Mobile dual arm robotic workers with embedded cognition for hybrid and dynamically reconfigurable manufacturing systems

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Summary:

The final version of the hardware and software components adapted into Automotive Use Case's needs are presented in this document. In addition, the final version of Automotive pilot case's physical setup in PSA premises is presented.

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1. EXECUTIVE SUMMARY

The present deliverable presents the THOMAS Open Production Station (OPS) deployment in the THOMAS automotive pilot case. THOMAS aim is to create dynamically re-configurable shopfloors by introducing flexible mobile dual arm robots in THOMAS OPS. These flexible robot workers, the so-called THOMAS Mobile Robot Platforms (MRPs), able to autonomously navigate in different workstations of the shopfloor undertaking multiple assembly operations. The target for the MRP is to assist human operators by undertaking the strenuous and repetitive tasks. To enable this flexible behaviour, THOMAS OPS integrates a set of individual technologies for enabling:

- Mobility on products and resources.
- Human-Robot and Robot-Robot collaboration in a safe way.
- Perception and skills to automatically program and execute multiple tasks.
- Dynamic work balancing and resources' redirecting to stations.

All THOMAS individual enabling technologies have been integrated in THOMAS OPS, considering both the hardware and software components. These components have been then customized to meet the requirements of the automotive use case which focuses on the assembly of a passenger's vehicle front axle. For the initial integration and testing of THOMAS technologies in the automotive use case, the initial version of the THOMAS has been installed at LMS premises. After the validation of THOMAS automotive OPS at LMS, THOMAS partners focused on transferring the automotive use case in STELLANTIS premises.

This document presents the deployment of THOMAS OPS at STELLANTIS factory in Mulhouse, France. The use case focuses on the pre-assembly, compression and assembly of the passenger vehicle's dampers on the disks involving three workstations: a) Damper's pre-assembly working area, b) Compression Machine working are, c) Mobile Product Platform (MPP) working area. The deployed layout is visualized in Figure 1.

An additional working area for MRP's battery recharging has been added in the final version of THOMAS automotive use case layout. In case of low battery event, THOMAS MRP is capable to autonomously navigate in this area in order to charge its battery.

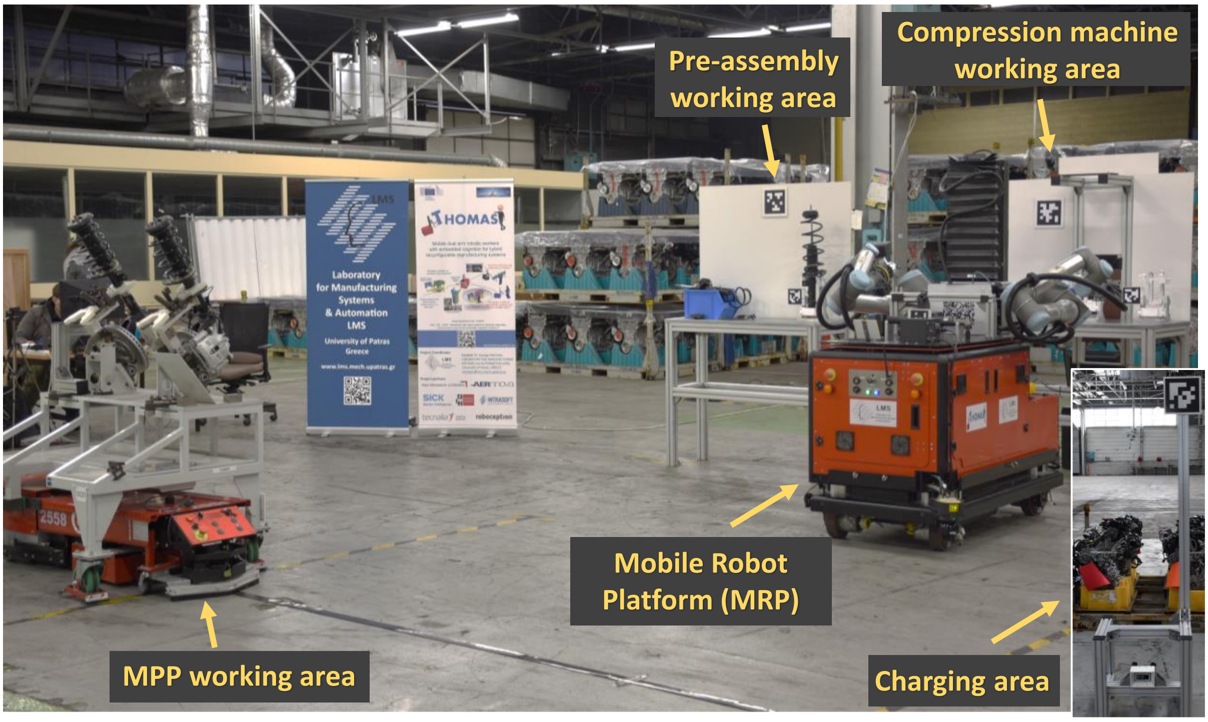


Figure 1: THOMAS Automotive use case physical layout

2. INTRODUCTION

THOMAS aim is to create dynamically re-configurable shopfloors including flexible mobile dual arm robots [1]. These robots are characterized as flexible resources based on their ability to perceive their environment, adapt their behaviour in case of environment changes and cooperate with other human and robot resources in the shopfloor. For this reason, different hardware and software components have been developed inside THOMAS project based on the four main objectives of the project [2]:

- Enabling mobility on products and resources.
- Human-Robot and Robot-Robot collaboration in a safe way.
- Perception and skills to automatically program and execute multiple tasks.
- Dynamic balancing and redirecting to stations.

For the initial integration and testing of THOMAS technologies in the automotive use case, the initial version of this use case has been installed in LMS premises as shown in Figure 2.

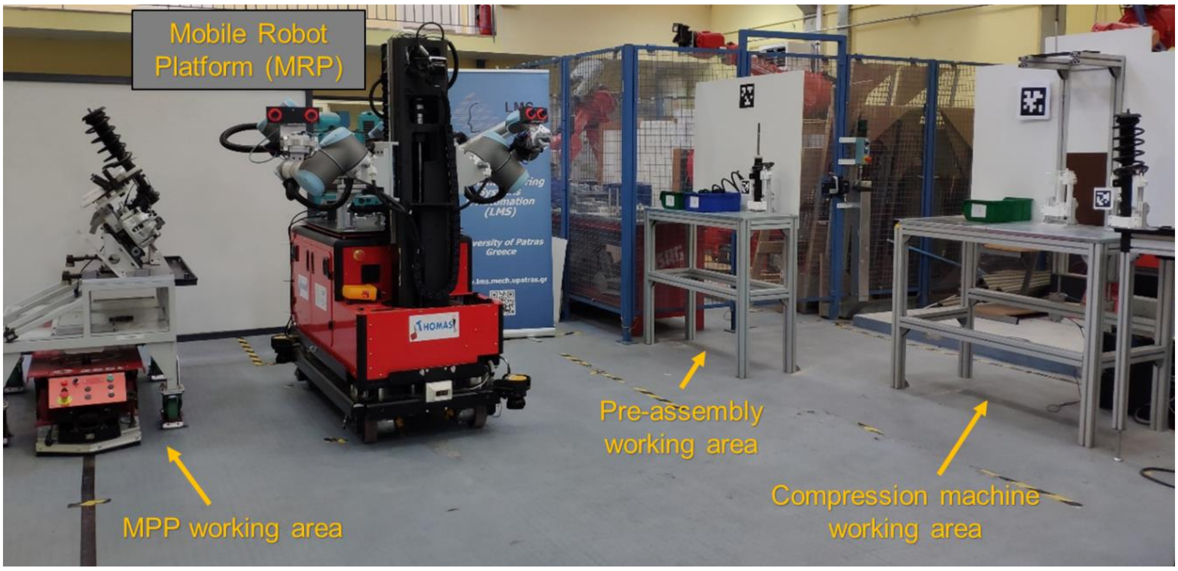


Figure 2: THOMAS Automotive OPS at LMS Machine Shop, Greece

After the validation of THOMAS automotive OPS inside LMS premise's setup, THOMAS partners focused on transferring the automotive use case in STELLANTIS premises (Figure 3). As an update of deliverable D7.3, this document focuses on the integration of different THOMAS developments in the automotive use case layout installed in STELLANTIS Mulhouse plant.

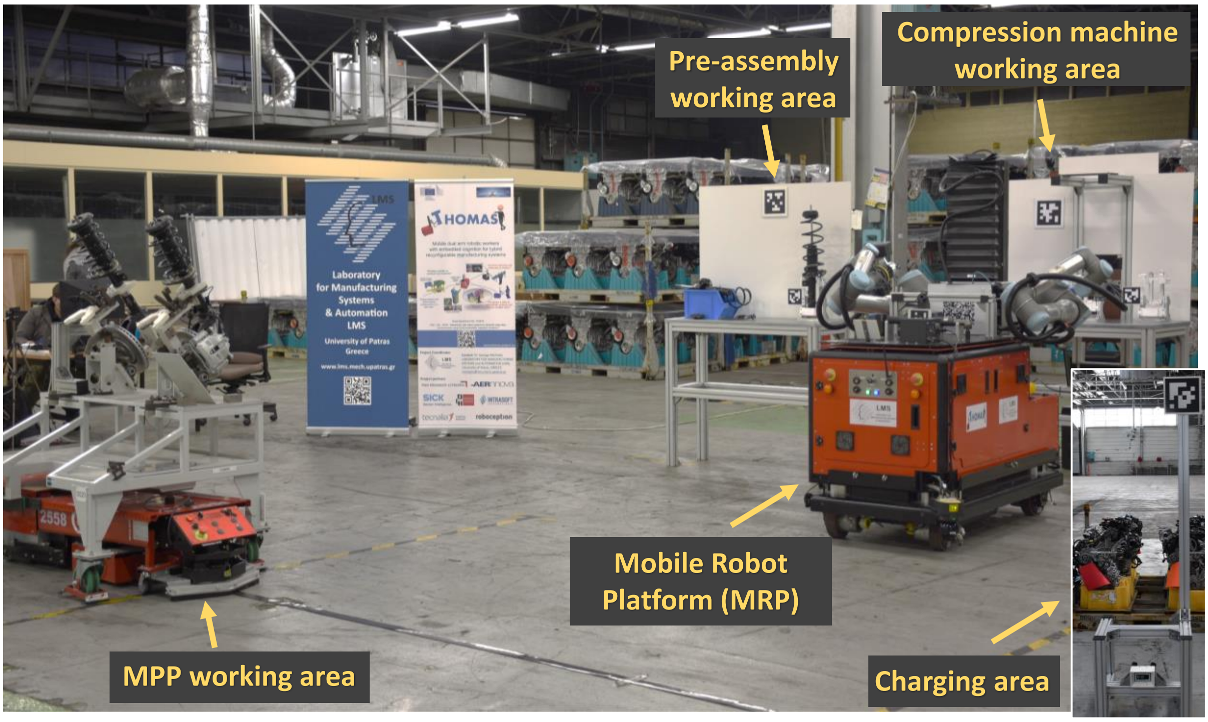


Figure 3: THOMAS Automotive OPS at STELLANTIS Mulhouse factory, France

The integration of each technology was developed under WP2-6 for automotive use case's needs is presented in this deliverable. The detailed presentation of the automotive use case layout as installed in STELLANTIS Mulhouse plant alongside with all the hardware and sensor components integration in the automotive use case layout are presented in Section 3.

The components of THOMAS automotive Open Production Station (OPS) are presented in Section 4. In more details, the following components are presented per subsection:

- THOMAS Automotive use case Mobile Robot Platform (MRP) in subsection 4.2.
- Network of services and work balancing in the automotive use case in subsection 4.3.
- Skill Engine's and CAD Programming software integration in the automotive use case in subsection 4.4.
- THOMAS Hybrid Human Robot Interaction (HHRI) and safety design of the automotive use case in subsection 4.5.
- Environment and process perception in the automotive use case in subsection 4.6.4.5.5
- Execution of Robot tasks per working area of the layout in subsection 4.7.

3. THOMAS AUTOMOTIVE USE CASE LAYOUT

3.1. General Overview

The layout of the automotive demonstrator is presented in this section of the document in order to help us describe in the best way the integration of the different hardware and software components. THOMAS automotive use case focuses on the assembly of the left damper from the front suspension of a vehicle car. For this reason, automotive use case demonstrator's layout consists of different working areas where assembly and screwing operations take place. The required tasks of damper's assembly process are presented in Table 1.

Table 1: Damper assembly process's tasks

Task	Working Area
Pre-assemble next damper	Pre-assembly area
Pre-compressed damper's transportation to the Compression Machine working area	Pre-assembly area → Compression machine
Insert Upper Cap and align damper to compression machine	Compression machine
Compress damper	Compression machine
Remove alignment rod	Compression machine
Insert nut	Compression machine
Compress	Compression machine
Compressed damper's transportation to the Mobile Product Platform working area	Compression machine → MPP
Insert cables and screws on the disk	MPP
Pick screwdriver	MPP
Screw damper – disk assembly	MPP

Based on the type of the operation executed in each working area for the assembly process of the damper, the states of the damper will be referenced in the next sections as follows:

- Pre-compressed damper, all the subcomponents of the damper have been assembled on the damper base part,
- Compressed damper, damper's spring has been compressed and the damper is ready to be assembled on the disk.
- Assembled damper, damper is assembled on the relevant disk and ready to be installed in a vehicle.

3.2. Damper's pre-Assembly working area

Both human and robot resources execute assembly tasks in the first working area of the designed layout, namely damper's pre-assembly working area. THOMAS MRP enters this area in order to pick the pre-compressed damper and transfer it to the compression area while the human operator assembles the = damper to be compressed in the next cycle, using the dampers' subparts which are available on the top of the pre-assembly table.

3.2.1. Pre-assembly table

The main component of the pre-assembly working area is the pre-assembly table. This table is made of aluminum profiles and wooder plates. A fixture and a box are placed on the top of this table (Figure 4). The subparts of a pre-compressed damper are placed inside this box. As previously mentioned, th human operator enters the pre-assembly working area in order to use these parts for pre-assembling the damper. The fixture is used to support the damper base part, keeping it stable while the operator installs its subparts on it.

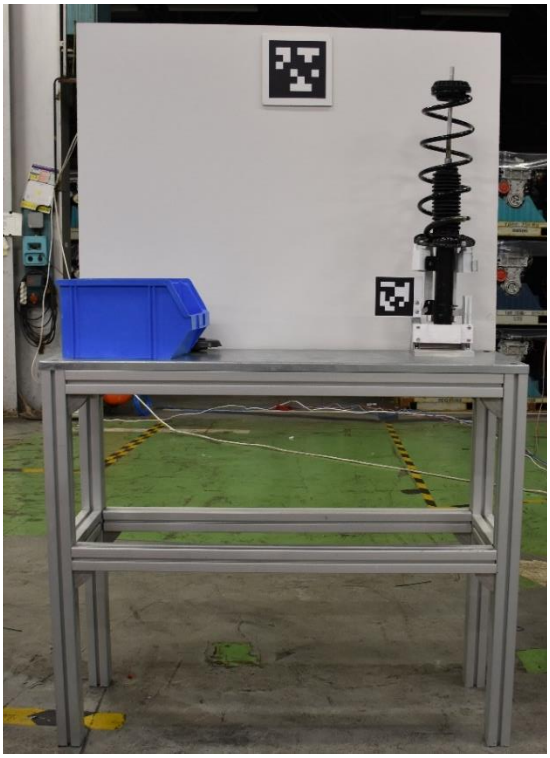


Figure 4: Pre-assembly table

3.3. Compression Machine working area

One of the most important tasks of the damper assembly process is damper's spring compression. In order to simulate the compression machine process, a mock compression . This mock up compression machine is an aluminum table with wooden plates and a custom mechanism emulating the compression process of a damper. The MRP cooperates with the human operator in this working area to achieve the successful compression of the damper.

3.3.1. Compression Machine mock-up table

As documented in the previous subsection, the compression machine table is an aluminum table with wooden plates and a custom mechanism emulating the compression process of a damper (Figure 5). This table's dimensions are based on the dimensions of a real compression machine. Accordingly, the two fixtures which are placed on the compression machine table but also the fixture placed on the top of the pre-assembly table are based on the design of the real compression machine's fixture. Compression machine table's fixtures are used for keeping stable the pre-compressed and compressed dampers. The compressed damper is the outcome of the compression process on the pre-compressed damper. However, the custom mechanism for emulating the compression process is not able to compress the spring of the damper. In this case, and in order to investigate the whole assembly process of the damper, a previously compressed damper is placed on the compression machine mockup in order to be transferred in the next working area of the assembly process.

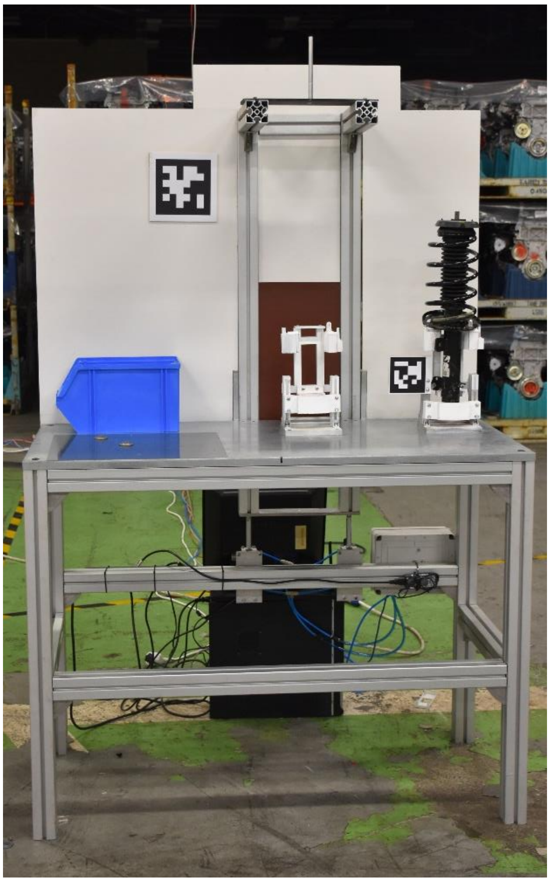


Figure 5: Compression Machine mock-up table

3.3.2. Compression Machine's Upper structure mechanism

In order to simulate the compression machine control process, an aluminum plate has been installed on the upper structure in which the alignment rod and the nut are placed. Compression machine's upper structure mechanism is a custom construction made of aluminum profiles capable to move up and down the compression plate emulating real compression machine's movement during the compression process (Figure 6). This motion is based on two air actuators which are installed behind the compression machine table.

Figure 6: Compression Machine Upper Structure mechanism

Damper's compression process is emulated using a Denkovi USB relay controller board and 2 pneumatic actuators (Figure 7). A PC is connected with this relay using a USB cable. A dedicated interface is deployed for the communication of the compression machine mock up mechanism to the THOMAS OPS control execution system.

