LMS with the collaboration of LMS and KTH partners. The human motion intention module utilizes a Kinect v2 sensor to capture the operator's skeleton data, specifically focusing on two engaged actions as depicted in Figure 70. This captured data serves as the foundation for training a Neural Network model. This NN model results are transmitted to the OpenFlow via a UDP/IP connection and published to a ROS topic. Using this module's results, the OpenFlow adapts the production plan as follows:

- ➢ If the operator is in working state, then the UR10 robot place the manipulated parts on assembly table's shelf.
- ➢ If the operator is in standing state, then the UR10 robot goes to an idle position near the human operator and he/she takes the robot grasped parts directly from the collaborative robot's gripper.

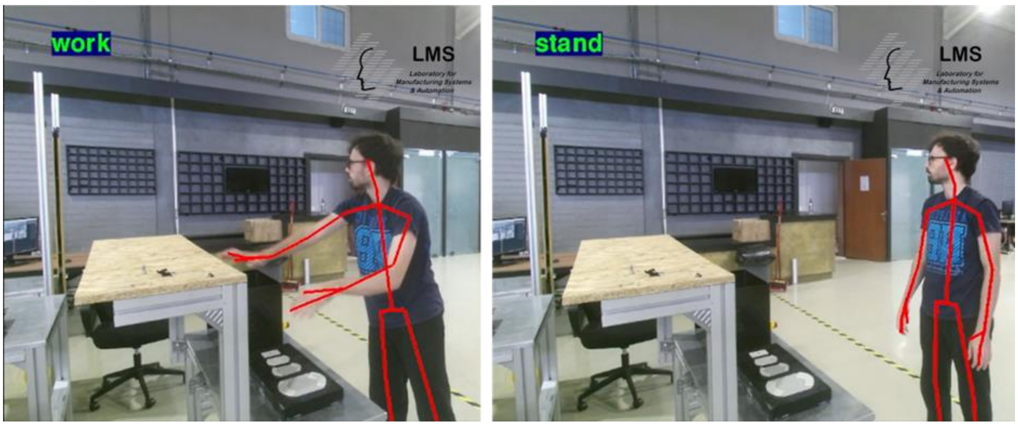


Figure 70: Human motion intention module integration in White Goods demonstrator

- Human gesture recognition

Using the human gesture recognition module, the operator of the White Goods pilot is able to interact directly with the controller of the UR10 robot and send teleoperation commands to the robotic arm. In this case, the operator is able to easily move the robot arm in case of fault detection actions or in any other case this teleoperation process is beneficial for him/her. Using the dedicated settings options through the AR interface the operator can activate the module. A Kinect v1 sensor tracks the gestures of the operator and a server translates them into distinct movements for the arm. After the desired movements were executed, the operator just needs to de-activate the module through the same AR interface, resulting in seamless interaction with the robot without impeding the schedule or the assembly process.

Figure 71: **UR10 controlling through the human gesture recognition module**

5.2.1.3 Smart human side interfaces

Two different type of human side interfaces are integrated in the pre-industrial demonstrator at LMS premises to achieve the required human-robot interaction for assembly tasks' execution. Both interfaces are detailly presented in deliverables D2.5 and D2.6.

- AR operator support application

Information and controls related to the tasks assigned operator and the robot are transferred to the operator through the AR application. Different virtual buttons with options and a virtual menu have been created to assist the operator to navigate when using the module. The operator is informed through a visualization of the results in the AR glasses, for the assembly instructions and for the use of the interactive robot tool.

Figure 72: **AR operator support application in White Goods pre-industrial demonstrator**

- Projector-based interface

This module's integration in the White Goods pre-industrial demonstrator is based on the installation of a projector on a crane inside the investigated layout.

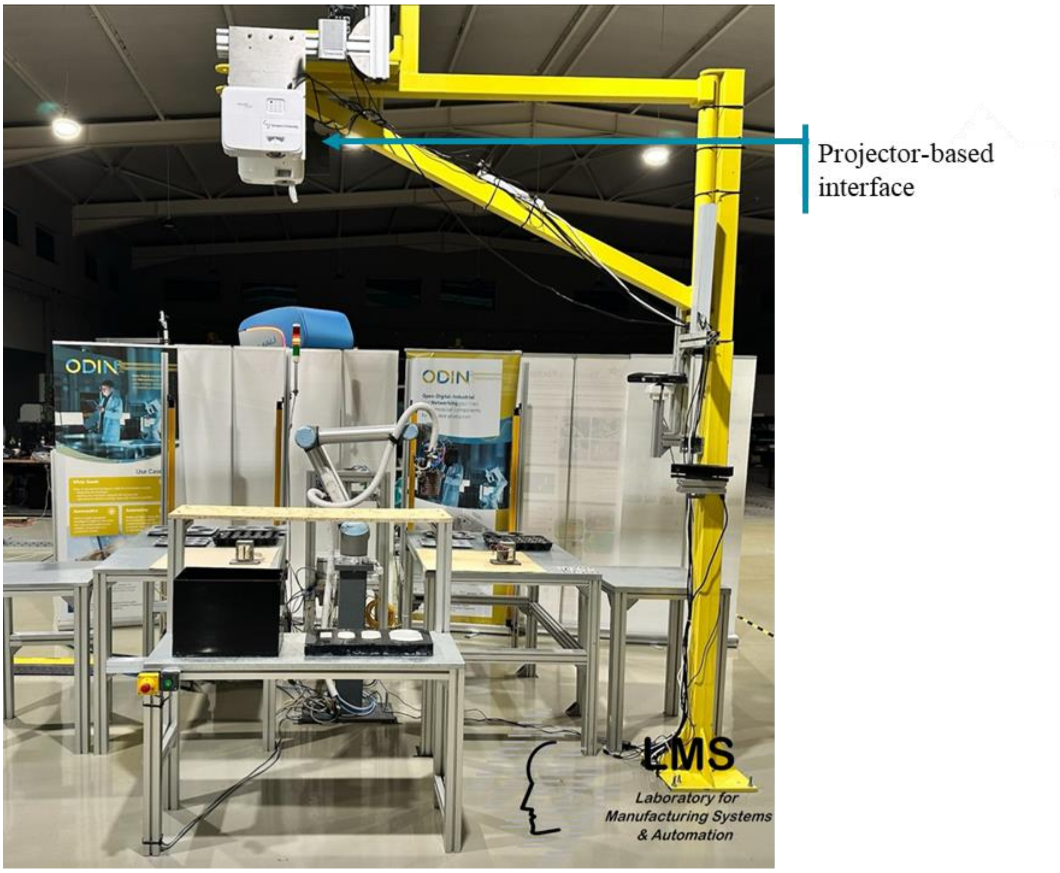


Figure 73: Projector's installation in White Goods pre-industrial demonstrator

The installation and implementation at LMS demonstrator have been completed by through the following steps:

1. Calibration of camera and projectors to display smart interface and static borders.
2. Calibration of camera with robot for global depth map generation.
3. Display of smart interface that can start/stop a robot task.
4. Detection of interactions with the smart interface.
5. Display of static borders for robot to place transformers and cooktop components in appropriate pickup place.
6. Monitoring the crossing of safety borders to raise a violation event and stop the robot.

The perception and data capturing routines are discussed in D2.4. Correspondingly calibrations and projection features are discussed in D2.5.

The first step is about calibrating the camera and projectors. This is followed by calibration of the display zone(s) where it is possible to display the smart user interface. To do so, the calibration needs the four corners of the display zone. The ArUco markers were used to determine their locations (Figure 74). D2.5 provides additional and more detailed information about the calibration procedures.

Figure 74: The display zone for the smart user-interface on mobile table (Left) and for the static borders (Right) are defined, with the help of ArUco markers.

The calibration between the camera and the robot has been done through a wizard to generate a global scene. A view of this scene is illustrated in Figure 75.

Figure 75: Scene from the Azure Kinect for the LMS White Goods test setup. Self for the assembled components in the centre. Mobile table for mobile projected UI at right.

The smart interface and the static borders are displayed after launching the OpenFlow application. The OpenFlow will send a series of messages to initialize the projector HMI environment. E.g. the booking system is initialised, positions of the slots associated with the booking system are initialised and displayed, user interface including buttons and their shape, text, and colour are set (Figure 76).

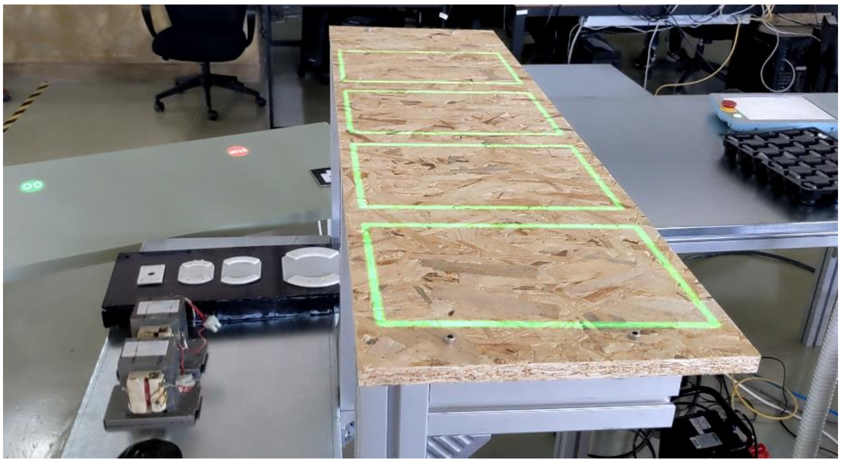


Figure 76: Slots and their static borders are projected on the self, where the operator is picking up the parts. Mobile UI projected on table is visible at back left.

When the user hovers his/her hand over the start button, the robot starts to picking-up objects from the trays. Object is either transformer or a part for the cooktop assembly. In the meantime, OpenFlow review the availability of the slots (i.e. which slot is empty) and book the slot for the robot. The booking system changes the colour of the booked border to a predefined colour. This will be the location where the object will be placed, so the operator should not try to access this location while it is booked. The booking system reserves the adjacent slots and activates their borders for extra safety measures. After the task, OpenFlow releases the booking of the slot, associated borders are marked free (green or blue), and the operator is free to reach for the object (Figure 76).

During the robot pick and place task, all reserved slots and their borders are monitored to detect a potential violation. If a crossing happens with the booked slot, the system raises a border violation event which stops the robot and changes the colour of the border crossed. A hand detector and approach direction of the operator's hand are used to distinguish border crossing between the operator and the robot. While the later can cross the border without implications (Figure 77).

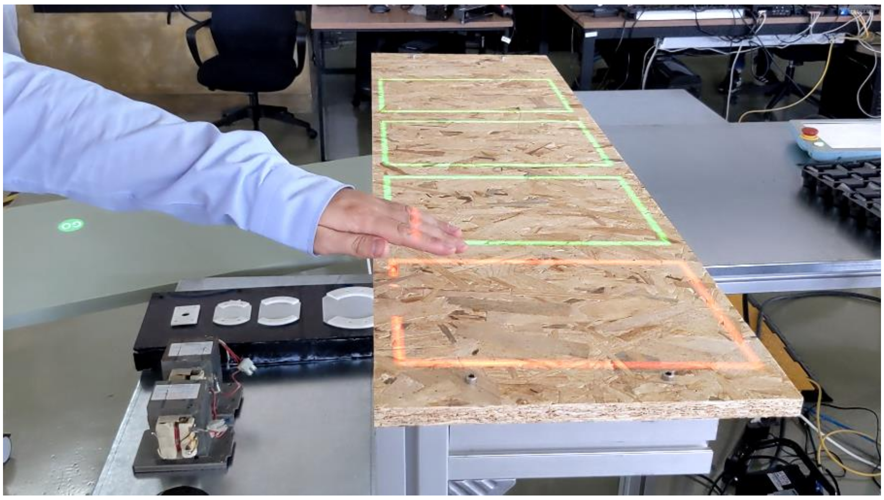


Figure 77: Operator is violating the border by placing his hand over it.