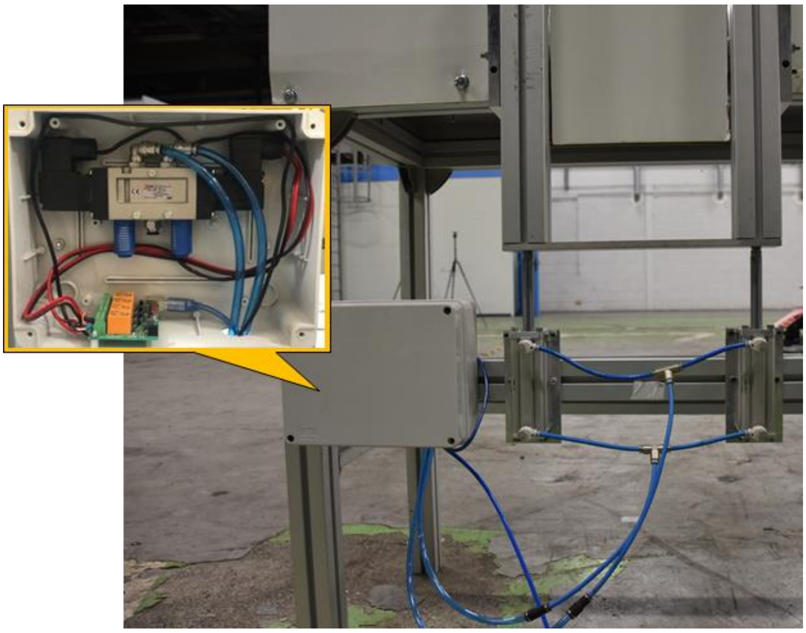


Figure 7: Compression Machine upper structure controlling device

3.3.3. SICK 3D safety camera as hardware component

SICK has been investigating the possibility to turn the workspace around the compression machine (CM) into an unfenced, open workspace, as introduced in Deliverable 2.6, Section 5. This idea went along with the development of a safety-related 3D camera, which has been going on next to the THOMAS project. Since the necessary efforts for the actual development of a safety-related 3D camera are out-of-scope of a research project like THOMAS, the activities inside THOMAS focused on the development of algorithms to extend its functionality to use cases like in THOMAS.

A modified SICK Visionary-S[1] served as hardware for the development of these algorithms. It is not suitable for safety-related applications requiring a high performance level, but uses a comparable optics unit that allows the usage of the measurement data for the developed algorithms described in Section 4.5.4.

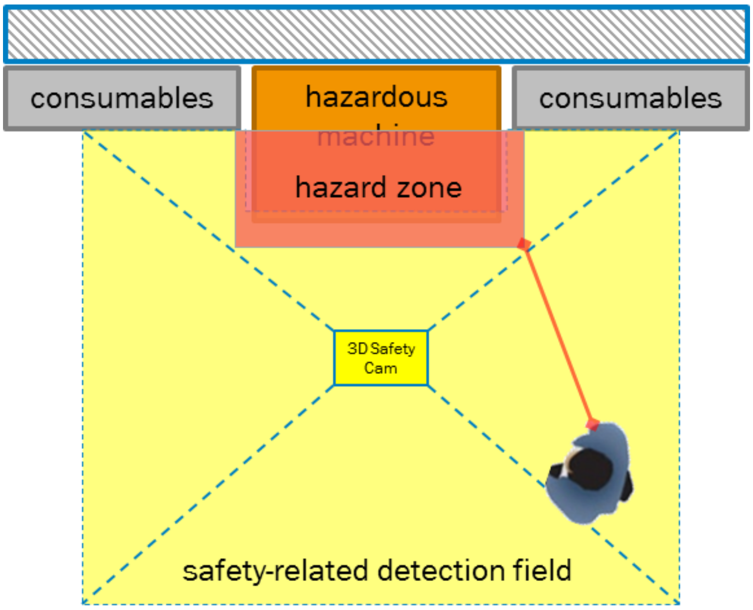


Figure 8: Schematic of the envisioned open workspace at the PSA compression machine

Unfortunately, there were delays in the development of the 3D safety camera hardware preventing a replacement of the hardware. As part of the THOMAS automotive use case, a SICK Visionary-S has thus been installed to monitor the workspace around the compression machine. Figure 9 shows the installation of the 3D camera above the compression machine.

Figure 9: Installation of the structured light 3D camera as part of the automotive use case

[1] Link to Visonary-S product site

Table 2 lists the characteristics of the SICK Visionary-S mounted above the compression machine working area. Figure 10 shows the images provided by the sensor. The monochrome image on the left gives an impression of the IR dot pattern used for the stereo vision.

Table 2: Characteristics of the installed SICK Visionary-S

Image sources	Depth image, gray scale image
Image resolution	640 px x 512 px
Opening angle	60° x 50°
Mounting height	~3.75 m
Field of view (at 3.75 m)	4.5 m x 3.6 m
Pixel size (at 3.75 m)	7 mm x 7 mm
Frame rate	30 fps
Pixel depth (monochrome)	8 bit
Depth resolution	1 mm
Precision (at 3.75 m)	~20 mm

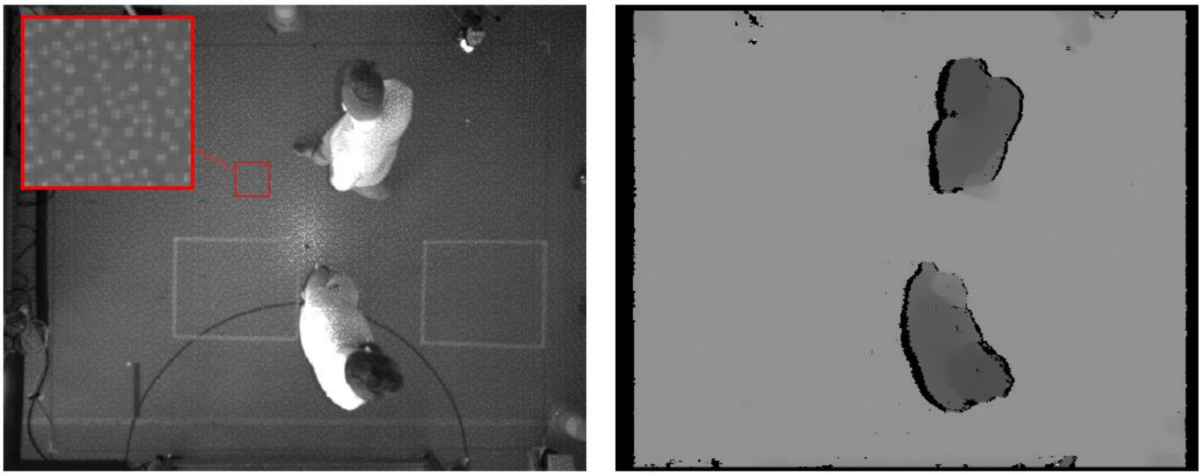


Figure 10: Images provided by the Visionary-S (left: grayscale, right: depth image)

3.4. THOMAS Mobile Product Platform's (MPP) working area

The last working area of the automotive use case called Mobile Product Platforms' (MPP) working area. In this working area, cabling and screwing tasks for compressed damper's connection with a disk take place.

Figure 11: THOMAS Automotive use case MPP working area

THOMAS Mobile Product Platform (MPP) consists of an Upper Structure used for damper's placement and an Automated Guided Vehicle (AGV) for executing navigation tasks in the automotive use case shopfloor (Figure 12). On the top of the Upper Structure there are two fixtures for the left and the right brake of a vehicle car (Figure 13).

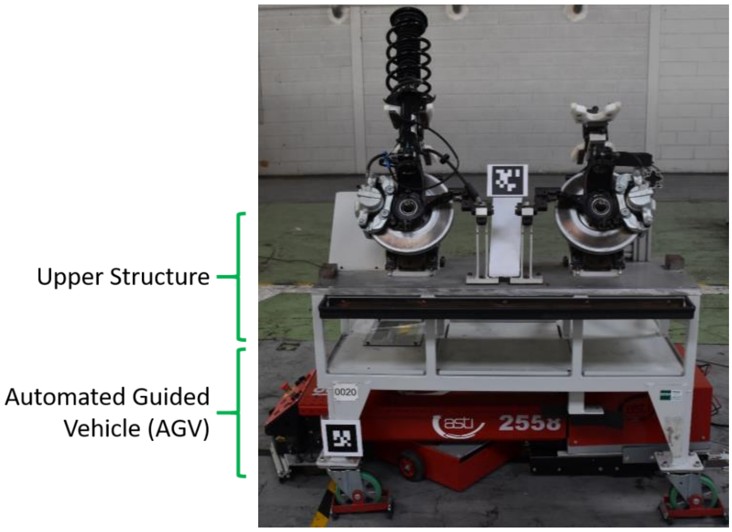


Figure 12: THOMAS MPP's components

Figure 13: THOMAS MPP's fixture model

In order to connect the compressed damper with its corresponding disk, a screwing task takes place in the MPP working area. This task is assigned to THOMAS MRP. Taking in consideration the mobility of both MPP and MRP resources, THOMAS solution introduces a screwing while moving operation. This operation takes place while the MRP is co-navigating with the MPP. A custom device installed on the Upper Structure of the MPP for placing the screwdriver on the MPP has been designed by LMS as presented in Figure 14.

Figure 14: THOMAS MPP's screwdriver fixture

3.4.1.1. MPP controller interface

The THOMAS MPP control is based on a Raspberry Pi3 single board computer connected with MPP's controller. Raspbian OS is installed inside this computer (Figure 15). A dedicated control interface has been deployed of the communication of the MPP with THOMAS OPS central execution system.

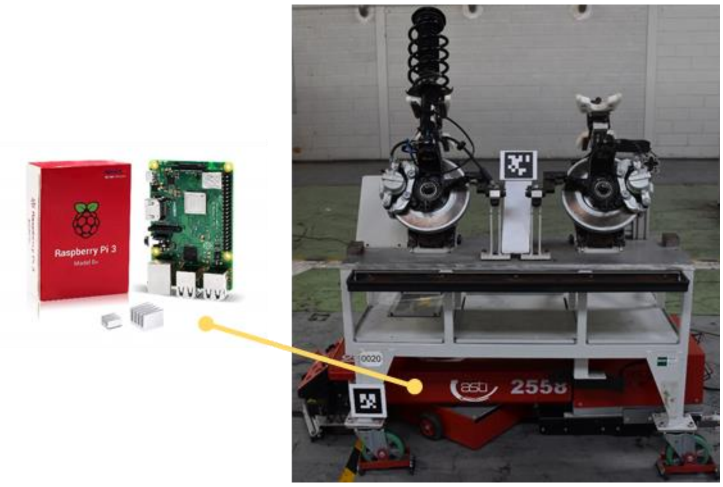


Figure 15: Raspberry Pi3 computer for MPP's controlling

4. THOMAS AUTOMOTIVE OPS

4.1. General Overview

A set of software modules were developed in THOMAS project based on the four objectives of the project as presented in the introduction section of this document. In this way, THOMAS software developed modules focused on the following technologies:

- Safe human-robot and robot-robot collaborative shopfloor,
- Hybrid Human Robot Interaction mechanisms
- Process and environment perception for robot's behaviour adaptation,
- Human robot collaborative task planning and execution control.

Additionally, THOMAS MRP and the different hardware and sensors components used in the automotive use case are presented in the following sub-sections.

4.2. THOMAS Mobile Robot Platform's (MRP)

Several updates on the initial version of the MRP as delivered by Robotnik took place on the electrical and manufacturing design of the MRP in order to fit THOMAS automotive use case's needs. In this document automotive use case's MRP will be called MRP_n2.

Figure 16: THOMAS Automotive use case MRP

4.2.1. THOMAS MRP_n2 arm tools

As already documented, damper assembly process consists of screwing and manipulation tasks. In order to create re-configurable shopfloors in THOMAS project, both human and robot resources should be able to execute most of the required tasks. In this way, THOMAS MRP may be equipped with manipulation (grippers) or screwing tools (screwdriver).

4.2.1.1. Grippers

THOMAS MRP may be equipped with two grippers in order to cope with objects' manipulation required inside the working areas of the automotive use case layout. In this case, a handling configuration is used per each robot arm of the MRP.

- **Left arm handling configuration**

The left arm handling configuration consist of a SMC MHS2 63D [5] pneumatic gripper, which is used for the manipulation of the nut and the alignment rod in the compression machine working area. A custom pair of fingers suitable for this gripper have been designed and produced by LMS accommodating the manipulation of both parts (Figure 17). The rest of the components included in this robot configuration will be presented in the following sections of this document.

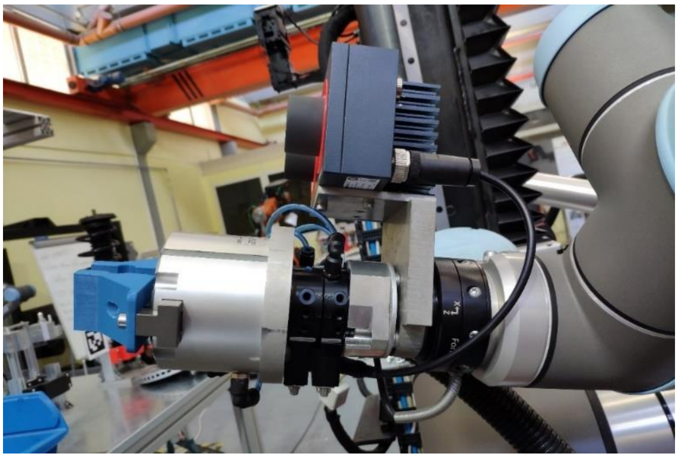


Figure 17: Left arm handling configuration

- **Right arm handling configuration**
  This configuration consists of a SMC MHL2 25D [6] pneumatic gripper used for the manipulation of the damper. A custom pair of fingers suitable for this gripper and the geometry of the damper have been designed and produced by LMS (Figure 18). The other components included in this robot configuration will be presented in the following sections of this deliverable.

Figure 18: Right arm handling configuration

4.2.1.2. Screwdriver

The third robot configuration focuses on the execution of the required screwing tasks. The main component of this configuration is an ESTIC electrical screwing machine which is attached on the robot arm and is used for the assembly of the damper to the disk. This screwdriver has been selected considering the remote-control possibility that it offers, allowing the autonomous tool change for the MRP robot arms from the handling configuration to the screwing configuration.

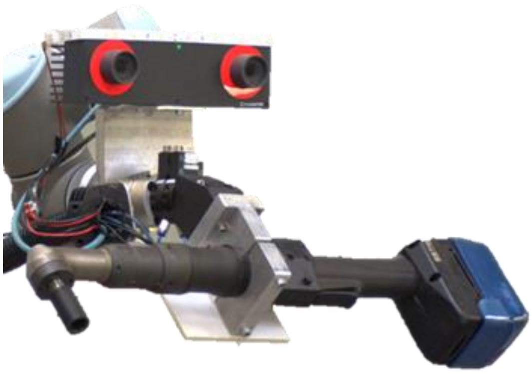


Figure 19: Right arm screwing configuration

4.2.1.3. Toolchange station

A tool station has been designed and installed on the back side of the MRP for the automated execution of tool change. This tool station consists of custom aluminum parts for screwdriver's and grippers' storage. In order to achieve the required accuracy for a successful tool change, two pair pins are installed on this tool station for each grippers' installation. These pins are inserted in the holes of the grippers' flanges during the tool changing process and hold the grippers. The second base has two parts that hold the screwdriver at its lower and upper side (Figure 20).

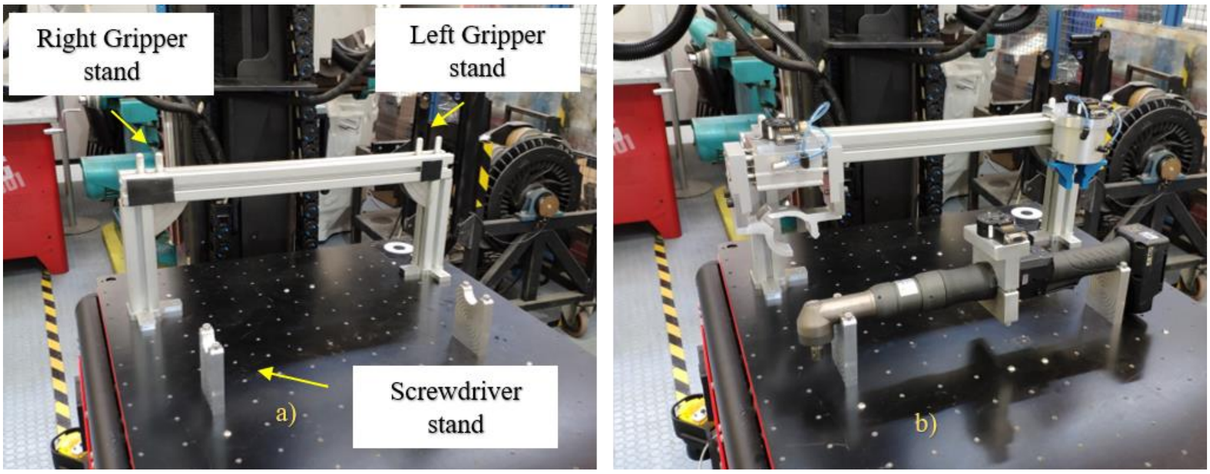


Figure 20: THOMAS Automotive use case toolstation a) with tools and b) without tools

4.2.2. THOMAS MRP_n2 sensor tools

THOMAS MRP_n2 is equipped with different type of sensors either for the execution of the required tasks for damper's assembly and for ensuring the safe human-robot collaboration in the automotive use case workspace. In the following subsections, these sensors, their usage during the assembly process will be introduced and further documented in section 4.5.1.

4.2.2.1. Force sensors

A force sensor is mounted on each arm of the MRP used to assist any of the robot's manipulations as well as for safety reasons. These sensors provide information about the forces and torques applied to the tools as well as useful information for programming the arms. MRP's left arm is equipped with one ROBOTIQ Force Sensor FT 300 [8] (Figure 21) and the right arm is equipped with one OnRobot HEX 6-axis force/torque sensor [14] (Figure 22).

Figure 21: The ROBOTIQ Force Sensor

Figure 22: OnRobot Force/Torque Sensor

4.2.2.2. Sensors for object’s detection

THOMAS MRP is able to perceive its environment in order to execute all the required tasks. THOMAS MRP is equipped with one stereo camera installed on each of its arm to detect the placement/grasping position of the different parts that need to be manipulated. In more details, one rc_visard 65 camera [1] is installed on the right arm of the MRP and one rc_visard 160 camera [1] on the left arm accordingly (Figure 23). Both cameras used for the detection process of all objects needed to be manipulated by the MRP.

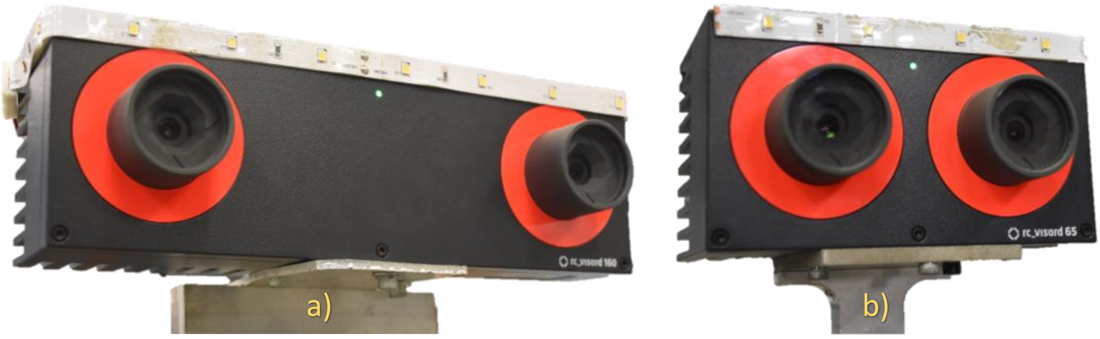


Figure 23: ROBOCEPTION a) rc_visard_65 and b) rc_visard_160 stereo cameras

4.2.2.3. Sensors for safe human-robot co-existence

One objective of THOMAS is the creation of a safe shopfloor for facilitating human-robot collaboration. To this direction, the use of different type of sensors was investigated by THOMAS consortium especially for the detection of operators inside robots’ working space. In this way, several safety sensors are installed on MRP_n2 for the creation of a safe human-robot collaborative environment.

4.2.2.3.1. Sensors for human detection

A Microsoft Realsense camera [9] is placed on the robot torso for the detection of human operators by capturing depth data. Additionally, two SICK microScan 3 laser scanner sensors [12] are installed on the MRP as visualized in Figure 24 b). Using these sensors and synthesizing the 2D and 3D data, THOMAS MRP is capable to detect humans and estimate their intentions.

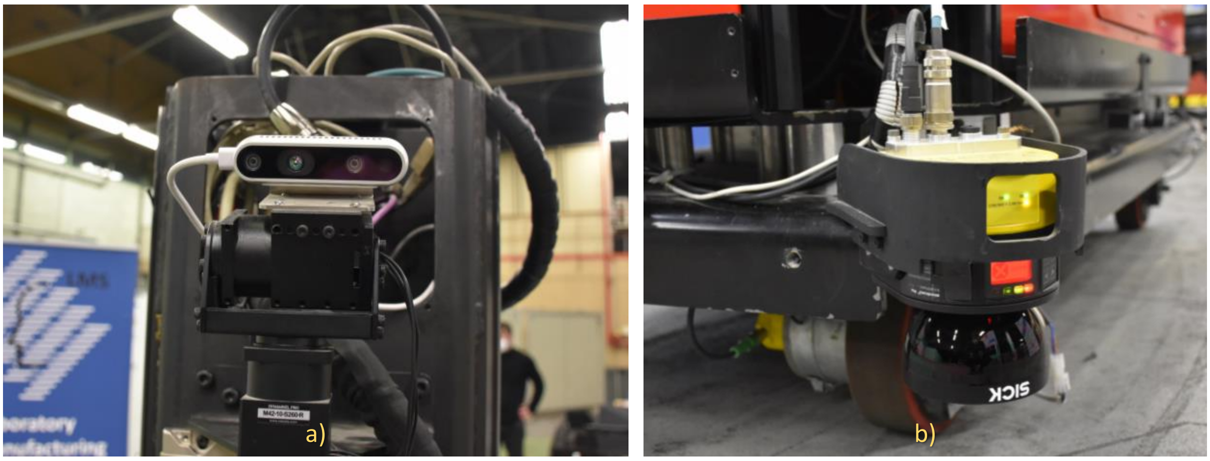


Figure 24: a) Microsoft Realsense and b) SICK microScan 3 sensors

4.2.2.3.2. SICK End-Of-Arm-Safeguarding (EOAS)

Collaborative robots aim to keep forces and pressures that occur during contact with a human inside limits defined by safety standards, e.g., ISO/TS 15066:2016. However, when assessing the entire system including tools, this is often not possible, resulting in the need for further risk reduction measures. SICK aims to target some of these applications by introducing an end-of-arm safeguard (EOAS) that detects the presence of, e.g., a human hand and prevents dangerous movements of the robot tool. Deliverable’s 2.6, Section 4, provided an introduction of the EOAS concept.

The EOAS has been integrated on the MRP as part of the THOMAS Automotive use case. The EOAS sensor ring is mounted on the left robot arm. An external safety PLC evaluates the received sensor signals. In case of an object infringing the protected area or communication failures, the safety PLC triggers an emergency stop of the robot.

Figure 25 gives an impression of the integrated EOAS on the MRP’s left robot arm. Depending on the distance to the perceived obstacles, the EOAS adapts the robot’s behaviour. To provide feedback to the user, LED elements display the status of the EOAS.

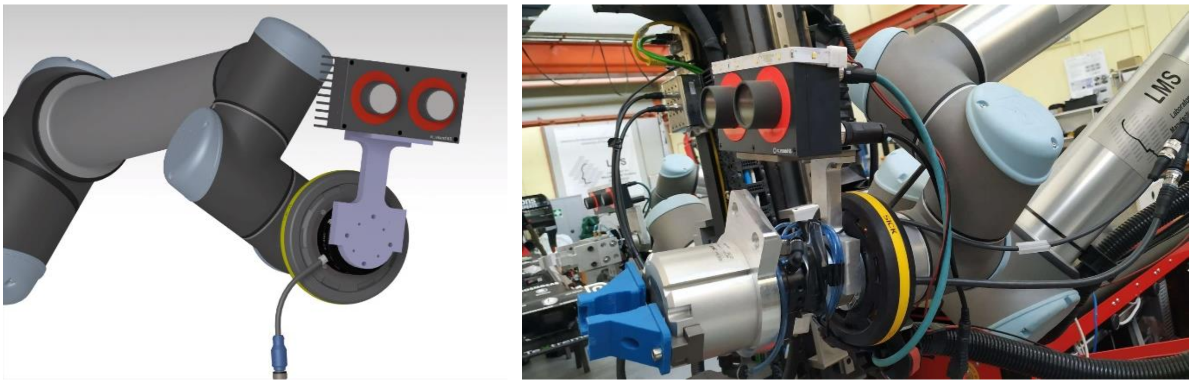


Figure 25: Integrated EOAS on the MRP's left robot arm

4.2.2.3.3. MRP Safety concept

To mitigate risks resulting from the operation of the MRP, an assessment of these risks took place to serve as basis for a safety concept. Deliverable 2.6, Section 3, described this safety concept and safety design in detail. The safety design included safety controllers, safe position sensors for monitoring the position of moving parts (robot and torso), safety encoders for monitoring the movement and orientation of the wheels and safety laser scanners for monitoring the area around the machine.

Figure 26 gives an impression of the deployed safety measures and provides an overview of so-called triggers (Txxx, green) and reactions (Rxxx, blue). For details, please refer to Deliverable 2.6, Section 3.

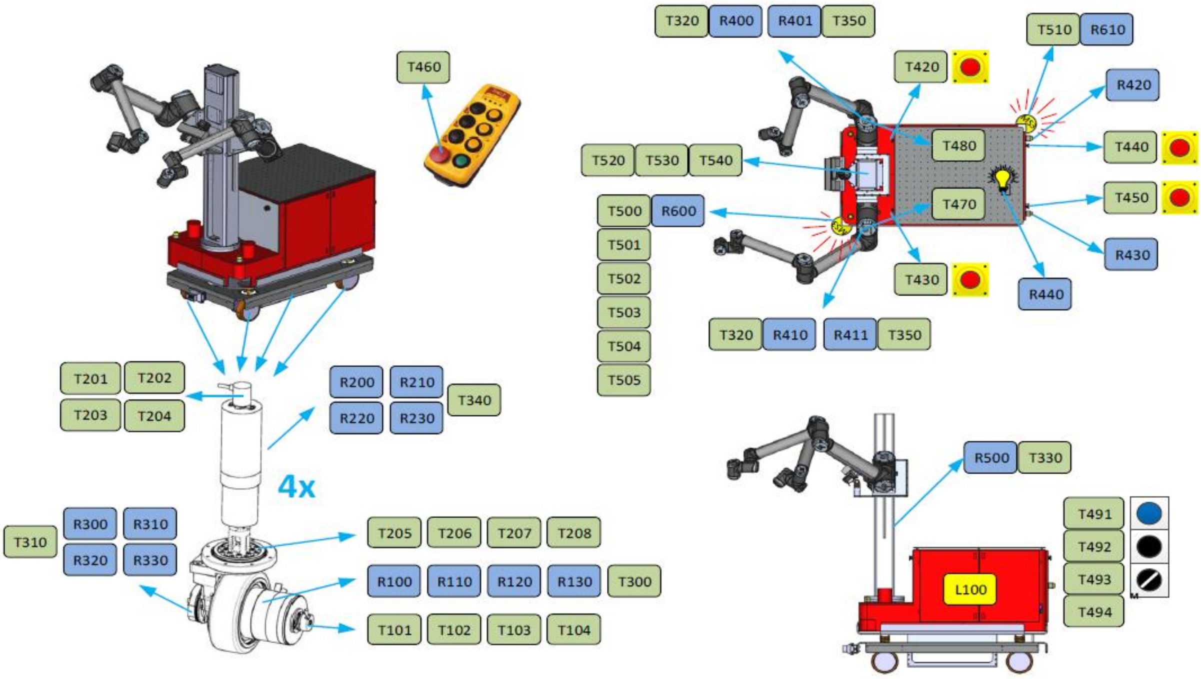
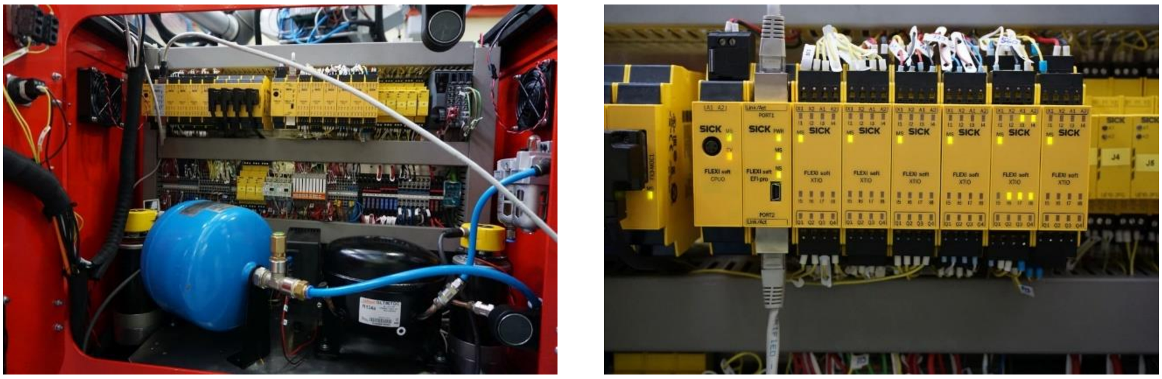


Figure 26: MRP protective measures

Figure 27 shows a subset of the installed safety components after the successful integration of the safety design into the MRP for the THOMAS automotive use case, as planned in Deliverable 2.6, Section 3.



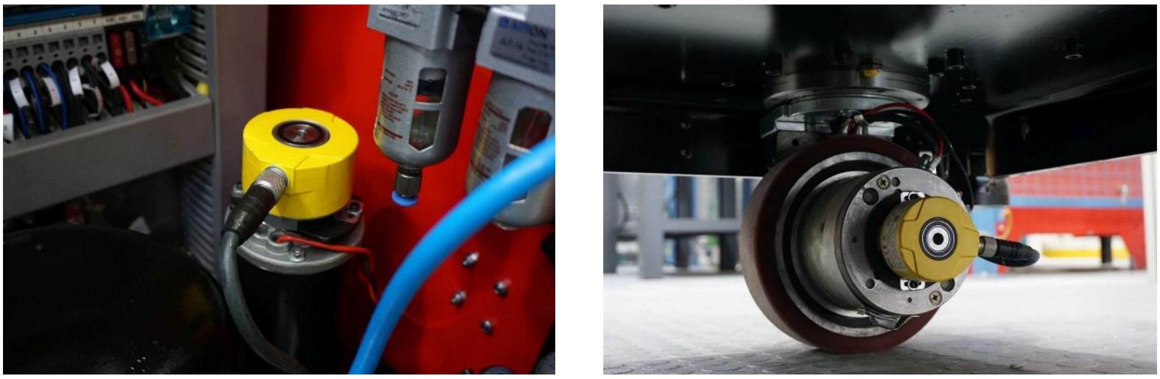


Figure 27: Impressions of a subset of installed MRP safety components

4.3. Network of services and work balancing

The communication framework developed inside THOMAS automotive use case for the execution of the required robot and human tasks is presented in this section of the document. All the required information exported from sensors of automotive use case can be accessed by both the runtime system as well as the THOMAS digital twin model, that can also visualize them.

For the more efficient and easier programming of robot tasks, inside THOMAS project each task may be broken down in several actions. These actions are assigned to the human and robot resources for execution. Actions' execution based on the use of custom services provided by THOMAS station controller platform. Different kind of services are provided by the station controller for the execution of robot motions and navigation actions but also for MPP's and other mechanisms control (compression process, gripper's functionality, screwdriver start/stop actions etc.).

The creation of THOMAS task plans through THOMAS task planner, their validation and execution inside the automotive use case is visualized in Figure 28. Different Task Plans for the assembly of the damper are created from the intelligent planner and evaluated inside the simulated layout of the automotive use case. The Station Controller is responsible to translate the tasks from human language to robot and simulated human actions. During the simulated execution of each task plan, the station controller calculates and save data regarding human and robot actions' execution (task's duration, navigation path length etc.) in order to be used for the evaluation of the different task plans by the intelligent task planner. After the task planning process, the best task plan can be sent for execution in the physical layout. The station controller is responsible to dispatch the actions to the different resources and monitor the execution of the task plan. In case of an exception, the station controller can pause the execution, request corrective actions and then resume the assembly process or directly attempt to retry the execution of an action. More information regarding the station controller, the intelligent task planner and the digital twin model used for the execution of the tasks are presented in the following sub sections.

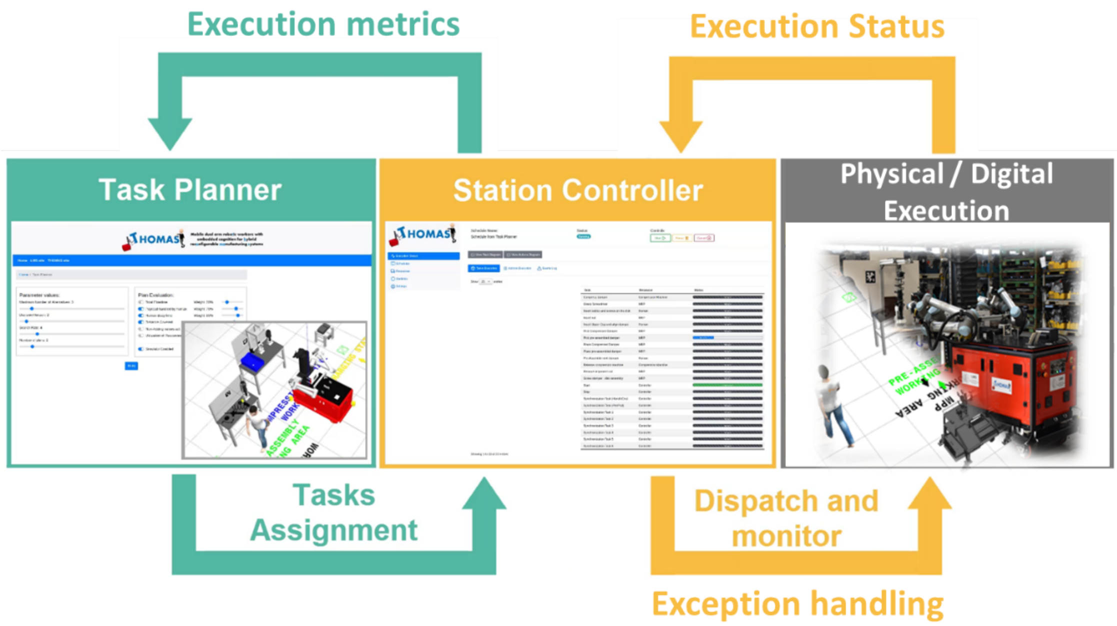


Figure 28: THOMAS Automotive use case task plans creation and execution

4.3.1. Digital World Model

THOMAS Digital World Model provides the real time scene reconstruction through the combination of the multiple sensors' data integrated in the system [3]. All the information exported from the sensors of the automotive use case shopfloor are stored in THOMAS unified repository to be visualized geometrically using the RViZ software. The data stored in the Digital World Model are consumed by the different perception modules for: a) collision free 2D based navigation, b) 3D based accurate localization for virtual docking, c) 3D based object detection for process perception and d) human presence and intention estimation. The moving obstacles and human operators and detected and dynamically added in the Digital World Model map in order to ensure the collision free path planning for the MRP. The protective fields that come directly from the safety PLC as well as the human operators detected are integrated in the Digital World Model as visualized in Figure 29.

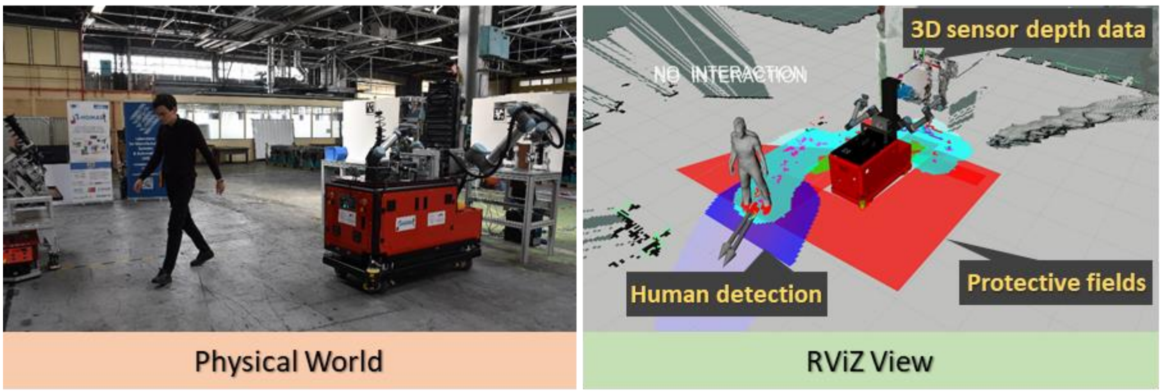


Figure 29: THOMAS Digital World Model

4.3.2. Station Controller

The execution of the damper's assembly process based on the communication and synchronization framework developed inside THOMAS project. THOMAS Station Controller is responsible to receive and translate the required assembly tasks from human language to robot actions. This "Station Controller" framework is responsible to monitor the required human and robot tasks' execution inside the automotive use case shopfloor but also for pausing the execution and requesting the reset the of MRP system in case of an emergency. Different kind of emergencies can be handled. such as a safety zones' violation by a human operator, the mobile platforms' low battery events or failed execution of a human or robot task.

The Station Controller also features a set of configurable, yet automated responses to potential network failure errors that allow the seamless and uninterrupted execution of a product plan even in the case of minor disturbances.

Through the Station Controller, the user may start a product plan such as the damper's assembly process. Using the developed GUI of Station Controller, the user can see an overview of the execution status and pause or resume the execution of a task if needed (Figure 30). Using the Station Controller GUI, the operator may create smaller sub-schedules based on the initial schedule of the assembly process and send it to the physical or simulated resources for execution.