5.2.2. Integration of Digital Component with White Goods initial industrial pilot

5.2.2.1 Digital Simulation

As presented in deliverable D5.2, the digital simulation of the White Goods pilot focuses on the assembly of oven and cooktop burners in a common workstation. The updated version of the simulation has been built using the Visual Components software. The simulated layout of the final demonstrator is visualized in the following figure including the hardware components for assembly tasks' execution.

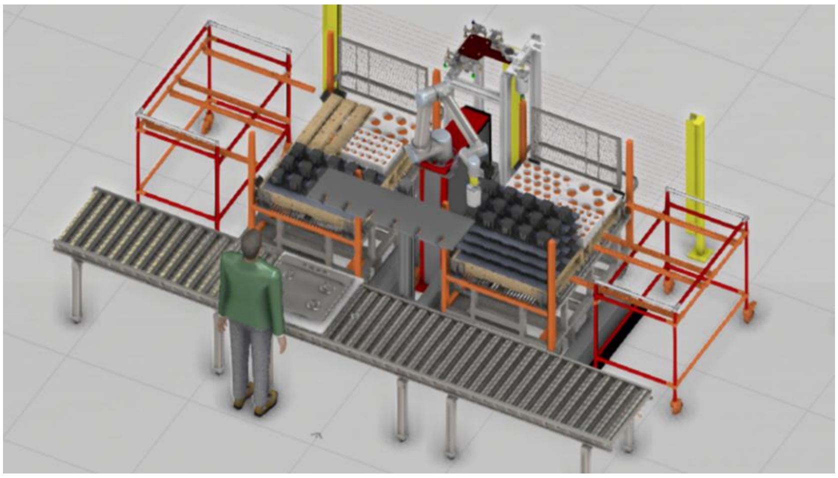


Figure 78: White Goods pilot demonstrator design for installation at WHEMAN premises

5.2.2.2 Digital Twin

This module's integration in the White Goods demonstrator is based on the ROS connectivity of UR10 robot controller and Visual Component software. ODIN DT utilizes the visualization and connectivity functionalities Visual Components software to present robots. The final version of the White Goods demonstrator Digital Twin includes the UR10 cobot, real-time sensor data and the layout of the corresponding demonstrator. The Digital Twin module of the White Goods demonstrator seamlessly integrates with the Robot Operating System (ROS) to acquire real-time data crucial for precise simulation. Unlike the approach used in the Automotive demonstrator, the Whitegoods module employs a TCP connection integrated from Visual Components, establishing a direct link and the UR10 controller. This connection ensures seamless access to the robot's joint states. Additionally, the module receives vital information from ROS, encompassing the enable or disable status of the three grippers and details regarding pick-and-place actions involving cooktops, transformers, cardboard components, and more.

For efficient data transmission except robot's joint values, the Digital Twin module utilizes UDP clients. These clients concurrently extract information from various ROS topics, allowing the module to subscribe to and extract essential information in real-time. In parallel, UDP servers of Visual Component software are utilized to receive, process and dynamically adjust the properties of relevant components based on the transmitted data. Through this dual communication approach — TCP for joint states and UDP for the additional data — the Digital Twin module establishes a real-time connection between ROS and Visual Components. This strategy ensures the precise synchronization of the virtual environment with dynamic events occurring in the physical Whitegoods demonstrator, enhancing the overall accuracy and reliability of the simulation (Figure 79).

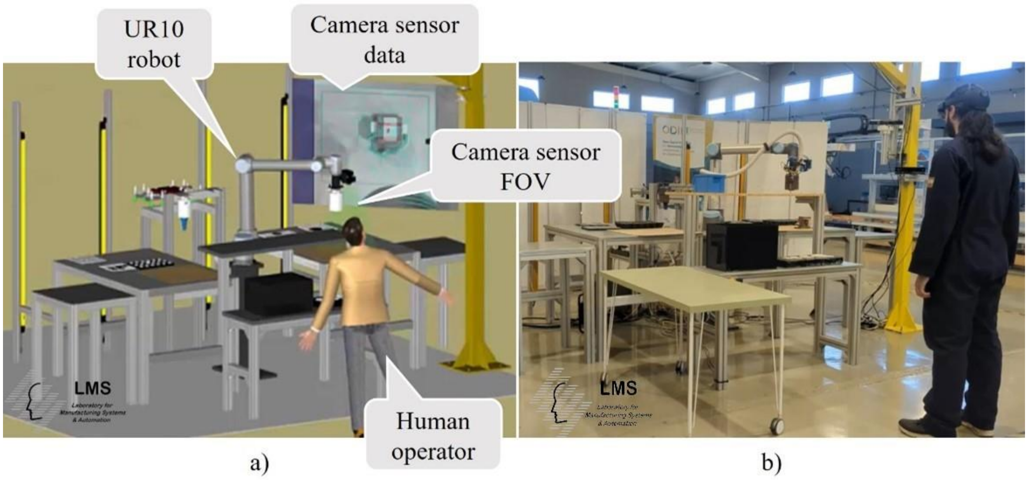


Figure 79: a) Digital Twin, b) Physical layout of White Goods pre-industrial demonstrator

5.2.2.3 AI Task Planner

The initial integration of the AI Task Planner module in the White Goods demonstrator at LMS premises has been presented in deliverable D5.2. The final version of the AI Task Planner enhances the reconfigurability of the workstation thanks to the dynamic re-scheduling functionalities of the planner. During the removal of the empty logistic carts, a human operator infringes the safety curtains on the back area of the cell. The workstation consists of two different kitting tables. One on the right side of the cobot and another one on its left side. In order to avoid stopping the cobot and increase the idle time of the production line, the AI Task Planner is triggered and updates the task plan. The cobot receives tasks in order to avoid collisions with human operators.

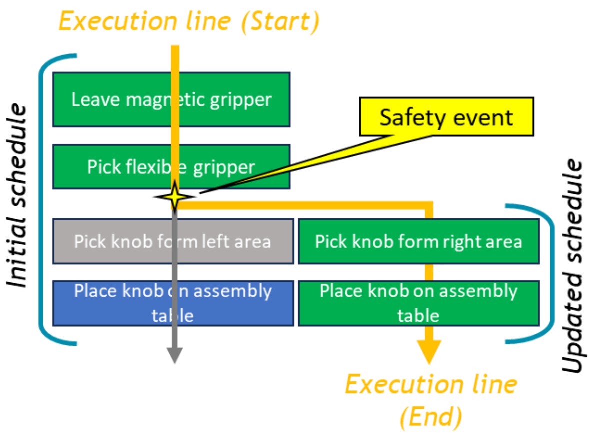


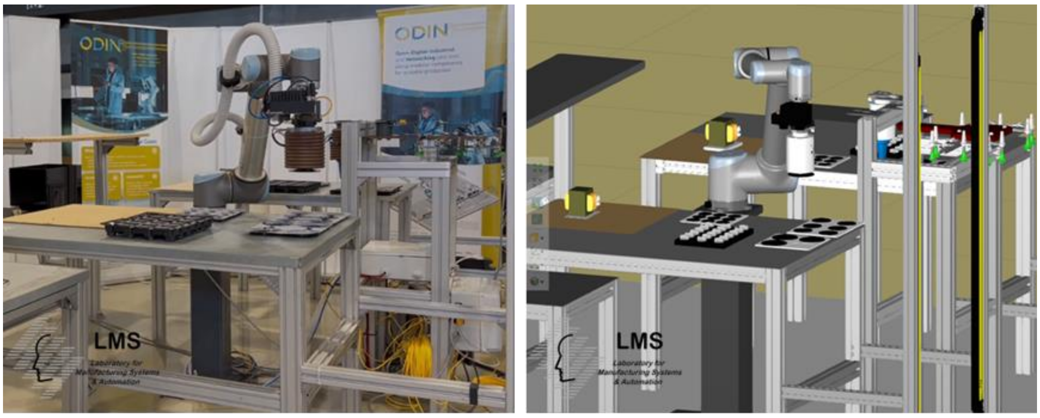
Figure 80: Indicative re-configuration of assembly task plan in case of a safety event

5.2.2.4 Virtual Commissioning

Virtual commissioning is based on the usage of Visual Component software and its functionality to generate executable programs for COMAU and Universal Robot controllers. The integration of this module under the White Goods demonstrator at LMS premises is focused on the validation of robots' trajectories generated by the VIS software inside the physical workstation of the pilot.

The White Goods pilot investigates the increase of oven assembly line reconfigurability at WHEMAN facilities. In order to proof this increasement, the assembly process of a gas cooktop product has been selected in order to be merged within the selected workstation. The required parts for gas cooktop product's assembly are being fed to the robotic workstation in the same cart used for the oven product's transformers. Based on the demand of the production, the robot is able to manipulate the corresponding parts using a set of reconfigurable robot tools. The gas cooktop assembly order consists of several subcomponents installation by the human operator. The collaborative robot of the workstation is able to provide the required parts to the human operator using the shelf of the existing workstation. The design and validation of the new robot trajectories for the pick and place tasks of each product's subcomponent might be a complex and time consuming process since several modification and tests in the real workstation are needed until finding the optimal location for part's feeding in terms of UR10 robot's reachability and singularities. The Virtual Commissioning module of ODIN seems to be the key component towards the ease of the reconfiguration process for the investigated workcell,

Using the digital replication of the workcell from the Visual Component software and its Virtual Commissioning feature, the production designer is able to program easily the new robot trajectories for new parts' manipulation by the collaborative robot. Thanks to the high accuracy of UR10 robot's simulated controller, the physical robot is able to execute the trajectories exported from the Visual Component software in the form of a .SCRIPT file and perform the required tasks.



a) b)

Figure 81: Virtual commissioning validation in the White Goods pre-industrial demonstrator

5.2.3. Integration of Networked Component with White Goods initial industrial pilot

5.2.3.1 OpenFlow

The final version of OpenFlow has been integrated in the White Goods demonstrator of LMS for orchestrating the execution of all the required tasks in the workstation by the human and the robot resources. Thanks to its connectivity with the final version of ODIN key modules, OpenFlow monitors the execution of each task and each resource's status in order to avoid production's pause and trigger the AI Task Planner for re-planning in case it is required.

Similarly with the other two pilots of ODIN, OpenFlow module's integration in the White Goods demonstrator is based on a docker image of the module installed and running in the central PC of the workstation.