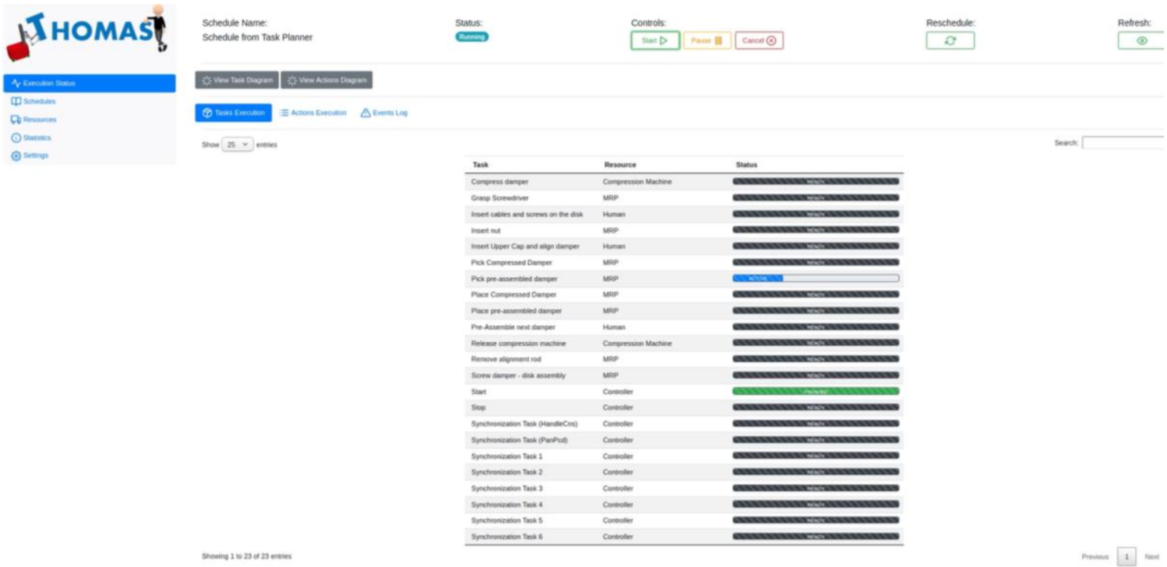


Figure 30: THOMAS Station Controller GUI

THOMAS station controller uses the ROS Action protocol to control multiple resources such as the MRP, MPP and screwing machine as well as communicate with the Human Operator Augmented Reality Glasses. The available handlers and their use are presented in the following table.

Table 3: Handlers controlled by THOMAS automotive use case station controller platform

Handler's Name	Handler's functionality
DetectionHandler	Receive messages for the rc_visard camera to be for the detection process and object's ID to be detected
FollowHandler	Receive messages about the start and stop command of mobile platforms' co-navigation
LocalizationHandler	Receive messages about the ID of apriltag to be detected for the refinement of navigation action result
MoveCartesianHandler	Receive messages about MRP's arm to execute the motion action and the desired location of arm's tool in reference to MRP's origin frame
MoveJointsHandler	Receive messages about MRP's arm to execute the motion action and the desired joint values of the arm
ScrewingHandler	Receive messages about screwdriver's ON/OFF action

SetIOHandler	Receive messages about the IO's ID and its desired location (ON/OFF)
NavigationHandler	Receive messages about the desired mobile robot's position and direction goal by using navigation
ExecuteHumanTaskHandler	Receives messages of normal tasks that need to be executed by the Human Operator
EmergencyHumanResponseHandler	Receives messages of emergency tasks that need to be executed by the Human Operator
CompressionHandler	Receives messages that control the compression machine
ManageNodeHandler	Receives messages that can activate and deactivate other handlers
MoveBaseHandler	Receives messages that can directly control the position of the MRP, without using navigation
MPPActionHandler	Receives messages that can directly control the position of the MRP, without using navigation
SetWheelOrientationHandler	Receives messages that can directly control the MRP wheels orientation
SimulateHandler	Receives messages that can request the simulation of particular schedule
MRPBatteryLevelHandler	Monitors the MRP battery level and communicates low battery events

In case of an emergency, the Station Controller is capable to reset the whole system by sending extra actions to the different resources (Human operators and MRP) in order to resume the assembly process. In Figure 31, Station Controller's architecture for handling emergency situations is visualized.

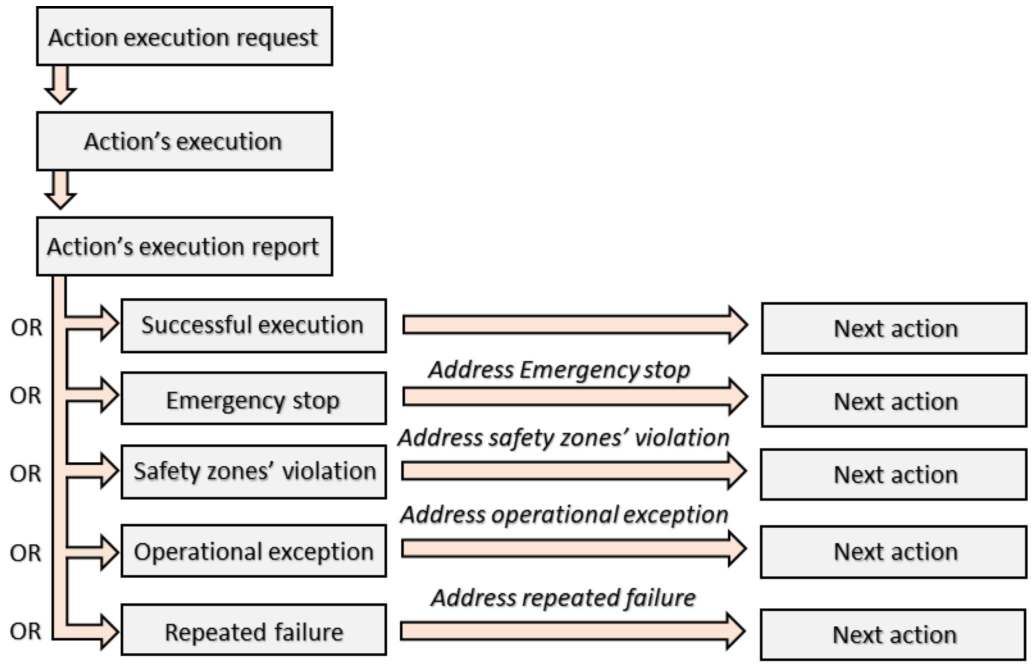


Figure 31: Action's execution architecture

4.3.3. Task planner

The sequence of tasks to be executed by the MRP and human operators inside the automotive use case are generated by THOMAS Task Planner as presented in deliverable D5.5. The initial task planning process is based on the static objects' location inside the shopfloor and damper's assembly process. Task planning process may be triggered by external requests from the human operators or unexpected resources breakdown. The Task planner is capable to receive this kind of information and accordingly re-assign the tasks to the available MRPs and human operators against user defined criteria. The final version of THOMAS task planner GUI which is available to the process designer in order to identify the most efficient task plan and send it for execution in the physical layout is presented in Figure 32.

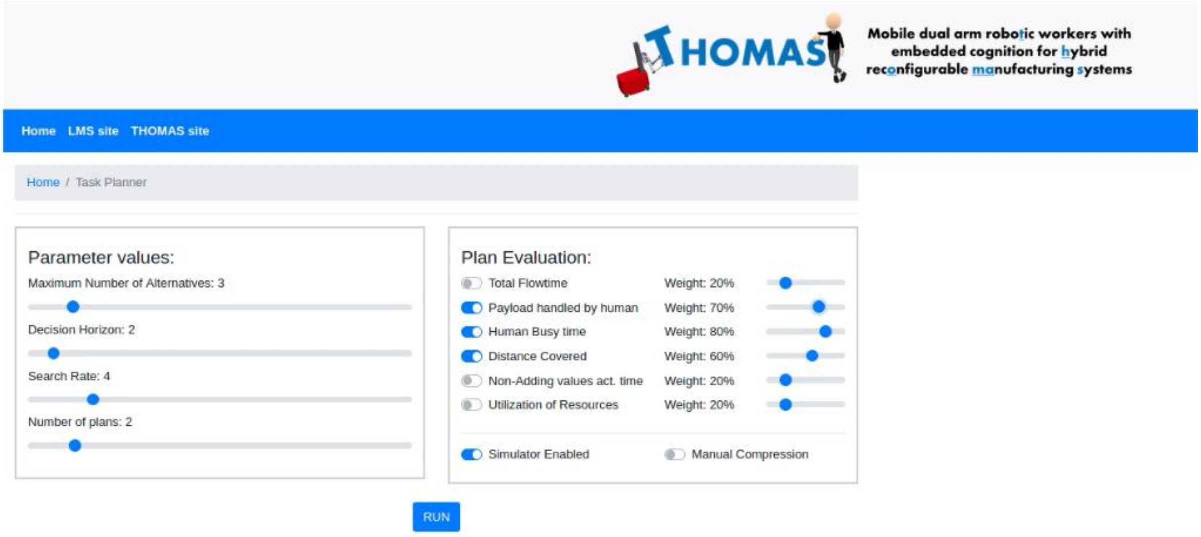


Figure 32: THOMAS Task Planner GUI

The different task plans generated by the task planner are evaluated based on a pre-defined set of metrics. Also, the generated task plans are simulated in the simulated layout of the automotive use case using the GAZEBO software. The results from the simulated execution of each task plan (tasks' execution duration and navigation/walking paths' length) are stored in the task planner's databased to be used as extra metrics for the evaluation of the generated task plans.

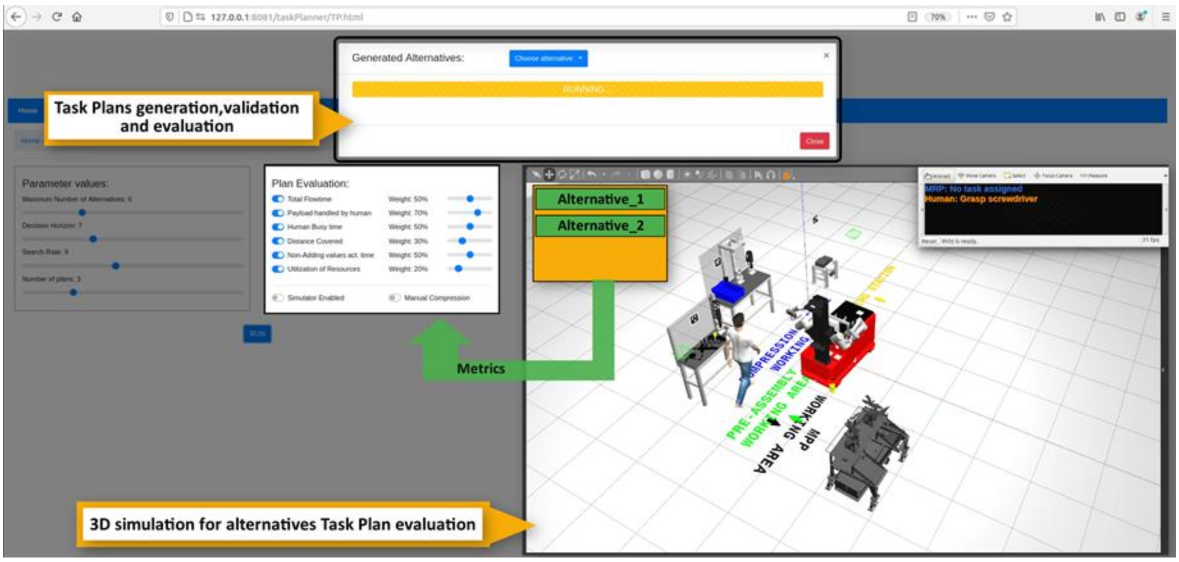
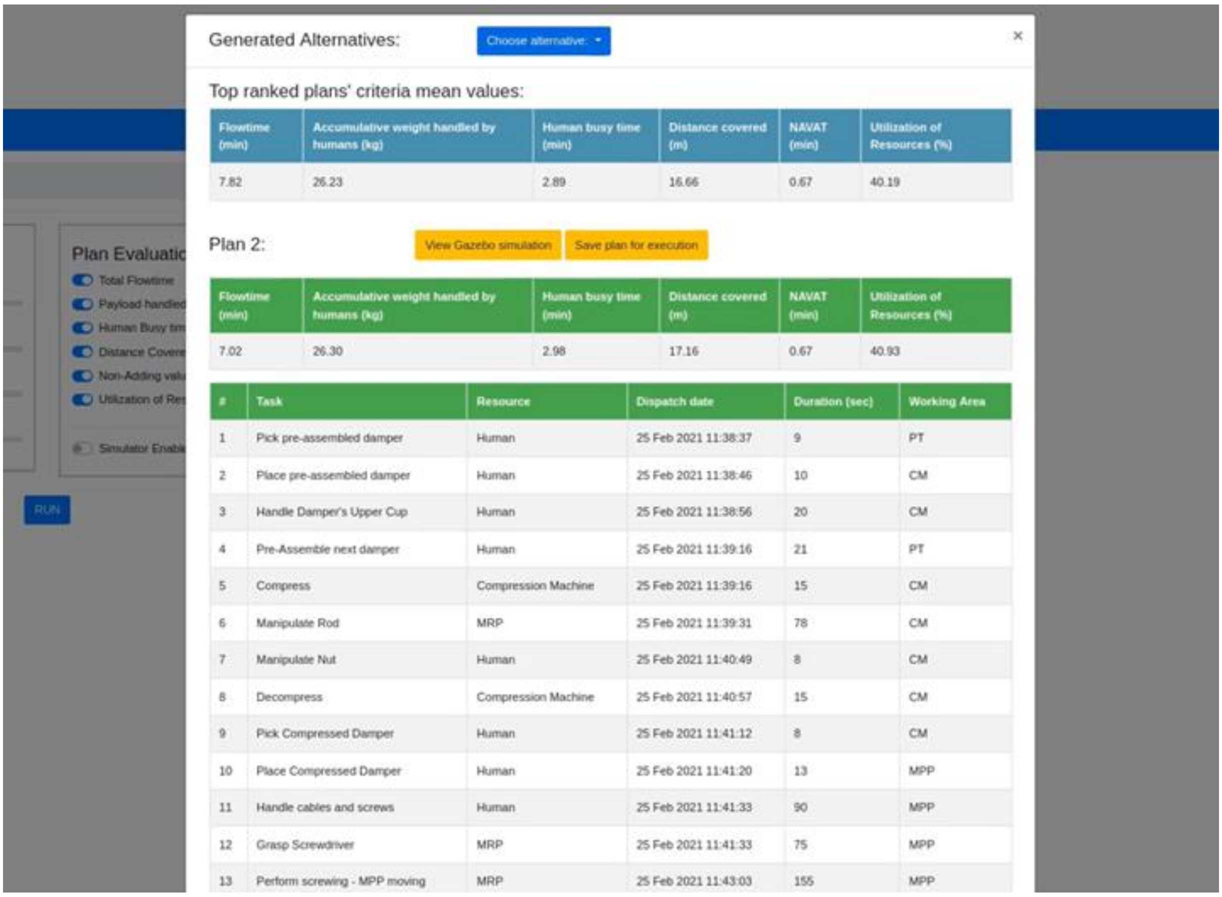


Figure 33: Task plans' validation process and evaluation metrics storage

After the evaluation of the different task plans by the task planner, a pre-defined number of task plans are available to the process designed in order to select the best task plan based on his personal experience. The task plans are visible to the process designer through the GUI of the task planner software (Figure 34). After the selection of the best task plan, the process designer can either send the selected task plan for simulated execution to check again the assembly process sequence or save the selected task plan for future execution in the physical layout.



Flowtime (min)	Accumulative weight handled by humans (kg)	Human busy time (min)	Distance covered (m)	NAVAT (min)	Utilization of Resources (%)
7.82	26.23	2.89	16.66	0.67	40.19

Flowtime (min)	Accumulative weight handled by humans (kg)	Human busy time (min)	Distance covered (m)	NAVAT (min)	Utilization of Resources (%)
7.02	26.30	2.98	17.16	0.67	40.93

#	Task	Resource	Dispatch date	Duration (sec)	Working Area
1	Pick pre-assembled damper	Human	25 Feb 2021 11:38:37	9	PT
2	Place pre-assembled damper	Human	25 Feb 2021 11:38:46	10	CM
3	Handle Damper's Upper Cup	Human	25 Feb 2021 11:38:56	20	CM
4	Pre-Assemble next damper	Human	25 Feb 2021 11:39:16	21	PT
5	Compress	Compression Machine	25 Feb 2021 11:39:16	15	CM
6	Manipulate Rod	MRP	25 Feb 2021 11:39:31	78	CM
7	Manipulate Nut	Human	25 Feb 2021 11:40:49	8	CM
8	Decompress	Compression Machine	25 Feb 2021 11:40:57	15	CM
9	Pick Compressed Damper	Human	25 Feb 2021 11:41:12	8	CM
10	Place Compressed Damper	Human	25 Feb 2021 11:41:20	13	MPP
11	Handle cables and screws	Human	25 Feb 2021 11:41:33	90	MPP
12	Grasp Screwdriver	MRP	25 Feb 2021 11:41:33	75	MPP
13	Perform screwing - MPP moving	MRP	25 Feb 2021 11:43:03	155	MPP

Figure 34: Best evaluated task plans' visualization thought the task planner GUI

4.4. Simplified robot programming and skills

THOMAS Skill Engine and CAD Programming software has been integrated in the automotive use case alongside with THOMAS Station Controller. Through the skill engine and the CAD programming software, the process designer may easily update the location of the different components inside the layout, simulate the different assembly tasks' execution and finally send robot tasks for execution in the physical shopfloor. Automotive use case's skills can be re-configurate quickly, avoiding almost all interactions with the real hardware for changing the programmed key points. The usage of the navigation skill for MRP's navigation to MPP working area is presented in Figure 35.

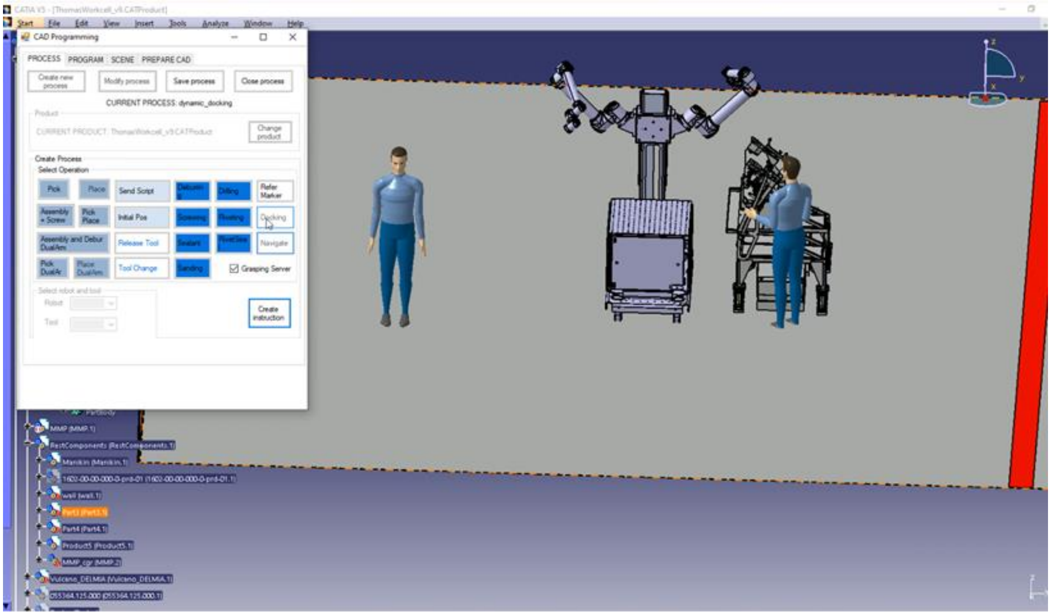


Figure 35: Skill engine's integration in the Automotive use case

4.5. Human Robot Interaction and Safety

4.5.1. Safety

The safety concept of THOMAS Automotive OPS is a 3-level safety system. This safety concept consists of the following components:

- MRP on-board safety
- MRP on-robot-arm safety
- OPS on-site safety

Figure 36: THOMAS OPS Safety concept

4.5.2. MRP on-board safety

This section focuses on the components installed on the MRP of the automotive use case to guarantee the safety inside the layout during platform's navigation.

4.5.2.1. Safe Environment Perception

Automotive use case's MRP is equipped as foreseen by the safety design compiled in Deliverable 2.6. Section 3 provides a description of the various hardware components integrated for this use case. A complex evaluation logic, designed on a SICK FlexiSoft based system, allows for a fenceless human-robot co-existence, consisting of the following main features:

- Adaptive protective fields
- Workstation detection

Following descriptions only serve as summary, since Deliverable 2.6, Section 3, already includes an in-depth explanation of these features.

Adaptive protective fields

The movement of the MRP base, robot arms and torso impose risks to humans that are in close proximity of the MRP. To mitigate these risks, it is necessary to avoid direct contact between the MRP and humans. The simplest approach would choose large safety fields in all directions to assure that no human is able to approach the MRP during operation, i.e., an emergency stop triggered by the safety system would prevent this. In consequence, navigation and operation of the MRP would always require large amounts of free space around it. The developed safety system prevents this by monitoring the current state of the wheels, torso and robot motion. Figure 37 gives an impression of the detection of the direction of movement and an exemplary safety field configuration, as a simplified example for illustration. Since the MRP is an omnidirectional platform with four independent wheels, eight encoders are necessary to derive the state of the MRP movement – four for the orientation of the wheels, four for the velocity. Deliverable 2.6, Section 3.4, provides the details, also on the calculation of the safety field dimensions.

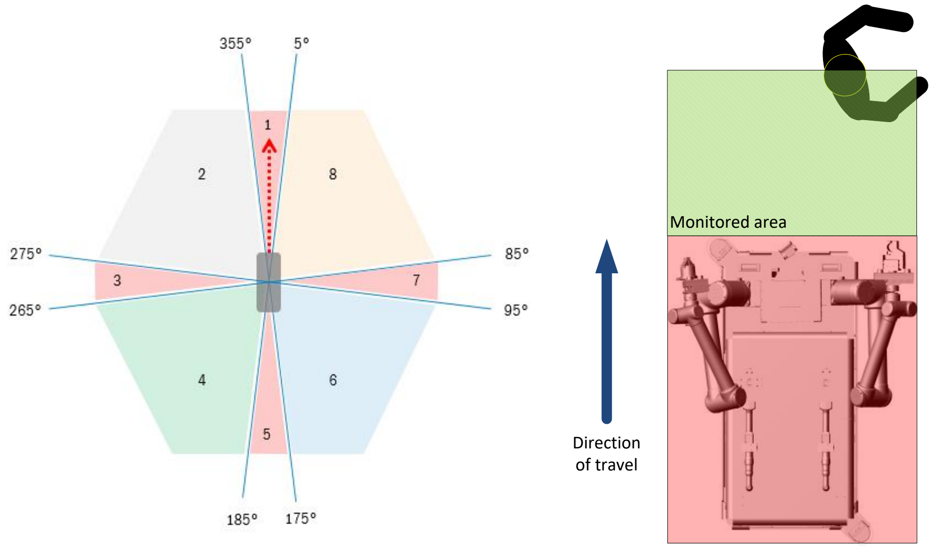


Figure 37: Example of the adaptive protective fields for forward motion

The human eye cannot capture the safety fields monitored by the laser scanners. Among others, one result of the THOMAS automotive use case is a communication interface that serves the current safety field configuration. In turn, a client forwards them to the station controller and a virtual reality display using the Microsoft HoloLens 2. Figure 49 gives an impression of the active safety field configuration during the MRP's operation at a workstation.

Workstation detection

The safety concept for the operation of the MRP enables adaptive safety fields, as described above. During an approach towards a workstation or even the MPP, a reduction of the safety fields' sizes is mandatory, to prevent the approach triggering an emergency stop by the safety system. However, a reduction in safety fields needs an information with high confidence, that the MRP reached the expected position.

The SICK microScan3 is able to monitor up to eight safety fields in parallel. By combining the inputs from both laser scanners in the SICK FlexiSoft system and monitoring several small “detection fields” in parallel, the safety system of the MRP is able to discover the presence of a specific workstation. Figure 38 shows these detection fields in a schematic way. In Figure 49, the virtual reality view even displays two of them in red colour around the table legs.

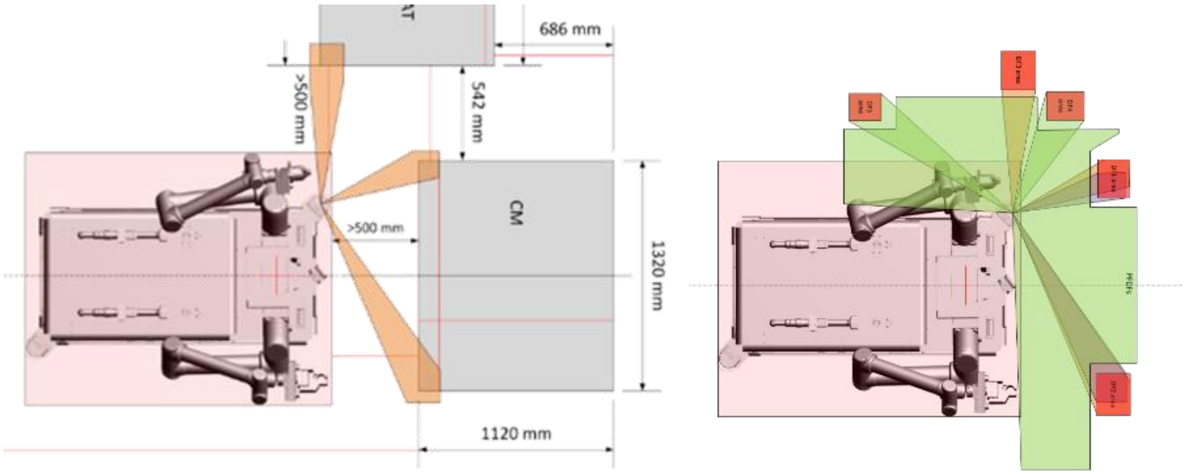


Figure 38: Detection fields for the discovery of the workstations

The safety zones are also visualized in RViZ. Based on the configuration of the MRP’s arms, the current configuration of the safety zones around the MRP is visualized in Figure 39 during the execution of each robot task in the automotive use case. In Figure 39 a), the safety zones during navigation and localization tasks are presented. The detection fields, used for the discovery of the workstation in the automotive use case layout, are visualized in Figure 39 b). Finally, when MRP’s arms exceed the safe position limits, the safety zones are increased in order to detect static and moving objects in a wider area around the MRP’s platform.

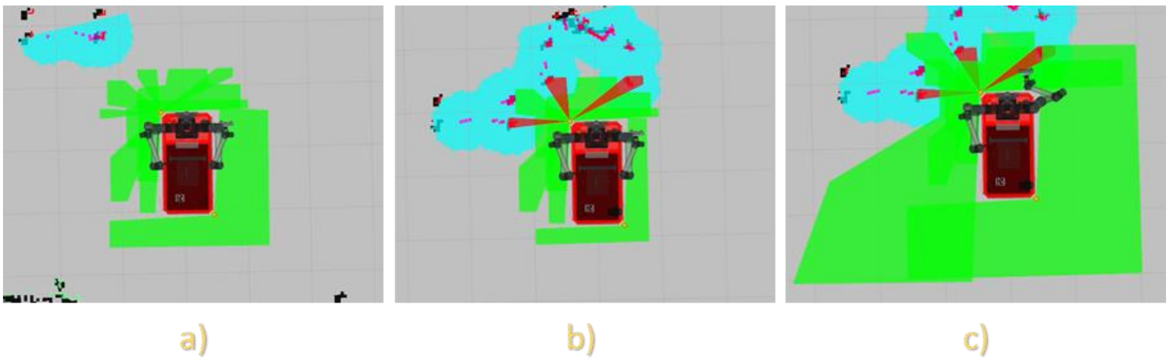


Figure 39: Safety zones dimensions a) while navigation and localization actions’ execution, b) for the discovery of the automotive use case’s workstations and c) while MRP’s arms exceed their safety limits

4.5.2.2. 2D Human detection

2D human detection works on the measurement data of the microScan3 safety laser scanners which are mounted on the MRP (Figure 24). Inside the Deliverable 2.3, an in-depth description of the developed algorithms is included, providing insights on:

- Ego motion compensation (i.e. the motion of the mobile platform hosting the sensors)
- Measurement noise
- Foreground / Background detection

- Initialization of new targets
- Modelling the target movement
- Data association between detections and known targets
- Object classification

The human detection runs on a DFI EC700-BT[2] fanless embedded system. A ROS node requests the detected objects from the EC700 and then forwards them to the station controller and other users. The same interface enables sharing the latest safety field configuration through ROS. Figure 40 gives an impression of the visualization of the detected objects inside the RViZ software.

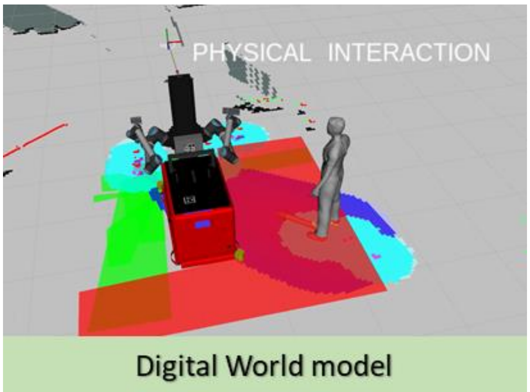


Figure 40: Protective fields' violation by the operator

4.5.3. MRP on-robot-arm safety

The safety components which are installed on the robot manipulators of THOMAS MRP are presented in this section. Section 4.2.2.3.2 provided a description of the EOAS hardware and overall concept. In terms of software, it consists of two major components:

- The program on the *external safety PLC*, that is responsible for the safety-related communication with the sensors and the robot and for the control of the robot depending on the sensor and robot inputs.
- The plugin, a.k.a. *URCap*, for the UR industrial robot that allows the configuration of the application by the user.

External safety PLC

The execution of the safety algorithms is performed on a safety PLC. The outputs correspond to the functionality described in Section 4.2.2.3.2 regarding the control of the robot and the user feedback using status LEDs. The function block constitutes the backend of the safety system and performs all safety-related execution.

URCap

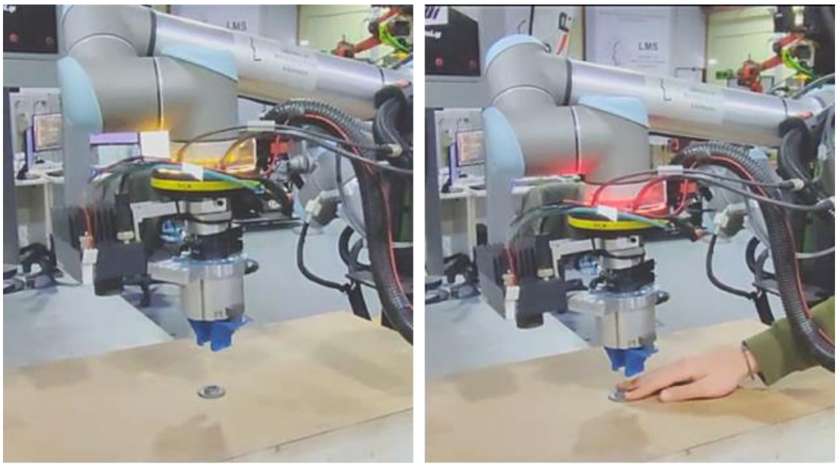
UR as a robot manufacturer coined the name 'URCap' as a plugin for UR robots to extend their functionality. UR build up a community around these URCaps to spread knowledge and provide an easy access for developers. Configuration of the application's characteristics happens through the URCap. The installation process ends with a verification step that ensures a valid configuration of the system. After a successful installation and configuration, the setup of the robot program follows.

The safety concept for the MRP in the automotive use case includes a safety laser scanner based human protection system (see Section 4.2.2.3.2) that monitors the environment depending on the current

[2] https://www.dfi.com/de/Product/Index/169

situation, i.e. speed of the MRP and its direction of movement. Due to the size of the MRP and potential robot movements at the height of a human head, the safety fields are still rather large. The EOAS introduces the possibility of reducing these safety fields further, both for the PSA use case, but also regarding the general THOMAS approach.

For the THOMAS automotive use case, the pickup of the nut used to fix the spring of the damper element, is safeguarded by the EOAS. Figure 41 shows the MRP picking up the nut with EOAS in operation.



a) b)

Figure 41: Nut manipulation with EOAS in operation while a) Human wrist not detected, b) Human wrist detected

4.5.4. OPS on-site safety

As part of the THOMAS automotive use case, interaction with the compression machine (CM) is required for both the MRP and the human. While it is essential to bring the machine to an emergency stop when a human is approaching during the operation of the CM, it is desirable not stopping it in case another machine like the MRP approaches. To avoid machine downtime, this results in a need for detection algorithms that are able to distinguish between the two. Section 3.3.3 gave an impression of the respective sensor setup to monitor the workspace around the compression machine.

Inside THOMAS, two detection algorithms have been investigated:

- Marker-based MRP detection
- Artificial neural network (ANN)-based marker-less human detection

Marker-based MRP detection

This algorithm follows a marker-based approach to distinguish the MRP from humans, detecting a pre-learned arrangement of markers. It has been described extensively in Deliverable 6.2, Section 5.2.

Following the promising results evaluated using a mockup of the MRP, the algorithm was adapted using the real MRP of the THOMAS automotive use case. Figure 42 gives an impression of the detected MRP and a human in front of the compression machine.

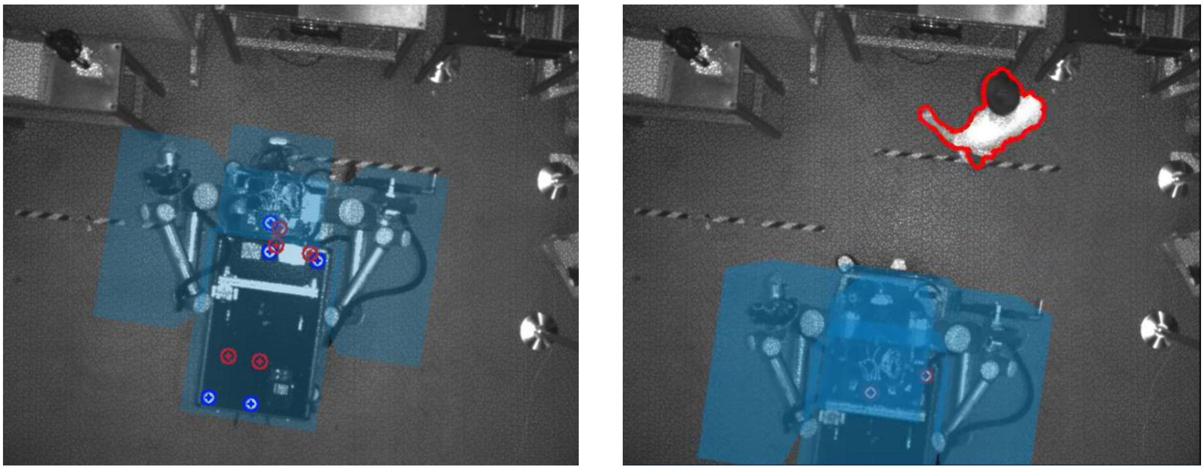


Figure 42: Detection of the MRP in front of the compression machine. red circles: detected markers; blue circles: projection of detected markers onto reference layer (used for matching)

The algorithm has been evaluated using the THOMAS automotive use case compression machine mockup table. Table 4 displays the confusion matrix of the experiment, as well as the true positive and false negative rate.

Table 4: Confusion Matrix of the MRP marker detection evaluation

		Detected: Human	Detected: Non-Human
Actual	Human	192	0
Actual	Non-Human	53	1280
	True Positive Rate		1.00
	False Positive Rate		0.04

The evaluation shows a true positive rate of 1.0, i.e., a very reliable detection of the human in every recorded frame. The detection of the MRP is successful for the majority of the frames. Still, the detection performance is less robust compared to initial tests using the MRP mock-up described in Deliverable 6.2, Section 5.2. This is due to the necessary derivation from the initial marker arrangement and false marker detections that occur on the white circular joints of the robotic arms. While the detection of the human is very reliable, further efforts would be necessary to avoid false detections of the MRP as human, thus ensuring a high availability of the system.

Artificial neural network (ANN)-based marker-less human detection

A second approach focused on the detection of humans inside the camera image using artificial intelligence, respectively convolutional neural networks (CNN). In contrast to the MRP detection, the human detection is non-invasive, as it does not require mounting markers on the objects of interest. This makes the approach suitable for a wider range of applications as no areas for marker placement are required.

To train the neural network, many training frames of humans and non-human objects are necessary. As no data set matching the properties of the used sensor is publicly available, large efforts were put into the creation and annotation of a new dedicated data set. The capturing was done using the replica of the production environment at SICK including the MRP mock-up described in Deliverable 6.2, Section 5.2.

Table 5: Number of candidates in the dataset. Manually annotated candidates in braces.

	Training	Evaluation	Total
Human	10950	2677	13627 (8161)
Non-Human	12505	1328	13833 (5358)

To increase the portability to different environments, this approach exclusively relies on depth data, similar to the approaches from [17] and [18]. The approach is based on the idea that illumination and colors do not have any influence on the depth data. While not assessing the gray scale images means discarding some of the available information, the depth data is uniform across different environments, objects and humans.
The processing pipeline of the human detection system consists of the following main features:

- Data preprocessing
- Candidate detection
- Classification using a trained convolutional neural network (CNN)

After building and training the system at the SICK test center using the mock-up of the MRP, the human detection was integrated at LMS for an evaluation of the detection performance. The human detection was applied to the same image series, which had been recorded to evaluate the marker-based MRP detection. While the detection performance on data captured at the SICK test center was remarkably good, the detection performance at LMS decreased significantly. The overall accuracy decreased to 21.3% (versus 98.4% at SICK test center). The true positive rate of 1.0 was still good, but the false positive rate of 0.85 was not acceptable. I.e., the MRP was classified as human most of the times. The different appearance of the real MRP compared to the mock-up used inside the training data set lead to a broad misclassification of the original MRP by the CNN. This showed the need for a large training data set including the real MRP. However, creating these data sets takes a lot of effort.

To keep efforts manageable inside THOMAS, the SICK training data set was enriched by 3910 images containing the original MRP captured at LMS for the sole purpose of enriching the training data. The CNN was then retrained from scratch. The resulting CNN showed a better detection performance. Figure 43 shows example frames and Table 6 lists the confusion matrix and the resulting true positive and false negative rates for the experiment. The overall accuracy improved to 73.3%. The true positive rate stayed high at 0.99 while the false positive rate improved to 0.29.