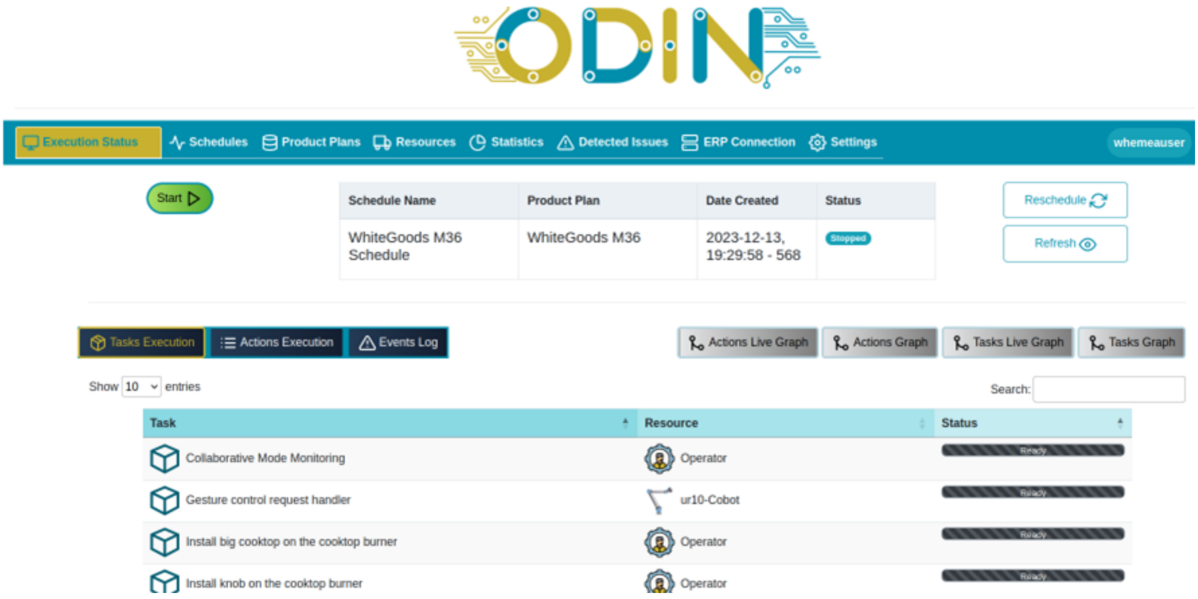


Figure 82: Integration of OpenFlow in the white goods pilot demonstrator

As presented previously in deliverable D5.2, several ROS action servers are utilized to achieve seamless control over the execution of White Goods assembly process. The expanded list of the required servers is presented in Table 4.

Table 4: ROS action servers for initial White Goods pilot execution

ROS Action Servers	Description
Move Cartesian Action Server	Action server for the planning and execution of robot motions using Cartesian space goals.
Move Joint Action Server	Action server for the planning and execution of robot motions using Joint space goals.
Configure Payload Execution Action Server	Action server for updating the payload of UR10 robot through ROS when robot carries high payload parts (transformer).
Configure TCP Action Server	Action server for updating the robot end effector through ROS when robot carries parts (move the end effector at the end of the carried part).
Detection Action Server	Action server for the pose estimation of parts need to be manipulated by the robot.
Gesture Control Server	Action server for enabling the gesture control functionality allowing the operator to move the robot using gestures.

ROS Action Servers	Description
Projector Interface Server	Action server that manipulates the zones presented in the shelf and the projection button for execution control by the operator.
Safety Action Server	Action server to communicate the Safety status of the cell to the Openflow module.
Execute Human Task Action Server	Action server for the connection of AR operator support application with the OpenFlow.
Control Gripper Action Server	Action server for enabling / disabling robot grippers.

The connection between the described ROS action servers and the OpenFlow module is depicted in detail in the following figure.

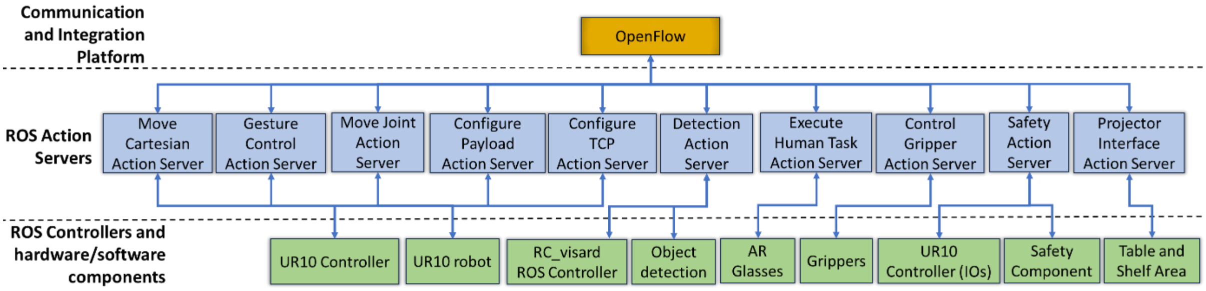


Figure 83: OpenFlow connection with ROS action servers for Whtie Goods pre-industrial demonstrator

5.2.3.2 Cyber security

The final version of the cyber security module has been integrated inside the White Goods pre-industrial demonstrator at LMS for the detection of cyber security threats in the local network of the cell. As presented in D4.3, this module is based on the connection of three different computers.

The monitored endpoint is running in the environment shared by the OpenFlow module cataloging the different events that the module undergoes (Figure 84). All loggings are delivered in the SIEM system, which for security reasons is located in a different system than the endpoint. The SIEM (Figure 86) is responsible for alerting the SOAR cloud-based system for any dedicated Alerts.

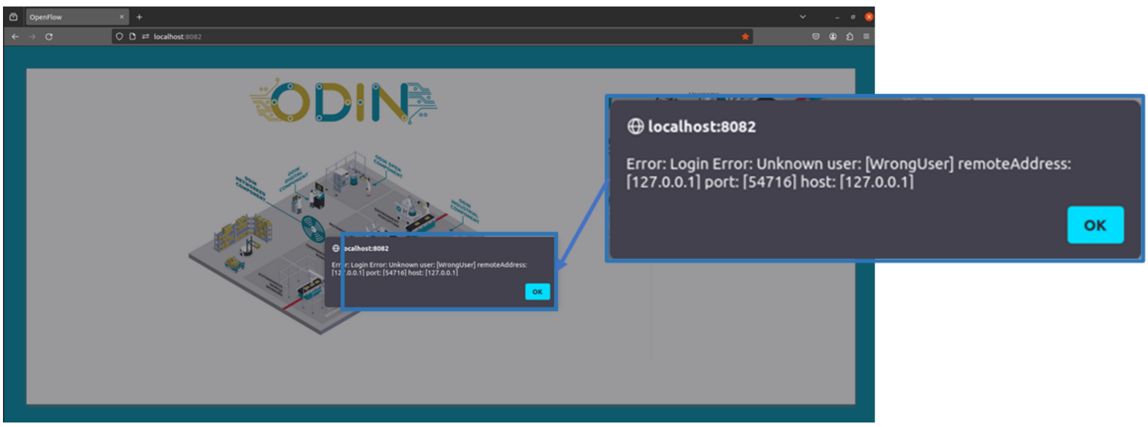


Figure 84: OpenFlow catalogging an Error Login event

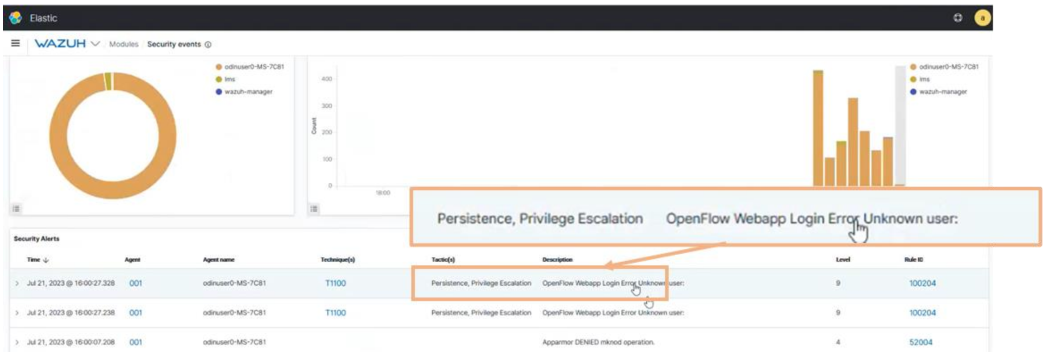


Figure 85: **SIEM Module UI**

The SOAR then directly communicates with the OpenFlow environment, informing the module for any Alert and taking the necessary actions for the infringement. Thanks to OpenFlow module's integration in the White Goods demonstrator of LMS, the cyber security module has been validated successfully providing information to OpenFlow in case of detected network threads but also informing human operators through the AR-based application of ODIN (Figure 86).

S

Figure 86: AR module notification for failed login event

5.2.4. White Goods pilot safety concept integration at LMS premises

The realization of ODIN safety concept in the White Goods demonstrator has been completed up to M36 of the project at the pre-industrial demonstrator of LMS.

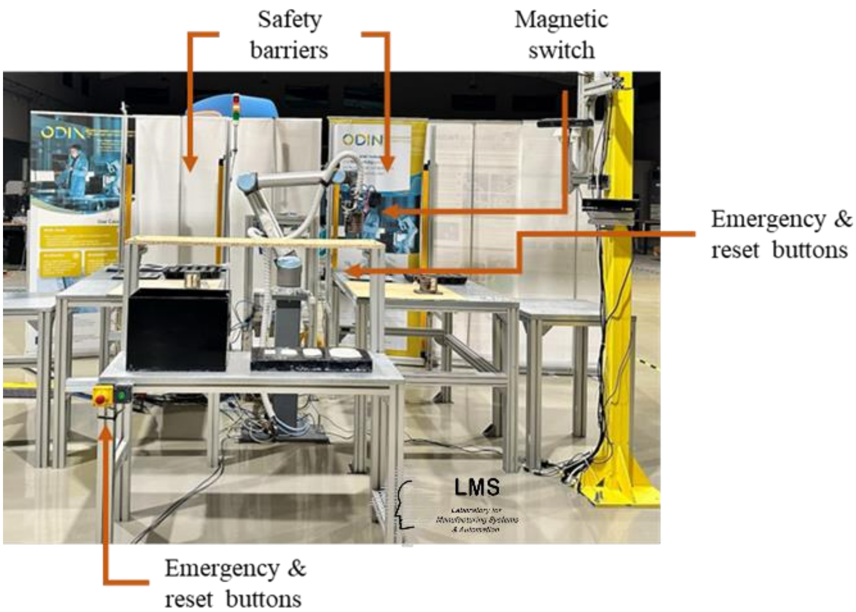


Figure 87: Safety components installed in the demonstrator layout at LMS premises

The safety concept of the White Goods demonstrator consists of the following items:

- Safety PLC

The safety PLC is connected with all the safety hardware devices of the workstation. The main safety logic is implemented inside this PLC for the realization of White Goods pilot safety concept.

- Safety magnetic switch of vacuum gripper

Using the safety magnetic switch of the vacuum gripper, the safety PLC and OpenFlow are aware about the equipped gripper on the cobot. Based on the risk assessment analysis, the collaborative robot should not operate when human operators enter the back area of the workstation and the vacuum gripper is attached to the robotic arm.

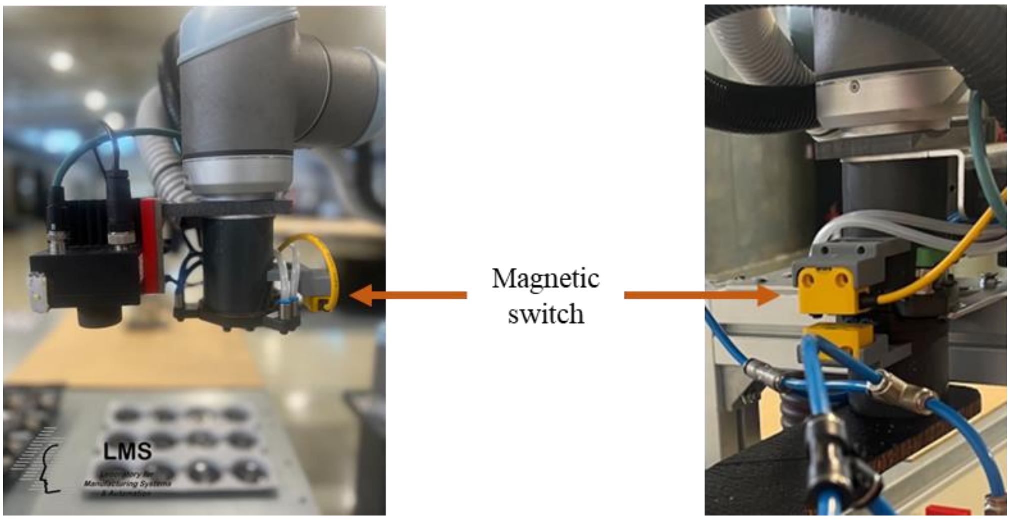


Figure 88: Safety magnetic switch installed on robot's end effector and vacuum gripper

- Safety curtains

Installation of safety curtains in the back area of the investigated workstation to detect human presence inside the robotic cell in a safe way and accordingly adapt the status of the production.

- Emergency buttons

Two emergency buttons are installed inside the workstation in order for the operator to stop the assembly process if it is required. These buttons are connected with the safety PLC of the demonstrator.

- Reset buttons

Two reset button are installed in the demonstrator layout in order for the operator to restart the system if required.

5.3. VR Safety Training of final demonstrator

The final version of the safety training module developed by TAU has been already implemented in the final demonstrator of the White Goods pilot. This is an offline tool so its integration with the final demonstrator was able to be achieved before the transferring of the pre-industrial pilot at WHEMAN premises.

The starting point for this pilot is the 3D model and process has been provided by the shared simulation model of Visual Components. Model is imported to our VR environment, and additional features are started to accumulate on it.

The aforementioned functionality from the previous section has been integrated also as preparation for the White Goods pilot. The features that are developed in this use case are as follows: light curtain, light curtains' control panel, robot workspace, collaborative workspace, assembly demo, and assembly procedure of transformers for microwave.

The light curtain visualizes the surface of laser beams where user can collide with. This area is designed in a way that when the user passes this border, an audio warning is played that reminds to user to exit from area after required task is performed, and then use Light curtain controller to re-activate corresponding light curtain bay (Figure 89).

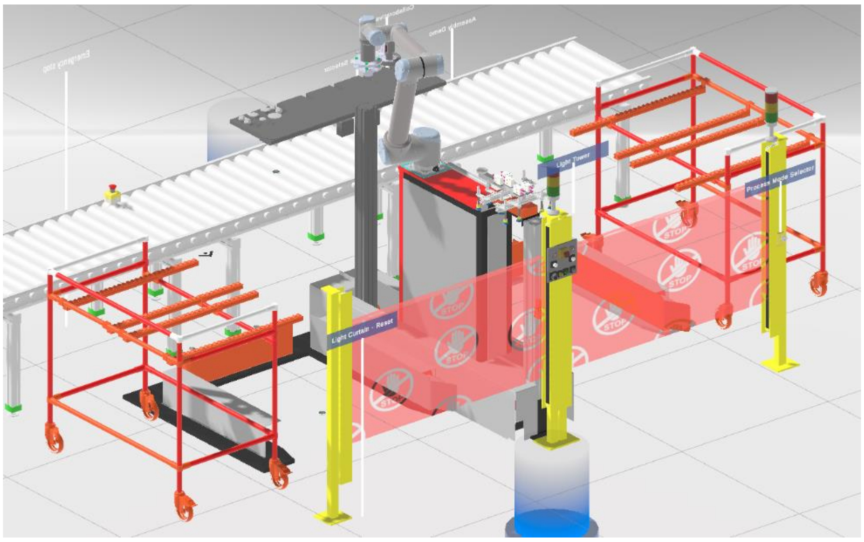


Figure 89: Definition of Light Curtain Areas

UI instructions are utilized in different places, such as assembly tasks, light curtain controller, definition of light indicator status. For instance, light curtain controller consists of instruction how to reset light curtains status and activate them after exiting the marked areas (Figure 90).

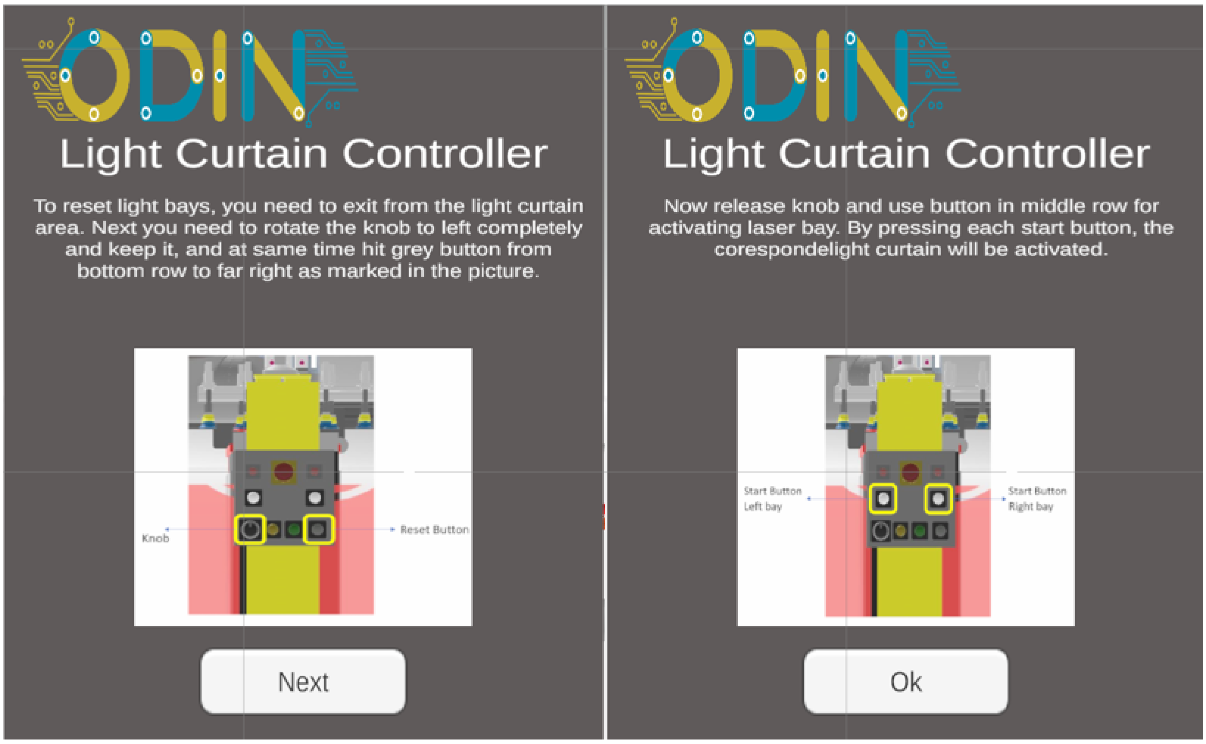


Figure 90: Light Curtain Reset Procedure from Control Panel

Similar to TAU HRC pilot application, the investigated assembly process contains human and robot tasks which are demonstrated with animations. Light curtain areas are visualized to familiarize the user regarding when and where these events are triggered. User is provided with information regarding the sequence of his/her tasks and additionally he/she is able to observe robot trajectory and task in continuous of assembly process. Place holders are utilized for demonstration of components correct placements and with colour coding guidance (Figure 91).

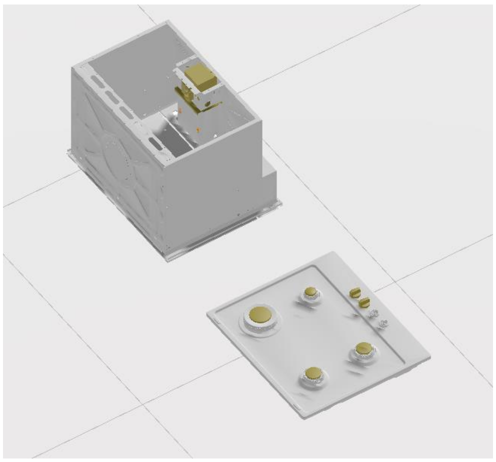


Figure 91: Placeholders for Assembly Components of Microwave and Cooktops

5.4. Safety Related Parts of Control System

The components and functions described herein represent an update of the safety functions described in sections 7.4 of deliverable D2.1.

These components and functions are defined on the basis of the Design-based Risk Assessment and related Safety Concepts described in sections 7.1 and 7.5 of deliverable D5.1 (M18), respectively. Each analysis represents the updates since the preliminary SRP/CS architecture definition included into Section 3.3 of deliverable D1.3 in M9, providing a higher level of detail.

For the White Goods Pilot the safety architecture has changed slightly with respect to D2.1. Image 1 below provides an updated overview of the architecture of the Safety Related Parts of Control System required for the implementation of the necessary Safety Functions. These functions are necessary to reduce the risks identified in D5.1 to acceptable limits where reduction by intrinsically safe design measures is not applicable.

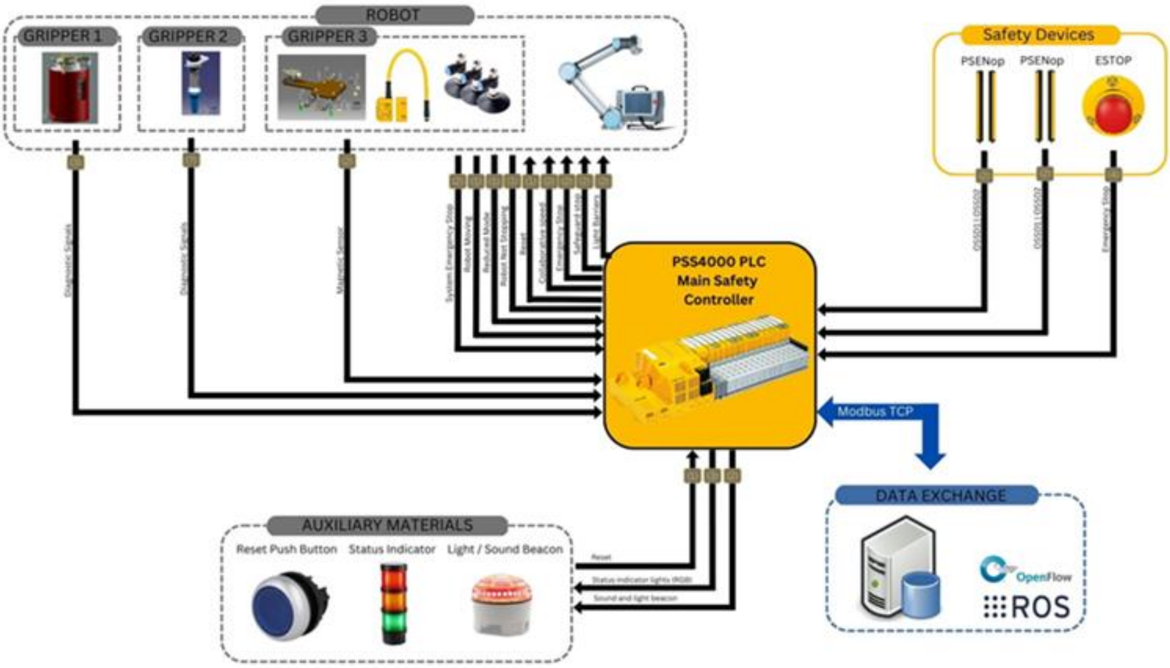


Figure 92: Safety Architecture for White Goods Pilot

Below is a list of the changes and updates in the Safety Related Parts of Control System with respect D2.1:

- A RevolutionPI will not be used as a bridge for the data exchange between the safety controller and Openflow. This data exchange will be conducted using a direct Modbus TCP connection. Safety configuration has prevalence over Openflow actions.
- No Reduced Speed mode allowed when the VacuumGripper is attached. This is enforced by the Safety PLC.
    - Safety Plane on frontal side will trigger reduced mode and a Safe Output will be used by the Safety PLC to trigger the Protective Stop when Vacuum Gripper is attached.
- Programming mode will have same safety boundaries as normal mode.