Conclusively, technical feasibility of the approach was shown for data recorded at the SICK test center using a mock-up of the MRP. However, the results using the real MRP did not quite reach up to the great results from the SICK test center, due to a lack of sufficient training data. This shows the need for more efforts to be put into the creation of a holistic training data set recorded in the final application.

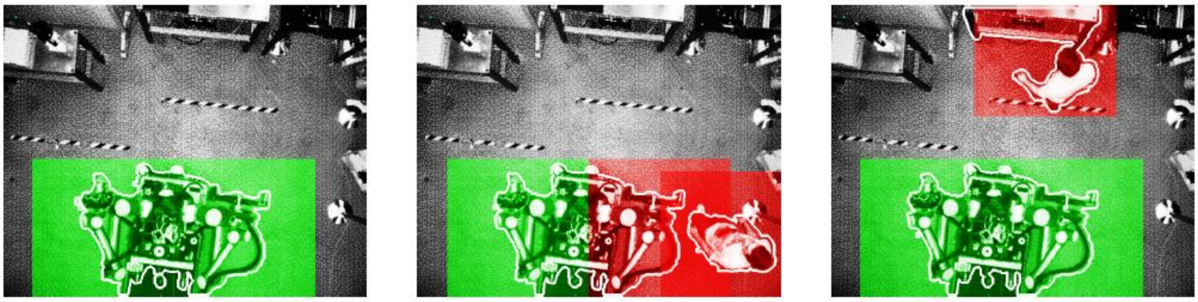


Figure 43: Evaluation of the CNN-based human detection at LMS. Red boxes mark a detected human, green boxes a non-human object. The white contour highlights the object's shape.

Table 6: Confusion Matrix of the CNN-based human detection
(a) trained on SICK data set, evaluated on LMS data set
(b) trained on LMS data set enriched by SICK data set, evaluated on LMS data set

		Predicted			
		(a) Human	(a) Non-Human	(b) Human	(b) Non-Human
Actual	Human	160	0	159	1
	Non-Human	1579	268	534	1313
	True Positive Rate		1		0.99
	False Positive Rate		0.85		0.29
		(a)		(b)	

4.5.5. Human Robot Interaction mechanisms

Hybrid Human Robot Interaction

THOMAS Hybrid HRI combines information from the different 2D and 3D sensors to monitor human state and based on the human location, direction of movement and velocity it classifies human intention in three states as follows:

- No interaction human state
- Remote interaction human state
- Physical interaction human state

No interaction human state

While THOMAS MRP executes navigation tasks, 2D human detection algorithm is running for the detection of moving human operators inside the working area of the robot. In case that a human operator is detected with a No interaction state and its walking path collides with the navigation path, the MRP enters in *Predictive Collision Avoidance mode*. In this control mode, the MRP identified the moving human in proximity and re-calculates the navigation path in order to avoid any collision.

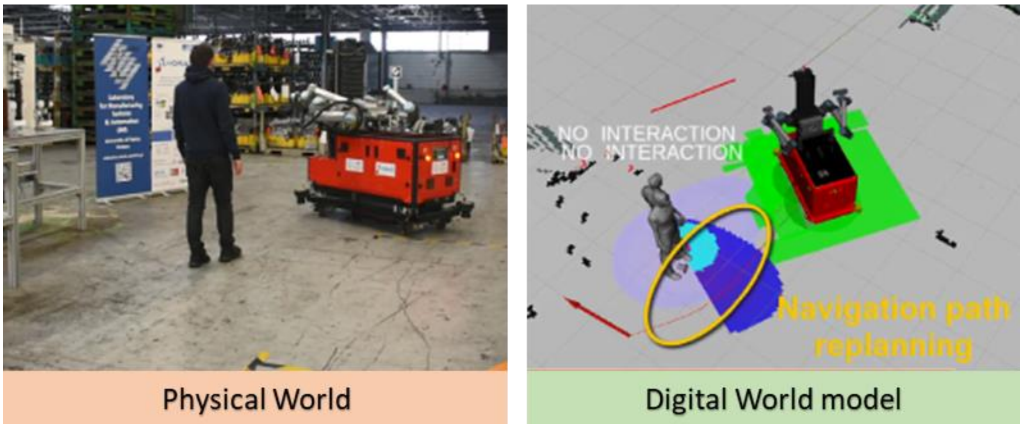


Figure 44: Predictive Collision Avoidance

Remote interaction human state

In case that the state of human has been detected as remote interaction, the MRP automatically switches to *Gestures Recognition* control mode and the human operator is able to move the mobile platform through simple gestures. A machine learning human gesture recognition algorithm has been developed and integrated in THOMAS OPS Realsense camera [9], MRP is able to perceive operator's movement inside the shopfloor and accordingly change the status of its actions (Figure 45). Using specific body poses which are able to be detected by the vision camera, the operator is able to control MRP's body and send navigation new requests.

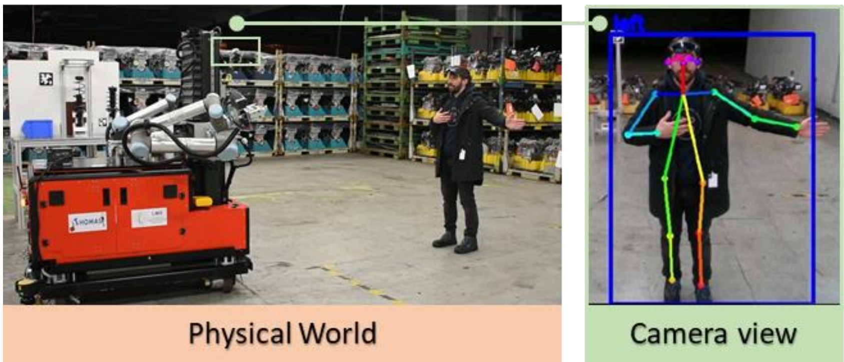


Figure 45: Human gesture recognition

<u>Physical interaction human state</u>

By the time a human operator is detected close enough to the MRP capable to touch the robot arm, the MRP enters the *Manual Guidance* control mode. In this mode, the robot manipulators of THOMAS MRP enter in Manual Guidance mode and the operator is capable to move the manipulators using his hands.

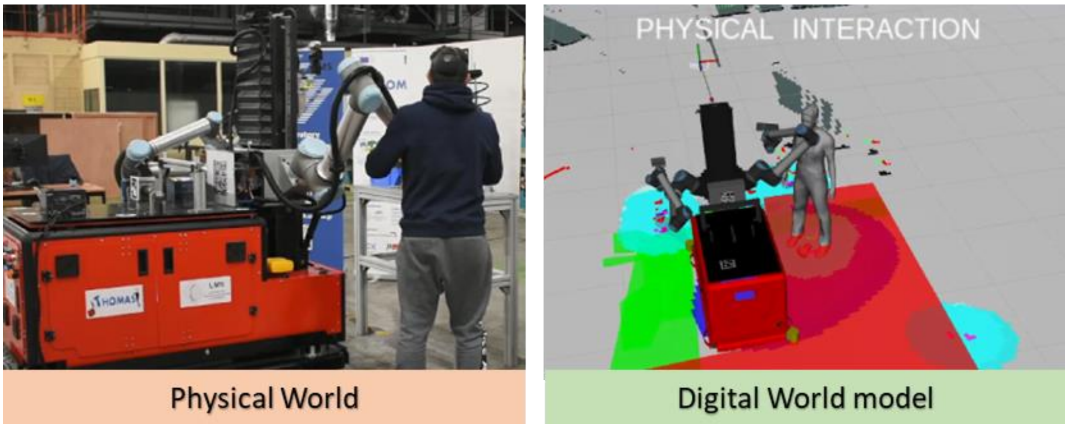


Figure 46: MRP's arms control through manual guidance

Figure 47: Predictive Collision Avoidance

Augmented Reality based Operator Support

To further support human operators in collaborative assembly an Augmented Reality (AR) application has been developed and deployed in Hololens 2 AR glasses. Through the menu panel of the AR application, the operator is capable to initialize the connection with THOMAS system and interact with the MRP (Figure 48).

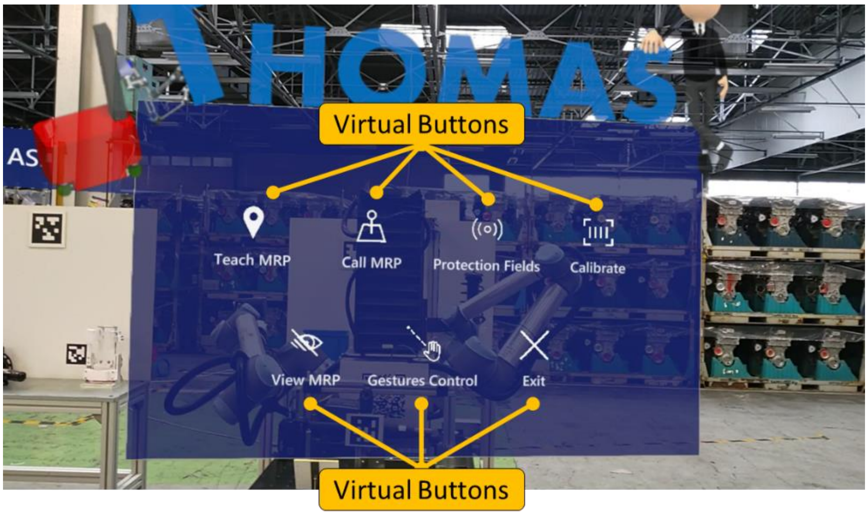


Figure 48: Human actions' execution buttons inside AR glasses

As previously presented, two SICK microScan 3 laser scanners are installed on MRP's base in order for the MRP to perceive static or moving obstacles inside its working area. Using the communication framework documented in D5.5, D5.4 and section 4.3.2, this information is transferred to the AR glasses system. THOMAS AR application enables the visualization of the safety fields around MRP's base inside the operator field of view in order to increase his safety awareness (Figure 49).

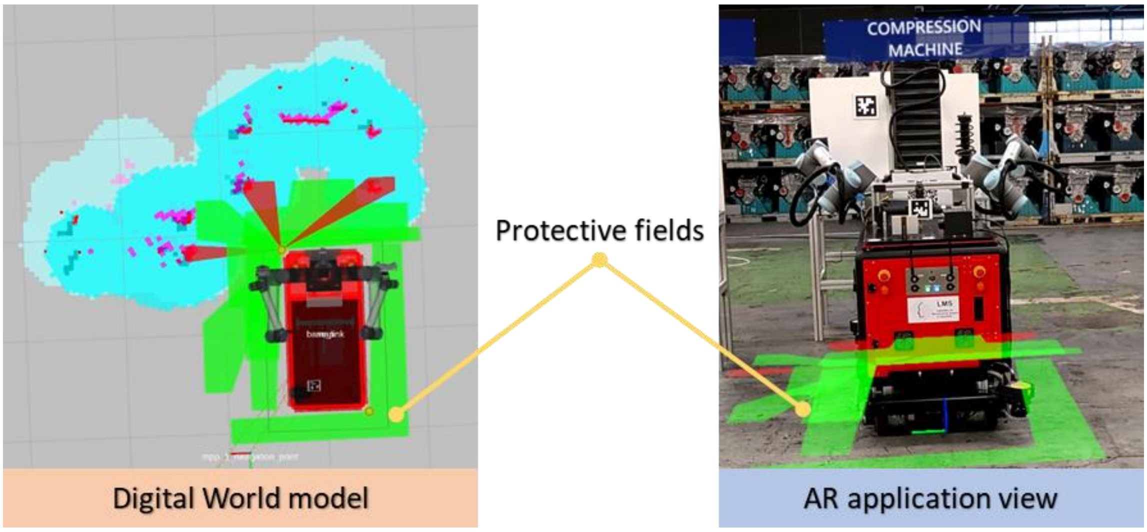


Figure 49: Protective fields' visualization through the AR glasses

As previously mentioned, damper's assembly process includes also human assembly tasks. When the Station Controller sends a human action execution request, a corresponding message is visualized in the virtual world of the AR application informing the operator about his assigned task. Operator informs THOMAS system about the successful execution of his task using a virtual button inside the virtual world of the HoloLens glasses (Figure 50).

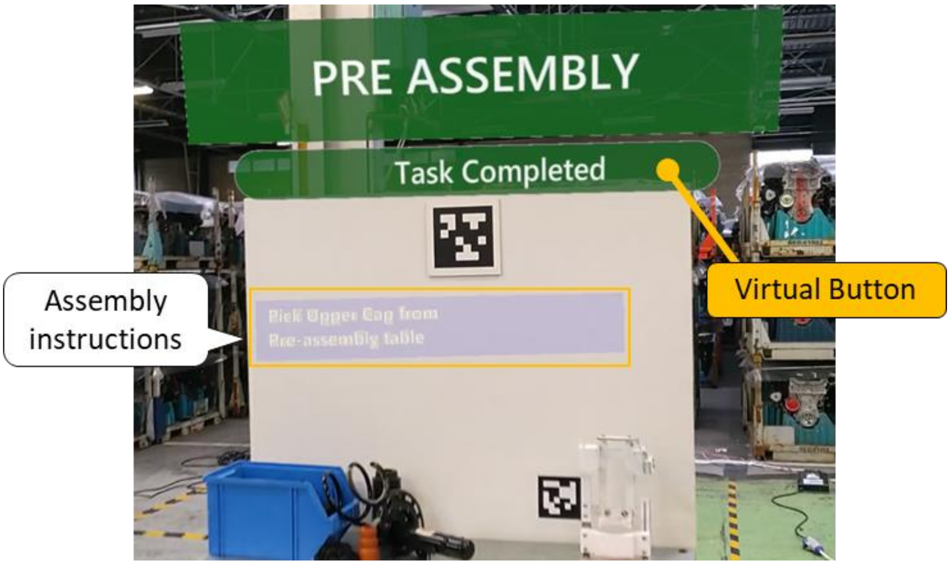


Figure 50: Human assembly tasks' instructions

Also, through the AR glasses, the operator may send navigation goals to the MRP based on pre-defined points in the shopfloor (Figure 51) or teach new navigation goals by moving a hologram of the MRP in the virtual world (Figure 52). This allows the human operators interact with the MRP without having a robot programming background.

Figure 51: Human operator is able to send MRP to needed workstation of the shopfloor

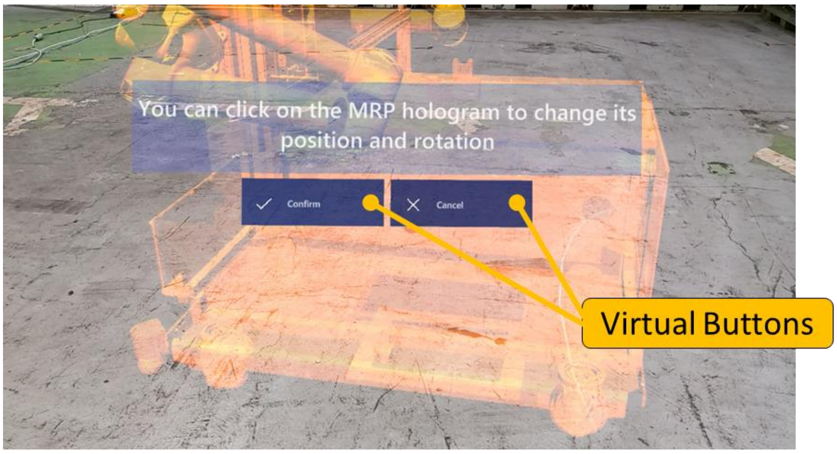


Figure 52: Teach new navigation goals to THOMAS MRP inside AR glasses

As already presented in section 4.3.2, Station Controller is capable to send requests for human and robot actions execution in case of an emergency in order to resume the damper's assembly process. In this case, instructions about how to recover the system from emergency mode are visualized inside the operator's field of view through the AR glasses (Figure 53). After the execution of the task, the operator informs the Station Controller about the successful execution of its task using the virtual button visualized in the virtual world inside the AR glasses.

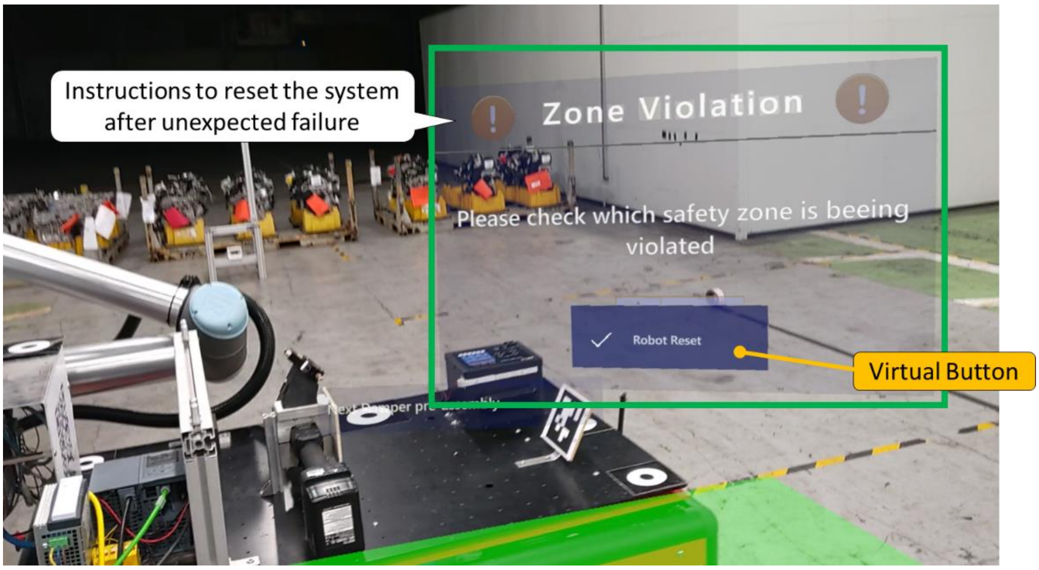


Figure 53: Instructions to reset the system inside AR glasses after unexpected failure of the system

4.6. Environment and Process perception

As already documented, THOMAS MRP is capable to autonomously navigate inside the layout of the automotive use case for the execution of multiple assembly operations.

4.6.1. Environment perception

Autonomous 2D based navigation

The main module that utilizes the shopfloor perception module is the movement of the robotic platform. The first step to this movement from workstation to workstation is the 2D Navigation. The navigation takes place inside a known map of the shopfloor and utilizes the SLAM algorithm. The static obstacles of this map are defined with a pre-execution mapping process that utilizes laser scanners. The mapping creates a costmap that is utilized by the algorithm to calculate the optimal path. The laser scanners are more qualified for navigation than cameras, since they can be used for omnidirectional perception, which would be too complex to do with mounted cameras, using too many sensors.

During the movement of the robot, the algorithm also detects any dynamic obstacles in close proximity, and the navigation then calculates new paths if it is deemed necessary as presented in Figure 54. The speed and accuracy of the navigation is configurable through changing the parameters of SLAM and of the costmap. Even with the best configuration, the minimum error of the algorithm is still too big for the effective and safe manipulation of objects on the workstation. The cause of the error may be due to irregularities on the floor, which lead to errors in odometry, or the fact that the algorithm is simply not accurate enough for the accuracy that is required.