Other safety functions described in D2.1 like robot Safety-Rated monitored Stop (SOS), Safety-Rated reduced Speed or safety boundaries have not been changed.

In general, the required performance level for the safety-related control system above described is PL "d" category "3" according to EN ISO 13849-1 [33]. This level is stipulated by standard type C EN ISO 10218-1 (in section 5.4) for robots and robotic systems.

5.4.1. Safety concept update

The modifications described herein represent an update of the safety concept described in sections 6.2 of deliverable D5.1.

Collaborative approach – back area

The back area will not be divided in two zones. The robot will work in a normal speed when the operator is not accessing the back area. 'Reduced Mode' will be triggered if any of the light barriers is interrupted while the robot is equipped with a soft gripper. An 'STOP' will be triggered if any of the light barriers is interrupted with vacuum gripper attached.

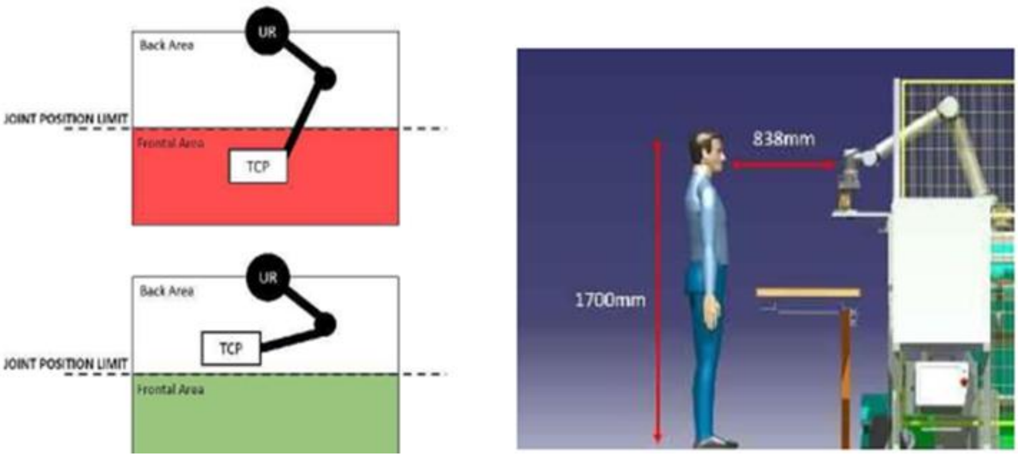


Figure 93: **Back area collaborative approach**

Collaborative speed

Preliminary PRMS Impact Measurements have been taken by PILZ for the White Goods pilot. With the results of the measurements, it was determined that a collaborative speed of 250 mm/s is safe for the operator during collaborative phases. The values of force and pressure for that speed were under the acceptable limits for all tests conducted based on the technical specification ISO TS 15066.

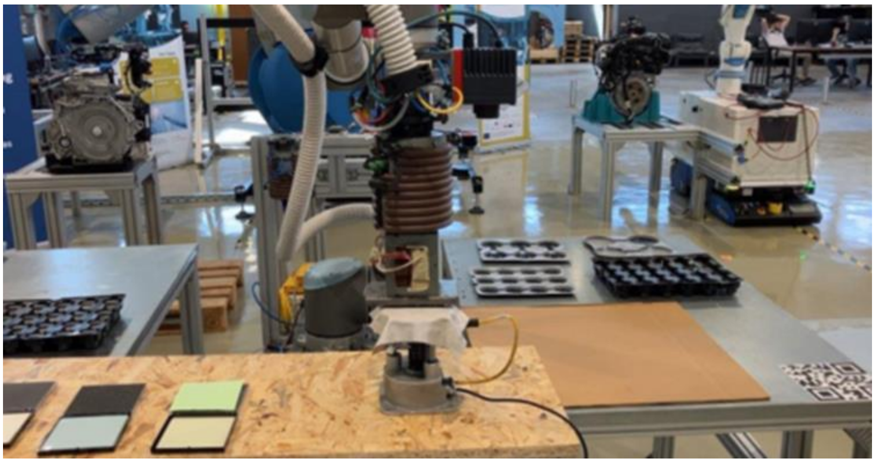


Figure 94: **White Goods PRMS tests with preliminary magnetic gripper**

Figure 95: **White Goods PRMS tests with preliminary vacuum gripper**

The PRMS results are presented in more detail under ANNEX I. The rest of safety functions required remain the same as the ones explained in D5.1.

6. Conclusions

The intermediate version of ODIN Industrial Component is presented in this deliverable. The focus is given on the large-scale pilot lines developed in ODIN. In The integration and testing of ODIN Open, Digital and Networked modules in each large-scale pilot has been detailly presented.

The main conclusion from Open, Digital and Networked Components integration inside ODIN industrial demonstrators at LMS and TECNALIA premises is that WP5 tasks are running as expected without any major delays. The following information per each demonstrator presented in this deliverable:

- Layouts designs of the full scales pilot demonstrators in their final and existing form.
- Successful integration of the ODIN Components and individual modules.
- First testing of pilots' execution flow utilizing the aforementioned modules in the existing setups.

The integration of Open, Digital and Networked Components in the three large-scale pilots of ODIN is a work in progress, and the descriptions presented in this deliverable will be enhanced during the development workflow of WP5 and the relevant tasks in this work package.

The final version of ODIN modules integration in ODIN pilots will be presented in D5.5 which is scheduled to be submitted on M48.

7. GLOSSARY

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AR	Augmented Reality
CAD	Computer Aided Design
CNN	Convolutional Neural Network
DC	Digital Component
FC	Fan Cowl
FOV	Field Of View
GUI	Graphical User Interface
HW	Hardware
OEM	Original Equipment Manufacturer
OISP	On-site Interactive Skill Programming
PLC	Programmable Logic Controller
QI	Quality Inspection
ROI	Regions of Interest
ROS	Robot Operating System
SOP	Start of production
SRP/CS	Safety-related parts of controls systems
SW	Software
TIER	Provider level
UDP	User Datagram Protocol
VC	Visual Components
XML	eXtensible markup language

8. References

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9. ANNEX I - PRMS IMPACT MEASUREMENTS WHITE GOODS PILOT CASE

Measurement report collision measurement according to ISO TS 15066

LMS

ODIN - PILZ - PRMS Impact Measurement - White Goods Pilot Case

Version V0A

1 Contact information

Customer	
Company name	LMS
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Zip / City:	Patras 2650
Country:	Greece
Contact person:	Apostolis PAPAVASILEIOU
Phone:	N/D
Email:	papavasileiou@lms.mech.upatras.gr

Inspector	
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2 Document

Document status	
Project description:	ODIN - PILZ - PRMS Impact Measurment - White Goods Pilot Case
Document number:	NA
Version:	V0A
Last edited:	25.07.2023

	Name	Signature	Date
Inspector:	Pedro Martins / Ramón Tresguerres		
Contact person Customer:	Apostolis PAPAVASILEIOU		

3 General Information

Machine information	
Machine name:	White Goods Pilot Case
Manufacturer:	LMS
Machine type:	N/A
Serial number:	N/A
Year of construction:	N/A

Robot Information	
Manufacturer:	Universal Robots
Robot type:	UR10
Serial number:	2015301090
Robot control:	N/A
Robot control Version:	N/A
Robot control Serial number:	N/A
Year of construction:	N/A

3.1 Introduction

The company Pilz Industrieelektronic, S.L. was commissioned to carry out a collision measurement for the above mentioned application. The measurement is based on the technical specification ISO TS 15066. During the measurement the permissible limits for force and pressure are used. The measuring points (RCMP) for the collision measurement were determined in advance and made available to the company Pilz Industrieelektronic, S.L.

The determined results are only a component of the safety tests of an MRK application. Safety tests of the entire application must be carried out additionally by the manufacturer of the application.

4 Measurement

4.1 General information about the collision measurement

Description	Type / Description / Name	Version / Number / Date
Measurement device	PRMS device	
Software Tool	PRMS Assistant	1.5.0-e3cc9d2
{Sensor	PRMS device	
Mounting	The mounting of the sensor incl. a linear spring. The spring simulates the compression constant of the respective body region. The foam rubber pad is mounted on the plate to simulate the skin.	

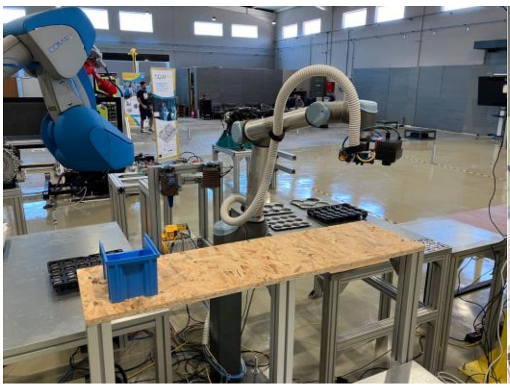
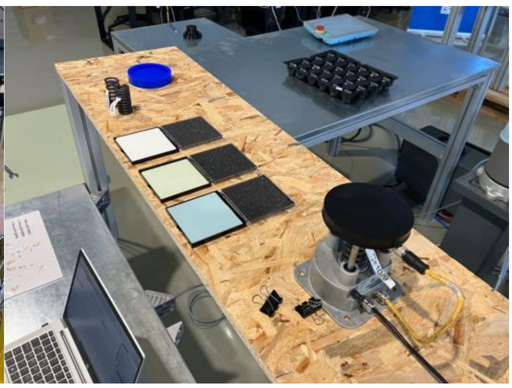
4.2 Staff

Inspector	Pedro Martins / Ramón Tresguerres
Contact person Customer	Apostolis PAPAVASILEIOU
Inspection date	25.07.2023

4.3 Checksum Robot control

Robot	Checksum	Version / Number / Date
Robot	366D	25.07.2023

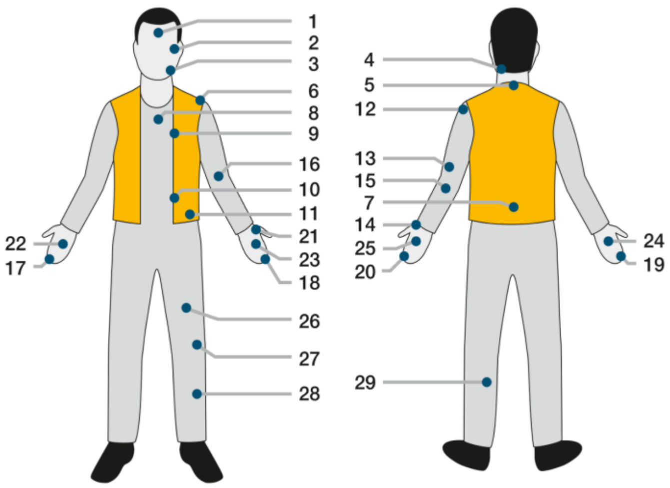
4.4 Application-specific data (load data tool etc.)

4.5 Limits according to ISO TS 15066

Body area (body region)		Specific body area	Quasi-static contact (clamping)		Transient contact (impact)	
			Maximum permissible pressure PS (N/cm²)	Maximum permissible force (N)	Maximum permissible pressure PS (N/cm²)	Maximum permissible force (N)
Skull and forehead	1	Middle of forehead	130	130	130	130
	2	Temple	110		110	
Face	3	Masticatory muscle	110	65	110	65
Neck	4	Neck muscle	140	150	280	300
	5	7th neck vertebra	210		420	
Back and shoulders	6	Shoulder joint	160	210	320	420
	7	5th lumbar vertebra	210		420	
Chest	8	Sternum	120	140	240	280
	9	Pectoral muscle	170		340	
Abdomen	10	Abdominal muscle	140	110	280	220
Pelvis	11	Pelvic bone	210	180	420	360
Upper arms and elbow joints	12	Deltoid muscle	190	150	380	300
	13	Humerus	220		440	
Lower arms and wrist joints	14	Radial bone	190	160	380	320
	15	Forearm muscle	180		360	
	16	Inside of elbow	180		360	
Hands and fingers	17	Forefinger pad D	300	140	600	280
	18	Forefinger pad ND	270		540	
	19	Forefinger end joint D	280		560	
	20	Forefinger end joint ND	220		440	
	21	Thenar eminence	200		400	
	22	Palm D	260		520	
	23	Palm ND	260		520	
	24	Back of the hand D	200		400	
	25	Back of the hand ND	190		380	
Thighs and knees	26	Thigh muscle	250	220	500	440
	27	Kneecap	220		440	
Lower legs	28	Middle of shin	220	130	440	260
	29	Calf muscle	210		420	

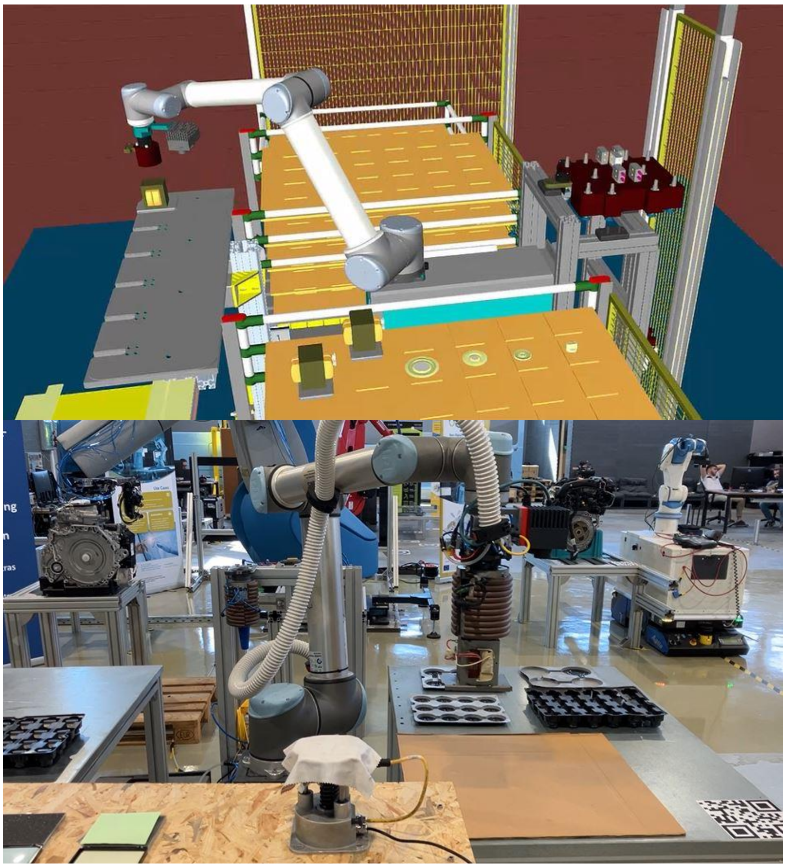
D = dominant ND = non-dominant



4.6 MP1_Q - Clamping between transformer and fixture

4.6.1 Description of the measurement setup

Measurement of force and pressure of a potential clamping against the back part of the hand during transformer placement. The worst-case scenario is the crushing of sharp edge part of back of hand of the operator. Temperature: 25,5ºC Humidity: 54,4%



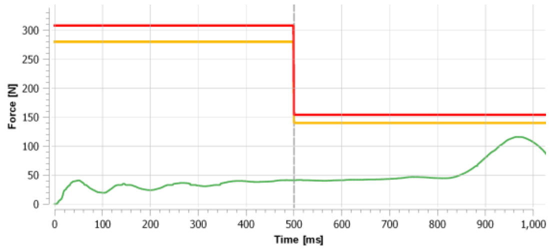
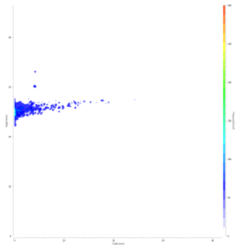
4.6.2 Measurement conditions

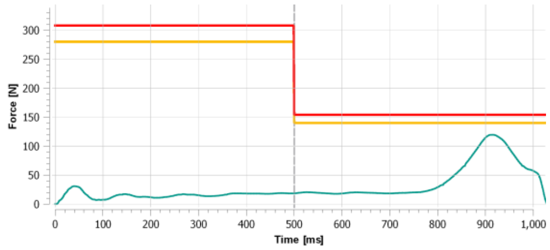
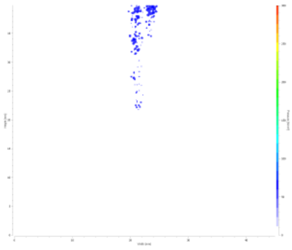
Contact type	quasi-static	**Spring [N/mm]**	75
Body region	Back of hand ND	**Pad**	black (Shore A 70)
Temperature [°C]	25	**Humidity [%]**	54
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	250

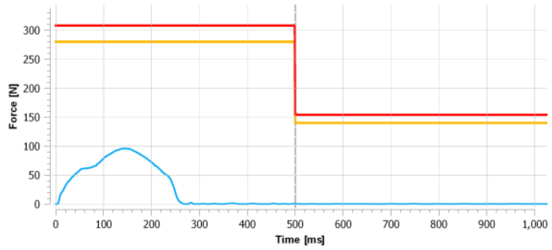
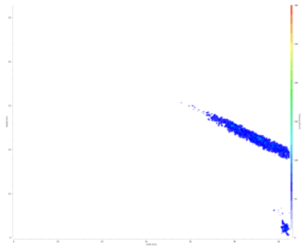
4.6.3 Limits

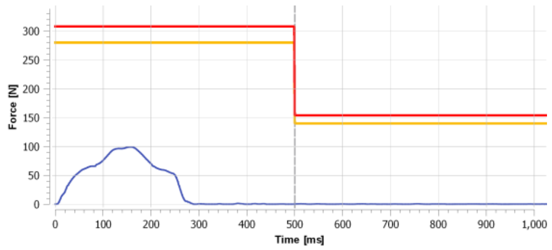
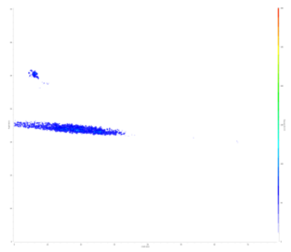
	F_T [N]	F_S [N]	P [N/cm²]
Limits according to ISO TS 15066	280	140	190
Maximum values of all measurements	116	120	183

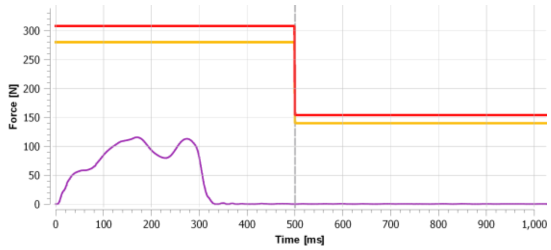
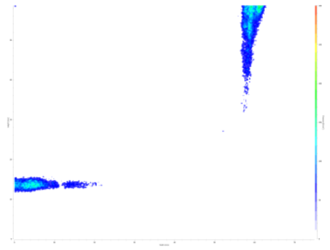
4.6.4 Measured values MP1_Q - Clamping between transformer and fixture

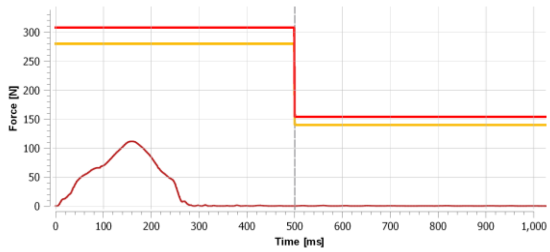
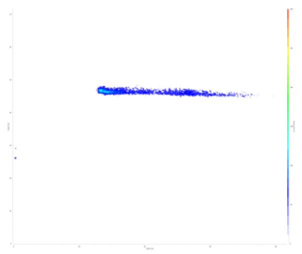
Measurement 1		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 41 **F_S [N] :** 116 **P [N/cm²] :** 157		

Measurement 2		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 31 **F_S [N] :** 120 **P [N/cm²] :** 75		

Measurement 3		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 96 **F_S [N] :** 1 **P [N/cm²] :** 121		

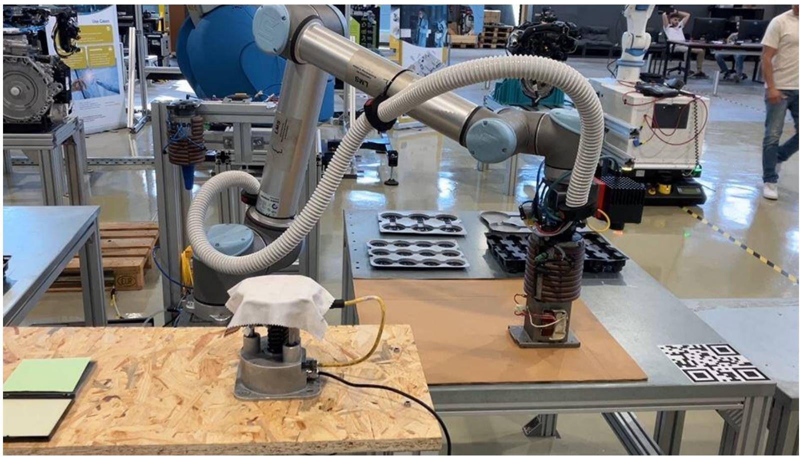
Measurement 4		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 99 **F_S [N] :** 1 **P [N/cm²] :** 122		

Measurement 5		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 116 **F_S [N] :** 1 **P [N/cm²] :** 183		

Measurement 6		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 112 **F_S [N] :** 1 **P [N/cm²] :** 159		

Remarks
The values of force and pressure are under the acceptable limits for quais-static collision established in table A.2 Annex A of ISO/TS 15066.

4.6.5 Robot positions

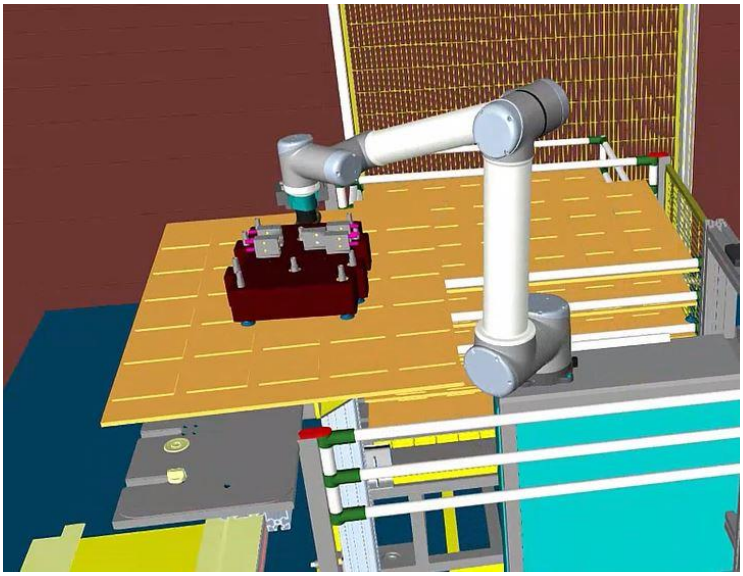
Start position of the measurement (SP)	
Axis 1 [°]: -90.04º Axis 2 [°]: -91.19º Axis 3 [°]: 89.03º Axis 4 [°]: -88.12º Axis 5 [°]: -90.10º Axis 6 [°]: -42.93º Axis 7 [°]: N/A	

Collision point of the measurement (CP)	
Axis 1 [°]: N/A Axis 2 [°]: N/A Axis 3 [°]: N/A Axis 4 [°]: N/A Axis 5 [°]: N/A Axis 6 [°]: N/A Axis 7 [°]: N/A	

Endpoint of the measurement (EP)	
Axis 1 [°]: -137.33º Axis 2 [°]: -75.75º Axis 3 [°]: 63.15º Axis 4 [°]: -77.35º Axis 5 [°]: -88.84º Axis 6 [°]: -87.40º Axis 7 [°]: N/A	

4.7 MP2_T-Contact with vacumm gripper in movement

4.7.1 Description of the measurement setup

The vacuum gripper is not a collaborative gripper, and this operation is not possible due to safety limitations.