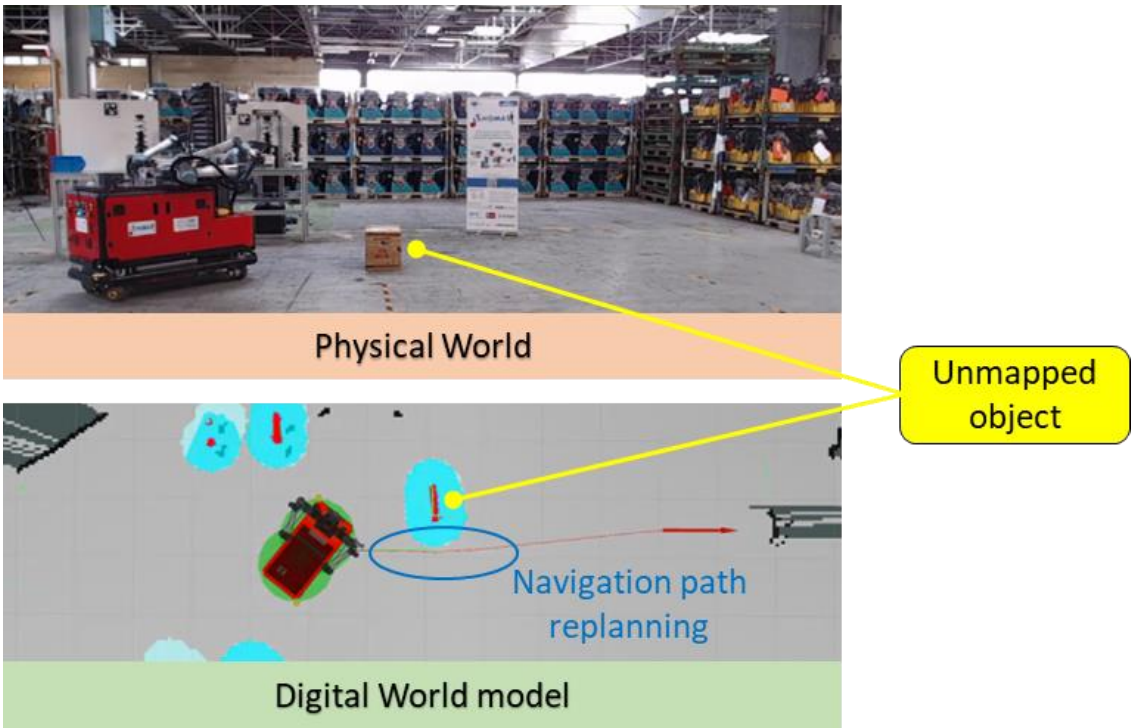


Figure 54: Autonomous 2D based navigation

3D based localization for virtual docking

For an industrial mobile robot, fast and accurate localization is required. The multitude of sensor data used in modern robotics can burden the data network and complex algorithms can enhance the computational complexity needlessly. Using only one type of sensor such as only cameras or only laser scanners for the navigation and localization will inevitably lead to ignoring the advantages of using multiple types of complementary sensors. Through THOMAS OPS a simple yet novel localization method based on robotic vision is proposed, which works in tandem with the navigation algorithm that use data collected from the laser scanners.

As explained in the precious subsection, the output of the navigation usually retains an error from the process. For this reason, a localization method is implemented after each navigation in front of workstations in order to localize and virtual dock the mobile robot accurately to the workstations, with a maximum error of 1cm. This method is based on input received from a stereo camera, in particular a Realsense camera. Specifically, the localization module is based on the detection of fiducial markers. In particular, the tag detector has been tested with two different markers families the AprilTags and the Alvar. The camera detects the corresponding tag for each workstation and then a reference frame is created for this marker.

Using this frame, the transformation between the robot reference frame and the marker, or else the position error is calculated, and the difference is fed to a closed loop PID velocity control, which then assigns the necessary speed to the omnidirectional wheels of the robot. The controller completes the localization when the error is under an acceptable value. The proportional, integral and derivative term values were calculated by trial and error and set to values that complete the process in a matter of seconds but do not cause the robot to succumb to oscillations due to high speeds when the process is finishing, since due to the control, when the closer the robot is to the targeted endpoint, the lesser the speed is.

The accuracy for the algorithm is configurable by modifying the finishing criteria and reconfiguring the PDI values to match. This results in a smooth and fast localization, accurate enough for industrial standards and simple enough to implement for every robotic system that utilizes a camera system. If a marker is not deemed appropriate for the desired layout, other detection methods may be used, such as feature detection and the output can be fed to the same PID control. An instance of the localization process as presented in the real world and the digital world model is shown in Figure 55.

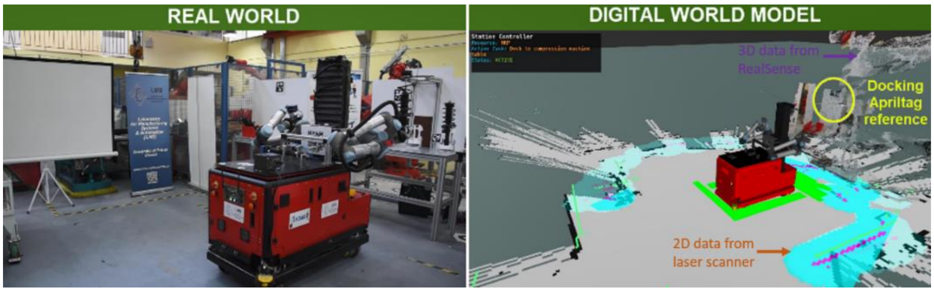


Figure 55: **Virtual docking for accurate localization**

4.6.2. Process perception

The successful execution of part's manipulation in each working area of THOMAS automotive use case layout is based on the usage of a detection algorithm developed and validated inside THOMAS project. This detection algorithm has been presented in detail in the previously submitted deliverable D3.5. During the last period of the project, this detection algorithm integrated in the automotive use case installed in STELLANTIS Mulhouse plant. The detection pipeline for the compressed damper fixture's detection in the compression machine working area is presented in Figure 56. The detection pipeline for each required component's detection inside the automotive use case layout will be presented in detail in section 4.7.

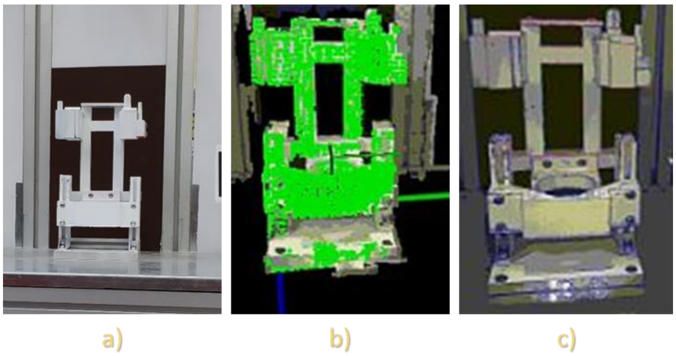


Figure 56: Process perception pipeline: a) physical model to be detected, b) Apriltag detection and c) CAD matching)

4.7. Robot-level scenario execution

The software and hardware components used by the station controller of the automotive use case for damper's assembly process are presented in the following subsections.

4.7.1. Damper's Pre-assembly working area

The robot tasks inside this working area focus on the transportation of the pre-compressed damper in the compression machine working area in order to be compressed. For this reason, the following robot tasks are executed inside the automotive use case's pre-assembly working area by the MRP_n2:

- MRP's navigation and localization to the pre-assembly working area
- Pre-compressed damper's detection
- Pre-compressed damper's manipulation

4.7.1.1. MRP's navigation and localization to Damper's pre-assembly working area

In order to remove the pre-compressed damper from the pre-assembly working aera, the MRP needs to be able to grasp it. For this reason, the MRP needs to navigate on the front of the pre-assembly table. This action based on the Navigation action handler and a quaternion specifying the target goal of the navigation action. Localization actions are executed after each navigation action to compensate the navigation action's error. Localization handler utilizes the Realsense camera placed on MRP's torso for the detection of Apriltag_a in this working area (Figure 57). This handler calculates the distance between the position of the MRP's origin frame in respect to the detected Apriltag_a of the pre-assemble working area.

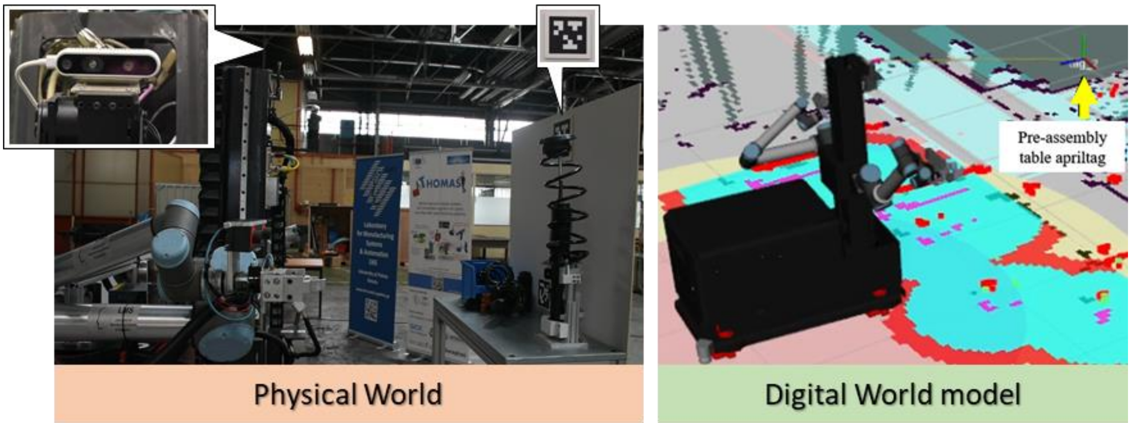


Figure 57: Localization to pre-assembly table using Realsense camera

4.7.1.2. Objects' Detection inside the pre-assembly working area

Damper's grasping action execution by THOMAS MRP_n2 requires a high level of accuracy on damper's location relative to THOMAS MRP base. Through the detection algorithm developed inside WP3 trained with the CAD model of the pre-compressed damper, THOMAS MRP_n2 is capable to successfully pick up the pre-compressed damper. The detection task is carried out by the detection handler. The ROBOCEPTION rc_visard 160 stereo camera is used to provide information regarding pre-compressed damper's and Apriltag_b's location inside this working area. Using the rc_visard 160 and Apriltag_b of the pre-assembly working area, information regarding the exact position of the pre-compressed damper is returned to THOMAS system. The detection process of the pre-compressed damper is presented in Figure 58.

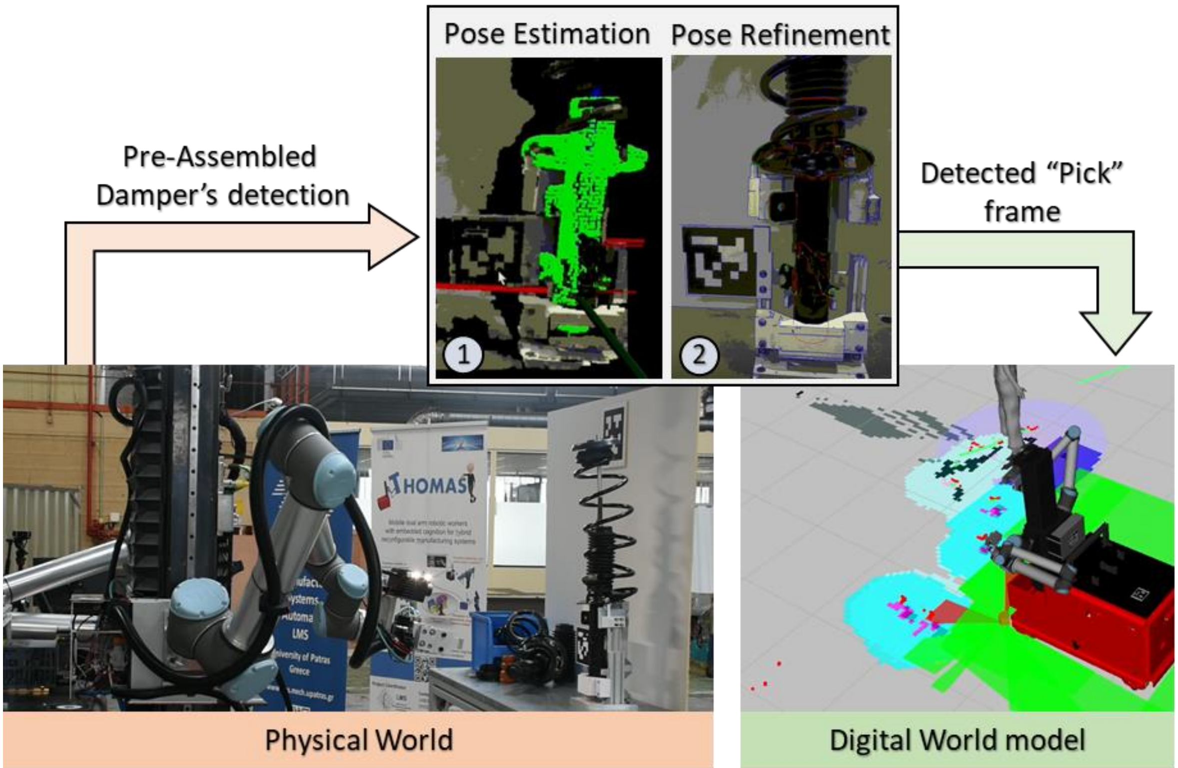


Figure 58: Pre-compressed damper's detection

4.7.1.3. Pre-compressed damper's manipulation

After the detection of the pre-compressed damper, THOMAS MRP removes the pre-compressed damper from the pre-assembly working area's fixture. These actions' execution based on the pick frame created from the detection handler as presented in the previous subsection, MoveJointHandler and MoveCartesianHandler handlers using Joint and Cartesian goals respectively. In both cases, MRP's arms moves to the desired position in order to pick the pre-compressed damper and remove it from the fixture. A parallel pneumatic gripper equipped with a custom pair of fingers as presented in Figure 18 is used for damper's picking action. Gripper's action is controlled by the SetIOHandler provided by THOMAS station controller. Station controller sends electric signals to MRP's electro valves which provide air to the pneumatic gripper accordingly (Figure 59).

Figure 59: Pick pre-assembled damper from the fixture

4.7.2. Compression Machine physical working area

In the compression machine working area, the MRP needs to perform the following tasks in order to place the pre-compressed damper on the mock-up compression machine, emulate the compression process and pick the compressed damper:

- MRP's navigation and localization to the compression machine working area
- Fixture's detection
- Pre-compressed damper's placement to the compression machine working area
- Alignment rod's removal from the mockup compression machine's upper structure
- Nut's placement in the mockup compression machine's upper structure
- Compressed damper's manipulation

4.7.2.1. MRP's navigation and localization to Compression machine working area

For the execution of the "Pre-compressed damper placement in the compression machine working area" task, THOMAS MRP should navigate inside the compression machine working area. Following the same procedure as described in section 4.7.1.1 and the Apriltag_a of the compression machine working area, the required accuracy of the navigation action is achieved.

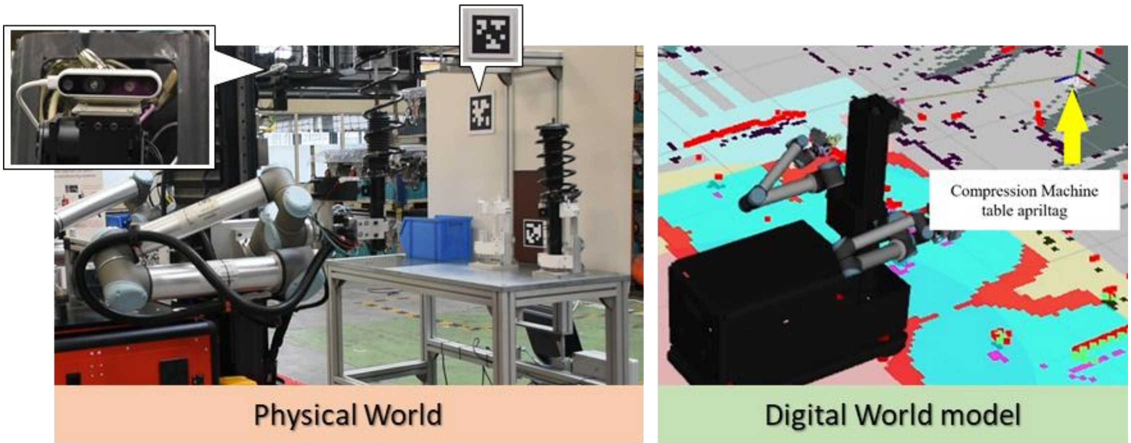


Figure 60: Localization to compression machine mock-up table using Realsense camera

4.7.2.2. Objects' Detection inside the compression machine working area

Based on the methodology presented in section 4.7.1.2, THOMAS MRP is capable to detect the exact position of the pre-compressed damper's fixture on the top of the compression machine mockup table. The ROBOCEPTION rc_visard 65 stereo camera is used to provide information regarding pre-compressed damper fixture's and Apriltag_b's location inside this working area. Using the rc_visard 65 and Apriltag_b of the compression machine working area, information regarding the exact position of the pre-compressed damper fixture is returned to THOMAS system. Information regarding the detected "Place" frame added in the digital world model of THOMAS project and may be visualized using RViZ software (Figure 61).