4.7.2 Measurement conditions

Contact type	transient	**Spring [N/mm]**	75
Body region	Masticatory muscle	**Pad**	black (Shore A 70)
Temperature [°C]	0	**Humidity [%]**	0
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	100

4.7.3 Limits

	F_T [N]	F_S [N]	P [N/cm²]
Limits according to ISO TS 15066	65	-	110
Maximum values of all measurements	0	-	0

4.8 MP3_T - Contact with sharp edges of the robot (camera and metal profiles)

4.8.1 Description of the measurement setup

Measurement of force of a potential impact of the sharp edges of the robot against the masticatory muscle of the operator during the transformer placement (simulated with vacuum gripper metal profile corner due to limitations imposed by LMS). The worst case scenario is the impact of the sharp edges of the robot in the face of the operator and this is expected only to happen during reasonably foreseeable misuse. Temperature: 26,3ºC Humidity: 55,1%

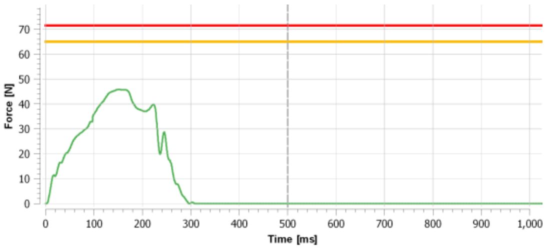

4.8.2 Measurement conditions

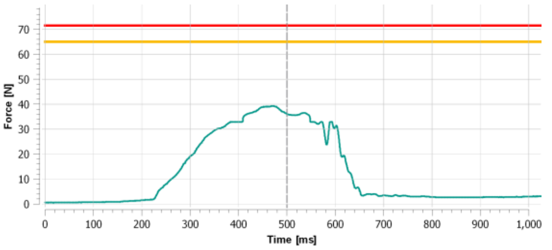
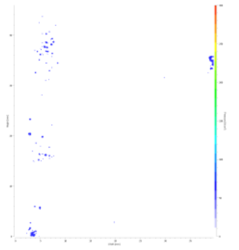
Contact type	transient	**Spring [N/mm]**	75
Body region	Masticatory muscle	**Pad**	black (Shore A 70)
Temperature [°C]	26	**Humidity [%]**	55
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	250

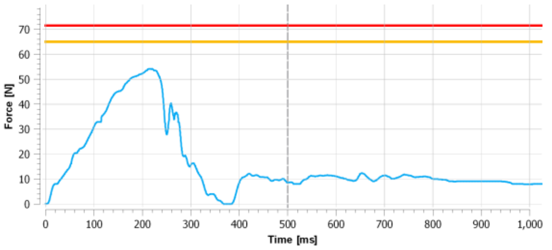
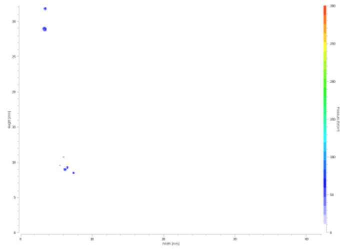
4.8.3 Limits

	F_T [N]	**F_S [N]**	**P [N/cm²]**
Limits according to ISO TS 15066	65	-	110
Maximum values of all measurements	54	-	88

4.8.4 Measured values MP3_T - Contact with sharp edges of the robot (camera and metal profiles)

Measurement 1		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 46 **F_S [N] :** - **P [N/cm²] :** 73		

Measurement 2		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 39 **F_S [N] :** - **P [N/cm²] :** 88		

Measurement 3		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 54 **F_S [N] :** - **P [N/cm²] :** 88		

Remarks
The values of force and pressure are under the acceptable limits for transient collision established in table A.2 Annex A of ISO/TS 15066.

4.8.5 Robot positions

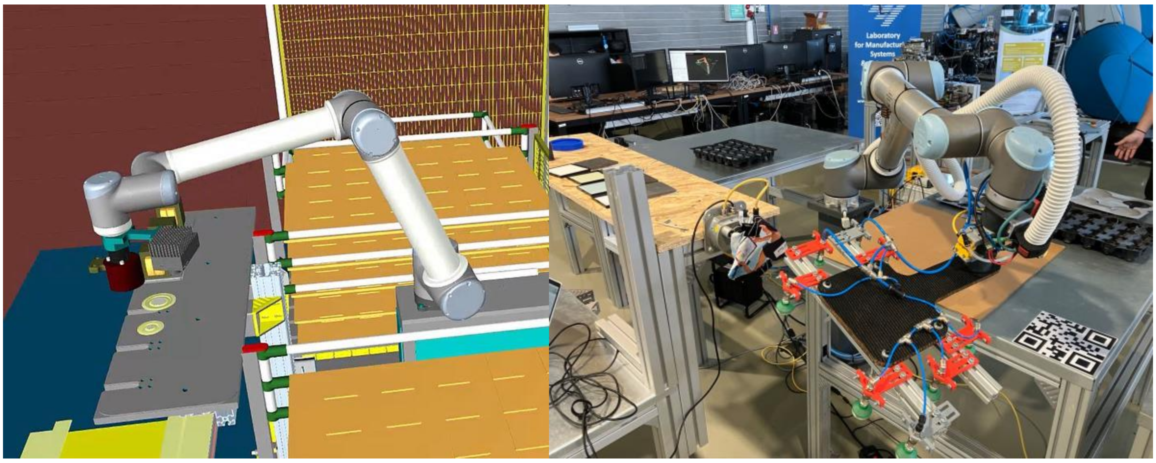
Start position of the measurement (SP)	
Axis 1 [°]: -137,36º Axis 2 [°]: -77.02º Axis 3 [°]: 61,76º Axis 4 [°]: -76,70º Axis 5 [°]: -88,87º Axis 6 [°]: -87,37º Axis 7 [°]: N/A	

Collision point of the measurement (CP)	
Axis 1 [°]: N/A Axis 2 [°]: N/A Axis 3 [°]: N/A Axis 4 [°]: N/A Axis 5 [°]: N/A Axis 6 [°]: N/A Axis 7 [°]: N/A	

Endpoint of the measurement (EP)	
Axis 1 [°]: -102.28º Axis 2 [°]: -73,95º Axis 3 [°]: 78,09º Axis 4 [°]: -78,96º Axis 5 [°]: -99,77º Axis 6 [°]: -17,40º Axis 7 [°]: N/A	

4.9 MP3_Q - Contact with sharp edges of the robot (camera and metal profiles)

4.9.1 Description of the measurement setup

Measurement of force and pressure of a potential impact of the sharp edges of the robot against the masticatory muscle of the operator during the knob placement in operator hand in the lateral side (simulated with vacuum gripper metal profile corner due to limitations imposed by LMS). The worst-case scenario is the crushing of the sharp edges of the robot between the face of the operator and the existing structure. Temperature: 26,6ºC Humidity: 55.8%


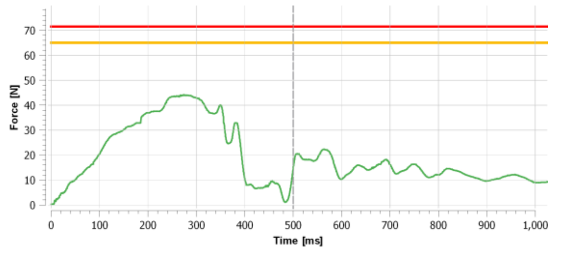
4.9.2 Measurement conditions

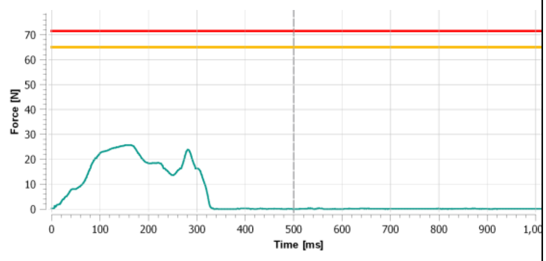
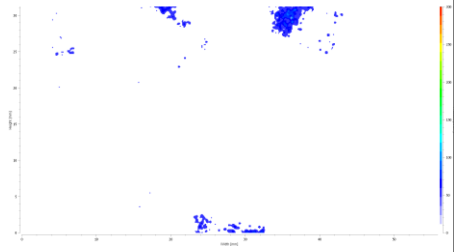
Contact type	quasi-static	**Spring [N/mm]**	75
Body region	Masticatory muscle	**Pad**	black (Shore A 70)
Temperature [°C]	24	**Humidity [%]**	51
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	250

4.9.3 Limits

	F_T [N]	**F_S [N]**	**P [N/cm²]**
Limits according to ISO TS 15066	65	65	110
Maximum values of all measurements	44	22	105

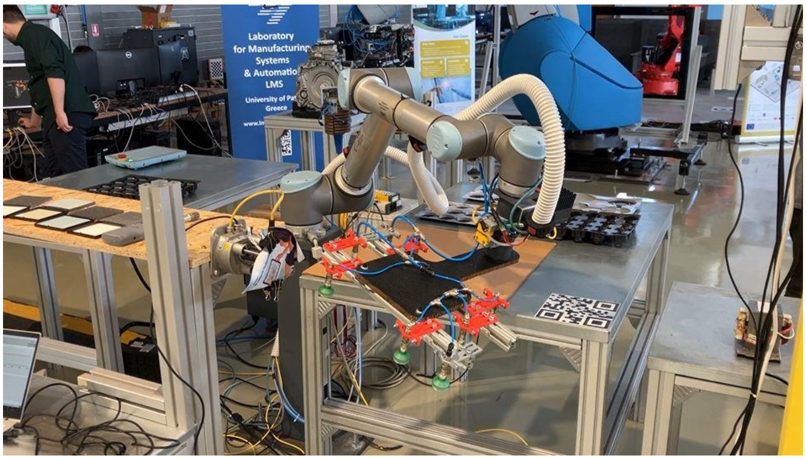
4.9.4 Measured values MP3_Q - Contact with sharp edges of the robot (camera and metal profiles)

Measurement 1		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 44 **F_S [N] :** 22 **P [N/cm²] :** 65		

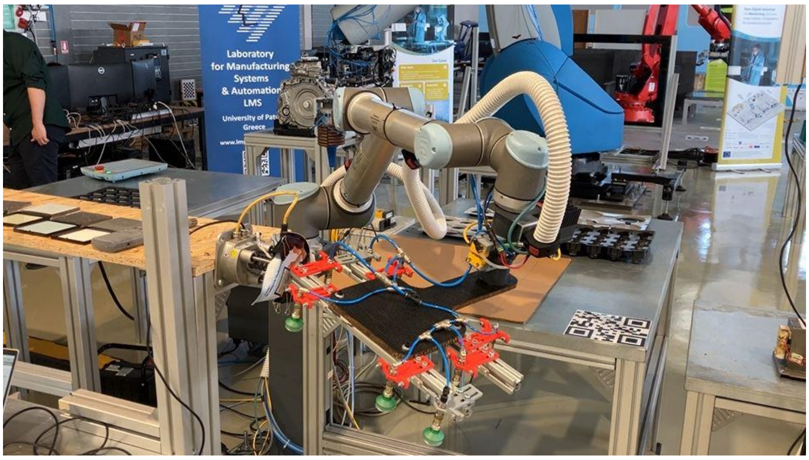
Measurement 2		
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 26 **F_S [N] :** 0 **P [N/cm²] :** 105		

Remarks
The values of force and pressure are under the acceptable limits for quais-static collision established in table A.2 Annex A of ISO/TS 15066.

4.9.5 Robot positions

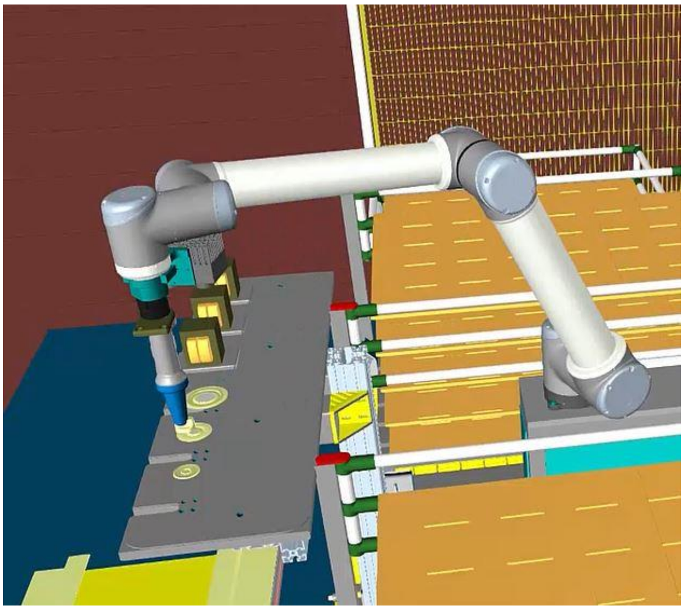
Start position of the measurement (SP)	
Axis 1 [°]: -85.14º Axis 2 [°]: -44,52º Axis 3 [°]: 48,15º Axis 4 [°]: -79,56º Axis 5 [°]: -97,62º Axis 6 [°]: -117,85 Axis 7 [°]: N/A	

Collision point of the measurement (CP)	
Axis 1 [°]: N/A Axis 2 [°]: N/A Axis 3 [°]: N/A Axis 4 [°]: N/A Axis 5 [°]: N/A Axis 6 [°]: N/A Axis 7 [°]: N/A	

Endpoint of the measurement (EP)	
Axis 1 [°]: -85,36º Axis 2 [°]: -44,65º Axis 3 [°]: 50,29º Axis 4 [°]: -82,65º Axis 5 [°]: -95,14º Axis 6 [°]: -106,49º Axis 7 [°]: N/A	

4.10 MP4_Q - Clamping between the adaptive gripper and plastic box

4.10.1 Description of the measurement setup

The adaptive gripper drops the cooktop in the box so there is no hazard associated to this operation.


4.10.2 Measurement conditions

Contact type	quasi-static	**Spring [N/mm]**	75
Body region	Forefinger pad ND	**Pad**	black (Shore A 70)
Temperature [°C]	0	**Humidity [%]**	0
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	100

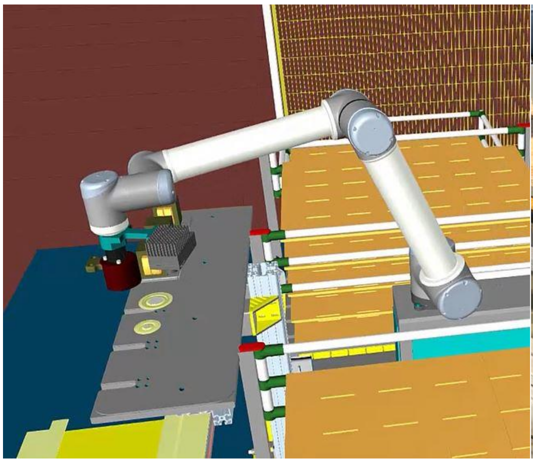
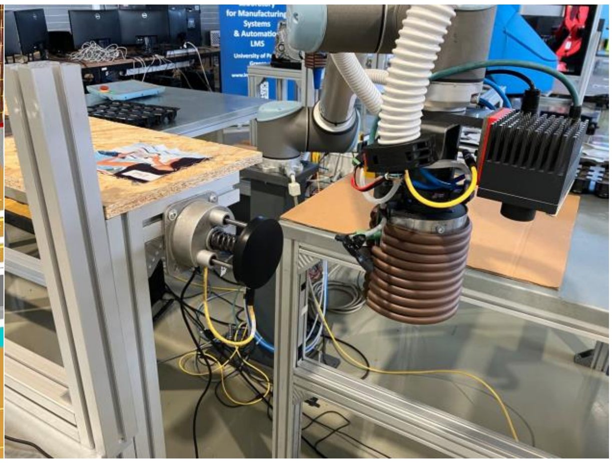
4.10.3 Limits

	F_T [N]	F_S [N]	P [N/cm²]
Limits according to ISO TS 15066	280	140	270
Maximum values of all measurements	0	0	0

4.11 MP5_Q - Clamping between magnetic gripper and lateral fixture

4.11.1 Description of the measurement setup

Measurement of force and pressure of a potential clamping of the magnetic gripper structure against the operator arm during the knob placement in operator hand in the lateral side. The worst case scenario is the clamping of the operator arm between the fixed structure and movable parts of the robot. Temperature: 25,9ºC Humidity: 53.8%

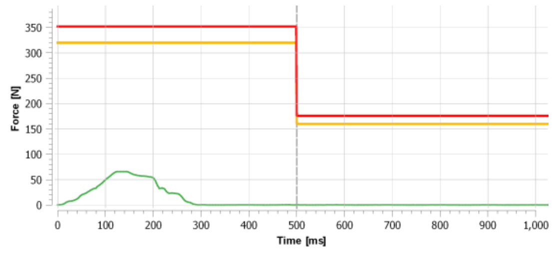
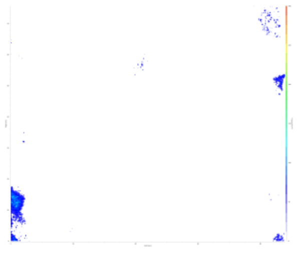
4.11.2 Measurement conditions

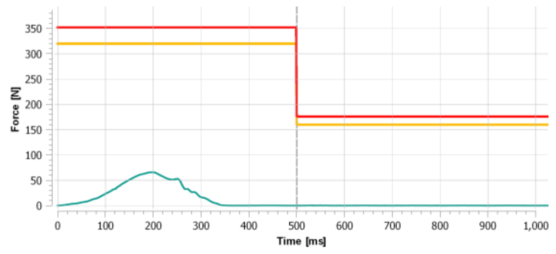
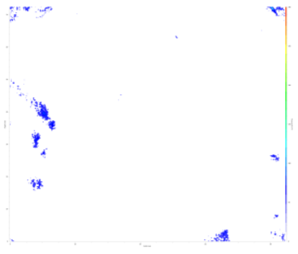
Contact type	quasi-static	**Spring [N/mm]**	40
Body region	Radial bone	**Pad**	black (Shore A 70)
Temperature [°C]	25	**Humidity [%]**	53
Force limit of the Robot	Setting no available	**Speed at the measurement in [mm/s]**	250

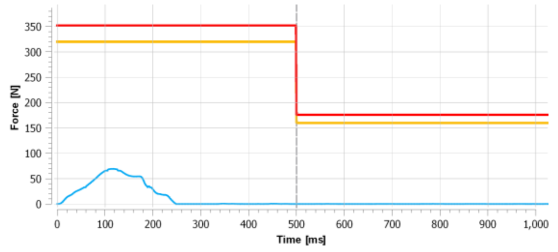
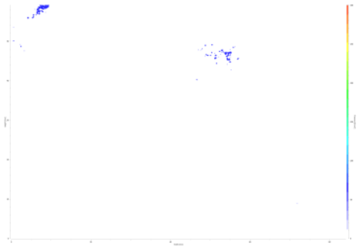
4.11.3 Limits

	F_T [N]	**F_S [N]**	**P [N/cm²]**
Limits according to ISO TS 15066	320	160	190
Maximum values of all measurements	69	0	161

4.11.4 Measured values MP5_Q - Clamping between magnetic gripper and lateral fixture

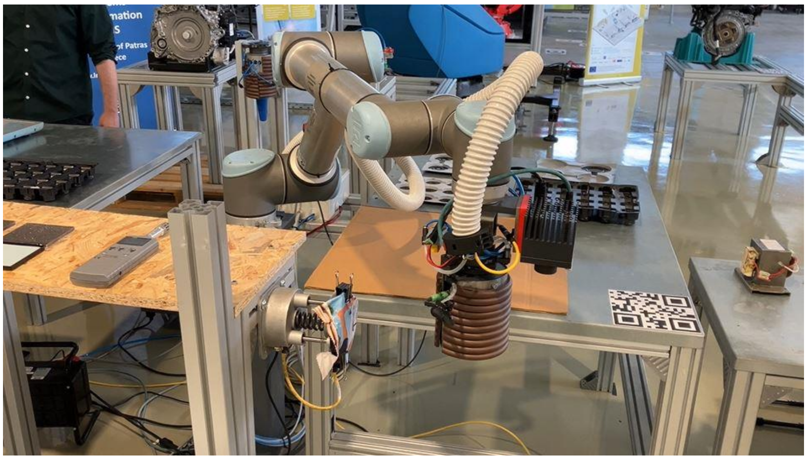
<table>
<tr><th colspan="3">Measurement 1</th></tr>
<tr><th>Measured values</th><th>Force curve</th><th>Pressure curve
Film: LLW</th></tr>
<tr><td>F_T [N] : 66
F_S [N] : 0
P [N/cm²] : 133</td><td>
</td><td></td></tr>
</table>

<table>
<tr><th colspan="3">Measurement 2</th></tr>
<tr><th>Measured values</th><th>Force curve</th><th>Pressure curve
Film: LLW</th></tr>
<tr><td>F_T [N] : 66
F_S [N] : 0
P [N/cm²] : 161</td><td>
</td><td></td></tr>
</table>

<table>
<tr><th colspan="3">Measurement 3</th></tr>
<tr><th>Measured values</th><th>Force curve</th><th>Pressure curve
Film: LLW</th></tr>
<tr><td>F_T [N] : 69
F_S [N] : 0
P [N/cm²] : 69</td><td>
</td><td></td></tr>
</table>

Remarks
The values of force and pressure are under the acceptable limits for quais-static collision established in table A.2 Annex A of ISO/TS 15066.

4.11.5 Robot positions

Start position of the measurement (SP)	
Axis 1 [°]: -104,74º Axis 2 [°]: -43,81º Axis 3 [°]: 46,53º Axis 4 [°]: -93,55º Axis 5 [°]: -90,15º Axis 6 [°]: -55,23º Axis 7 [°]: N/D	

Collision point of the measurement (CP)	
Axis 1 [°]: N/D Axis 2 [°]: N/D Axis 3 [°]: N/D Axis 4 [°]: N/D Axis 5 [°]: N/D Axis 6 [°]: N/D Axis 7 [°]: N/D	

Endpoint of the measurement (EP)	
Axis 1 [°]: N/D Axis 2 [°]: N/D Axis 3 [°]: N/D Axis 4 [°]: N/D Axis 5 [°]: N/D Axis 6 [°]: N/D Axis 7 [°]: N/D