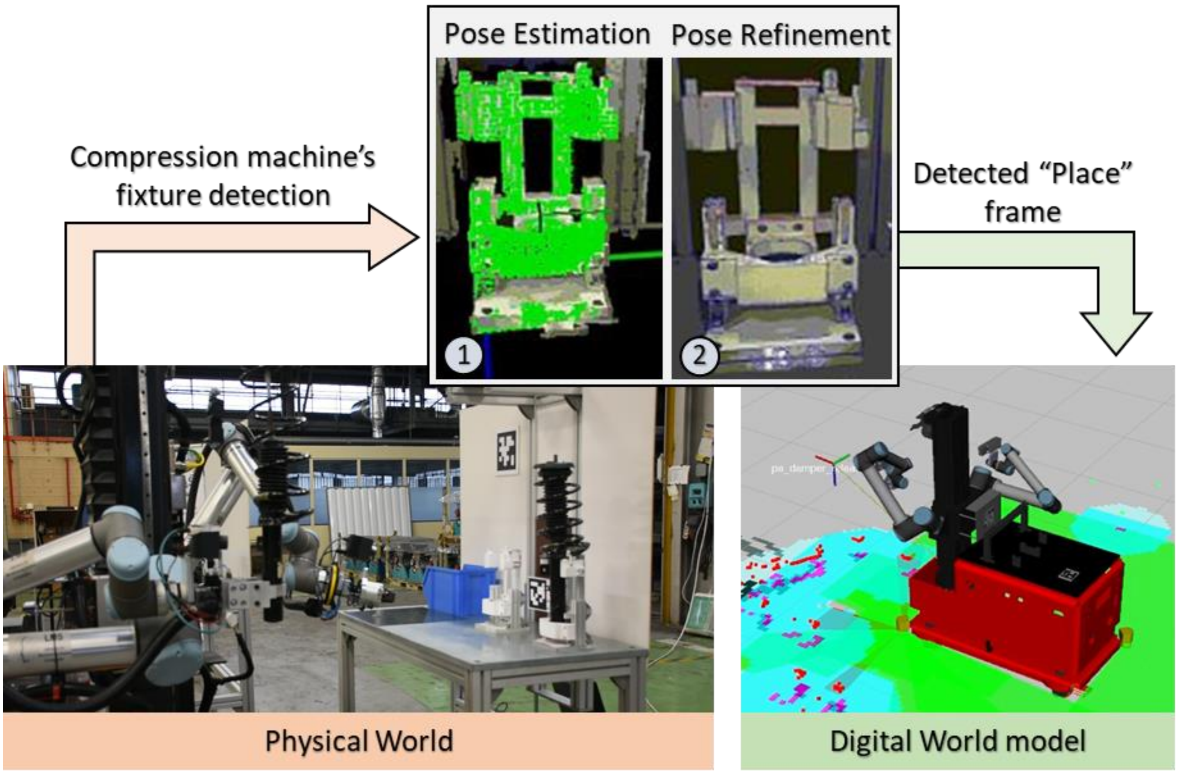
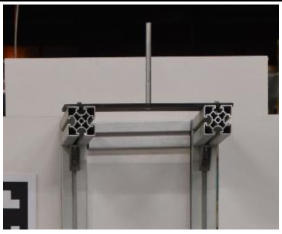
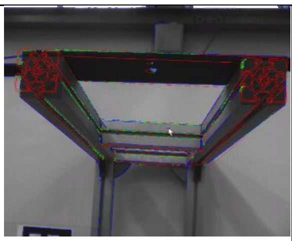
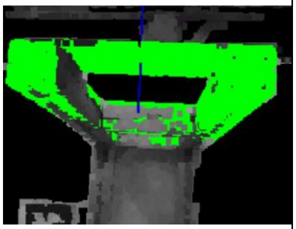
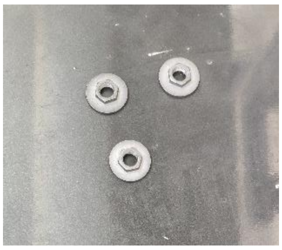
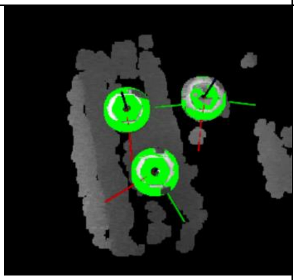
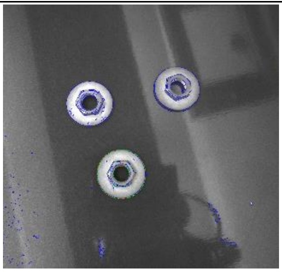
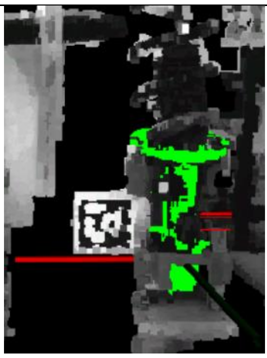
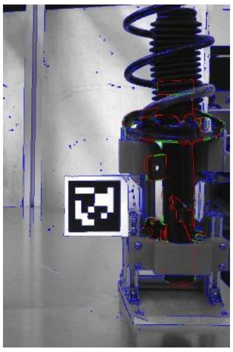


Figure 61: Compression machine's fixture detection

Following the same procedure, THOMAS MRP is able to detect four hardware components inside the compression machine working area for the execution of all required tasks in this area. These models' detection process is presented in Table 7. The Apriltag provides a rough estimation of the location of the target part, and afterwards the pose of the object is refined using the perception pipeline developed in WP3.

Table 7: Detection process in compression machine working area

Detected object (RC camera used)	Physical View	Pose Estimation	Pose refinement
Pre-compressed fixture (rc_visard 65)			

Mockup Compression Machine Upper Srtucture (rc_visard 65)			
Nuts (rc_visard 65)			
Compressed Damper (rc_visard 160)			

4.7.2.3. Objects' manipulation inside the compression machine working area

As presented in section 4.2.1.1, object's manipulation is based on two pneumatic grippers integrated on each MRP's arm. Both MRP's arms are equipped with a pneumatic gripper controlled by THOMAS station controller. Firstly, the MRP needs to place the pre-compressed damper in the pre-compressed damper's fixture placed on the top of the compression table using its right arm (Figure 62). Then, using its left arm handling configuration (Figure 17), the MRP unloads the alignment rod from the compression table and places the nut on the top of the compression table's upper structure (Figure 63, Figure 64) to be used for the drilling of the compressed damper after the spring's compression. After the compression takes place, the MRP detects the compressed damper and picks it from the compression table using its right arm's handling configuration (Figure 65).

Figure 62: Pre-assembled damper's placement in the fixture

Figure 63: Alignment rod detection and manipulation

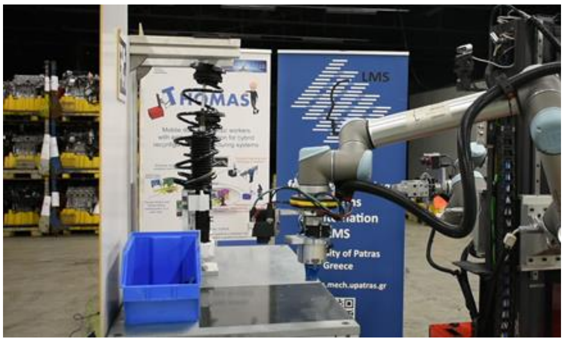


Figure 64: Nut detection and manipulation

Figure 65: Pick compressed damper from the fixture

4.7.3. THOMAS Mobile Product Platform's (MPP) physical working area

After the removal of the compressed damper from the compression machine working area, THOMAS MRP transfers the part on the MRP and inserts the damper on the disk. In the following subsections, the robot tasks for placing the compressed damper on MPP's fixture but also the screwing while both mobile platforms are co-navigating are described.

4.7.3.1. MRP's navigation and localization to MPP working area

In order to place the compressed damper on the MPP, MRP navigates to the MPP working area using the NavigationHandler of THOMAS station controller. The localization action is based on the Apriltag_a of this working area. For this purpose, a Basler camera is placed on the bottom side of MRP. This camera will be used also during mobile platform's co-navigation action (Figure 66).

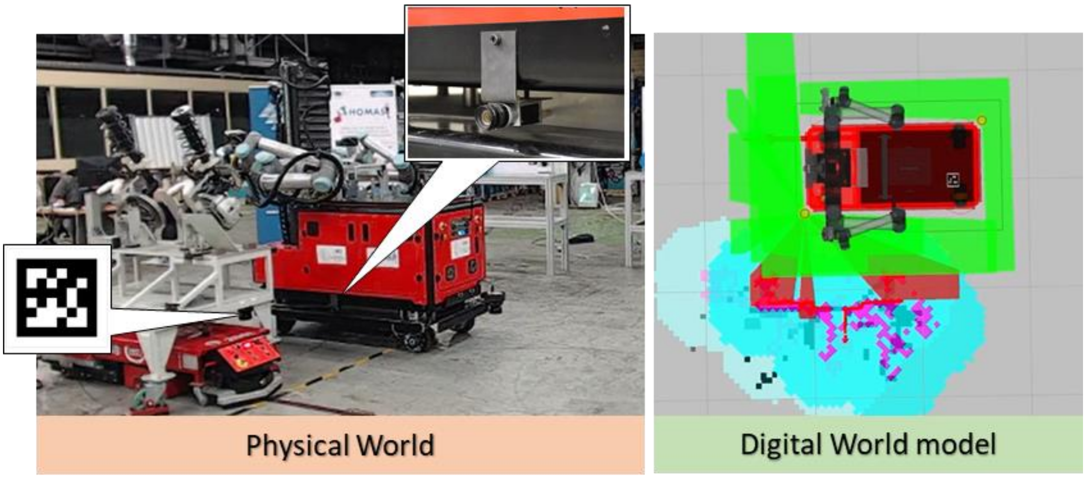


Figure 66: Localization to MPP working area using Basler camera

4.7.3.2. Objects' detection in the MPP working area

Objects need to be detected inside this working area are the disks placed on the MPP so that MPR to place the compressed dampers on them. This is achieved through the DetectionHandler handler, the rc_visard 65 stereo camera and the Apriltag_b which is placed between the two fixtures on the top of the MPP's upper structur. The detection process of the left suspension's disk is presented in Figure 67.

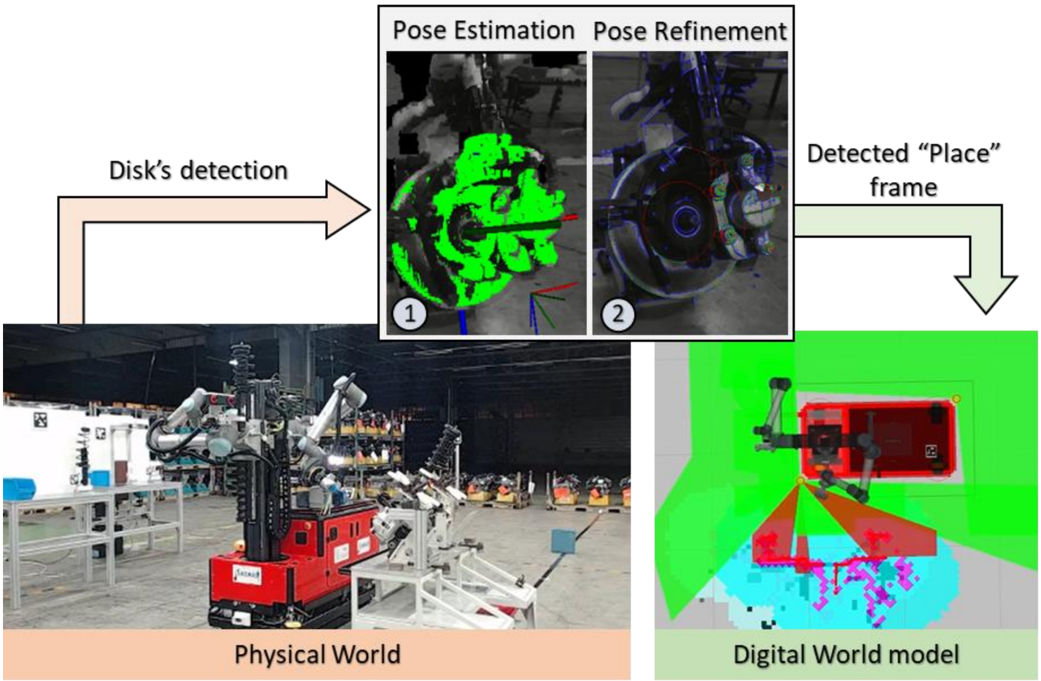


Figure 67: MPP fixture's detection

4.7.3.3. Compressed damper's placement on the MPP

After the successful detection of the left disk on the top of MPP's upper structure, THOMAS MRP places the compressed damper on the MPP working area using its right arm handling configuration Figure 62.

Figure 68: Compressed damper's placement on the MPP

4.7.3.4. From handling to screwing configuration

After the completion of the manipulation tasks, THOMAS MRP executes a toolchange task in order to switch from the right arm handling configuration to the screwing configuration. The MRP undocks from the MPP in order for the human operator to be able to execute cabling tasks in the MPP working area. As presented in Figure 69, THOMAS MRP releases the gripper in the tool station and automatically picks the screwdriver while the operator inserts the required cables and nut on the disk. After the successful change of right arm's tool, the MRP virtually docks again on the MPP following the same methodology as presented in section 4.7.3.1. Then the MRP places the screwdriver on the custom fixture installed on the upper structure of the MPP as presented in Figure 14. In order to achieve the required accuracy for screwdriver's placing task, the detection handler is used. THOMAS MRP detects the Apriltag_b of the MPP working area using the rc_visard 160 stereo camera.

Figure 69: Toolchange operation

4.7.3.5. MRP-MPP virtual docking mechanism

The MRP-MPP virtual docking task is technically the same with the MPP navigation task as presented in section 4.7.3.1. Again, the Basler camera detects the Apriltag_a placed on the bottom side of the MPP and send the position data to the LocalizationHandler (Figure 70).

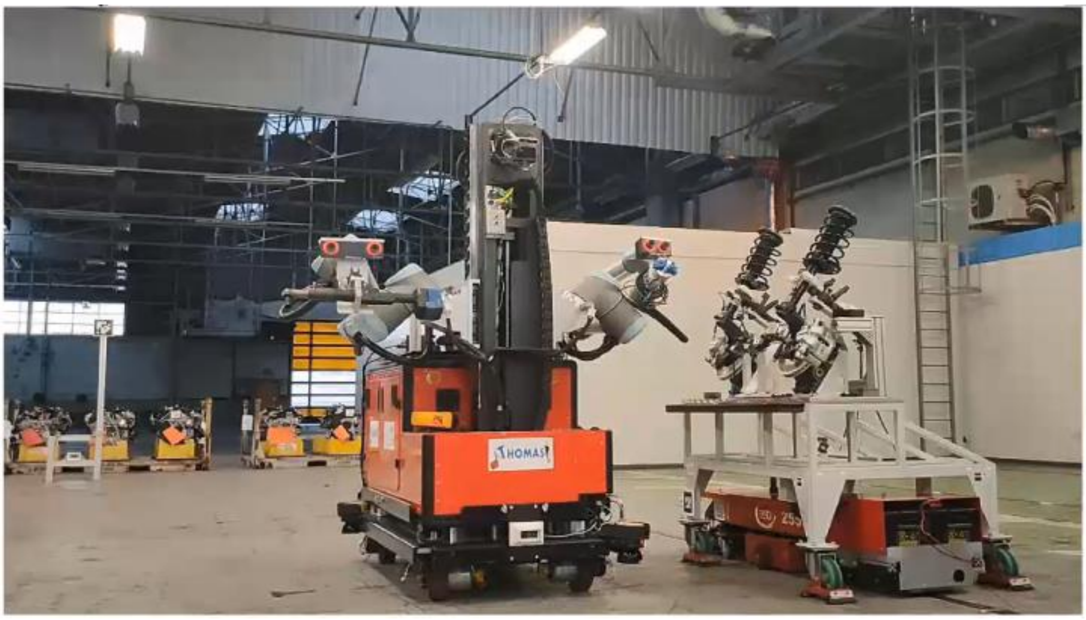


Figure 70: MRP - MPP virtual docking execution

4.7.3.6. MRP-MPP docked moving navigation

The MRP-MPP docked navigation is carried out by the Follow Handler. This ROS Action Server receives Follow action goals and undertakes the task to keep fixed the distance between MRP and MPP while the MPP moves in a straight line. The sensor used for this task is the Basler camera that detects the MPP Apriltag throughout the whole process and provides the FollowHandler with the relative distance between the MRP and MPP.

4.7.3.7. Screwing operation

In order to assemble the compressed damper with its corresponding disk, screwing tasks take place in the MPP working area. This task is assigned to THOMAS MRP. Taking under consideration the mobility of both MPP and MRP resources, THOMAS solution introduces a screwing while moving operation. This operation is based on the synchronous co-navigation of MRP and MPP while a nut is screwed on the disk connecting the compressed damper with the disk. The screwing operation is carried out by the Screwing Handler. This is a ROS Action Server that receives Screwing action goals to begin the screwing sequence. The screwing handler triggers the screwdriver to screw the nut and connect the compressed damper with the disk when the MPP starts to navigate inside the shopfloor. After the successful execution of the screwing task, the MRP approaches MPP and picks the screwdriver from its fixture.

Figure 71: Screwing operation execution

5. CONCLUSIONS

This document presents the final version of THOMAS automotive demonstrator deployed at STELLANTIS Mulhouse plant in France. The customization of THOMAS OPS hardware and software modules is described in detail of the execution of the front axle assembly operations included in this pilot case.

The workflow starts from the Task Planner that assigns the tasks to the available human operators and MRPs against user defined criteria such as human ergonomy and resources availability and utilization. Then the Station Controller retrieves this task plan being responsible for the dispatchment of the tasks to the human operators and mobile robots. From the human operators' side, an AR application is used enabling the integration of operators to the execution loop while supporting them in terms of safety awareness and programming interfaces. To enable the dynamic behaviour of the MRP in such a safe fenceless environment the information coming from the different integrated sensors are synthesized to compile the Digital World model that is then used for:

- Environment and process perception and
- Safe human robot co-existence and collaboration,

The developed technologies as well as the end-to-end assembly scenario execution have been tested and validated in the THOMAS OPS installation at STELLANTIS plant. The performance of the THOMAS OPS has been validated against a set of Key Performance Indicators (KPIs) as these have been defined in D1.1 that was delivered on M09 of the project. The results of this validation process are documented in deliverable D7.7. The results indicated that THOMAS OPS can highly contribute in the increase in human ergonomy as well as the flexibility of the system since it can facilitate the production of multiple product variants.

6. GLOSSARY

WP	Work package
MRP	Mobile Robot Platform
MPP	Mobile Product Platform
HRI	Human Robot Interaction
EOAS	End of Arm Safeguarding
HRC	Human Robot Collaboration
OPS	Open Production Station
AR	Augmented Reality
KPIs	Key Performance Indicators

7. References

[1] Makris, S., 2020, Cooperating Robots for Flexible Manufacturing, Springer.

[2] Kousi, N., Michalos, G., Aivaliots, S., Makris, S., 2018, An outlook on future assembly systems introducing robotic mobile dual arm workers, Procedia CIRP, 72:33-38.

[3] Kousi, N., Gkournelos, C., Aivaliotis, S., Giannoulis, C., Michalos, G., Makris, S., 2019, Digital twin for adaptation of robots' behavior in flexible robotic assembly lines, Procedia Manufacturing, 28:121-126.

[4] URL ROBOCETPION https://roboception.com/en/rc_visard-en/

[5] URL SMC MHS2-63D Gripping system https://www.smcpneumatics.com/MHS2-63D.html

[6] URL SMC MHL2-25D Gripping system https://www.smcpneumatics.com/MHL2-25D-X4529.html

[7] URL SCHUNK tool changing systems https://schunk.com/de_en/gripping-systems/series/sws/

[8] URL ROBOTIQ force sensor https://robotiq.com/products/ft-300-force-torque-sensor

[9] URL RealSense technology https://realsense.intel.com/

[10] URL Microsoft Kinect 2 https://developer.microsoft.com/en-us/windows/kinect

[11] URL SICK S300 laser scanners https://www.sick.com/ag/en/opto-electronic-protective-devices/safety-laser-scanners/s300-standard/c/g187239

[12] URL SICK MicroScan 3 https://www.sick.com/ag/en/opto-electronic-protective-devices/safety-laser-scanners/microscan3-core/c/g295658

[13] URL SICK Flexi Soft controller https://www.sick.com/be/en/senscontrol-safe-control-solutions/safety-controllers/flexi-soft/c/g186176

[14] URL On robot HEX – H force sensor https://onrobot.com/en/products/hex-6-axis-force-torque-sensor

[15] URL Denkovi relay https://denkovi.com/

[16] URL Microsoft Hololens (AR Glasses) https://www.microsoft.com/en-us/hololens

[17] D. Liciotti, M. Paolanti, R. Pietrini, E. Frontoni, and P. Zingaretti. Convolutional networks for semantic heads segmentation using top-view depth data in crowded environment. In 2018 24th International Conference on Pattern Recognition (ICPR), pages 1384–1389, Aug 2018. doi: 10.1109/ICPR.2018.8545397.

[18] Vincenzo Carletti, Luca Del Pizzo, Gennaro Percannella, and Mario Vento. An efficient and effective method for people detection from top-view depth cameras. 2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance, AVSS 2017, (August), 2017. doi: 10.1109/AVSS.2017.8078531.