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

Grant Agreement No	**:**	**723616**
Project Acronym	**:**	**THOMAS**
Project Start Date	**:**	**1st October, 2016**
Consortium	**:**	**UNIVERSITY OF PATRAS (LMS)** **PEUGEOT CITROEN AUTOMOBILES S.A. (PSA)** **SICK AG (SICK)** **FUNDATION TECHNALIA RESEARCH & INNOVATION (TECNALIA)** **ROBOCEPTION GMBH (ROBOCEPTION)** **DGH ROBOTICA, AUTOMATIZACION Y MANTENIMIENTO INDUSTRIAL SA (DGH)** **AERNNOVA AEROSPACE S.A.U. (AERNNOVA)** **INTRASOFT INTERNATIONAL SA (INTRASOFT)**

Title	**:**	**THOMAS Open Production Station – Intermediate Version**
Reference	**:**	**D6.2**
Availability	**:**	**Public**
Date	**:**	**15/12/2019**
Author/s	**:**	**DGH, LMS, PSA, SICK, TECNALIA, ROBOCEPTION, AERNNOVA, INTRASOFT**
Circulation	**:**	**EU, consortium**

Summary:

This document provides a detailed description of the intermediate version of THOMAS Open Production Station. The set up for the automotive and the aeronautics pilot cases at LMS and TECNALIA premises is documented in detail including the description of the hardware components as well as the software developments deployed under the intermediate THOMAS OPS.

Table of Contents

1. LIST OF FIGURES

2. LIST OF TABLES

3. EXECUTIVE SUMMARY

THOMAS aims to create dynamically reconfigurable shopfloors considering mobility as the main enabler. In particular, the project introduces: a) mobility in product level – Mobile Product Platforms (MPPs) and b) mobility in resources level – Mobile Robot Platforms (MRPs). The MRPs are mobile dual arm workers able to autonomously navigate inside the factory, undertaking multiple operations such as screwing, handling, drilling etc. Their key feature is that they can cooperate with other production resources such as MPPs while acting as assistants to human operators. To enable the autonomous and flexible behaviour of these robots, THOMAS partners have developed new solutions regarding environment and process perception for mobile robots (WP3) , safety functions and interfaces for intuitive collaboration between resources (WP2), robot skills and easy programming tools (WP4), digital world modelling methods and online work re-organization tools (WP5).

THOMAS Open Production Station as a Product includes all the individual software and hardware components developed in the project, integrated under a common system. THOMAS MRP are the main resources included in THOMAS OPS with the MPP supplementing the reconfigurable production system (Figure 1). WP6 is responsible for delivering THOMAS OPS as a product. Therefore, the activities under this WP are focusing on developing THOMAS MRPs and MPPs, finalizing the sensors and tools supported in THOMAS OPS, developing docking mechanisms for the mobile resources as well as integrating and validating the individual technology developments of WP2-5.

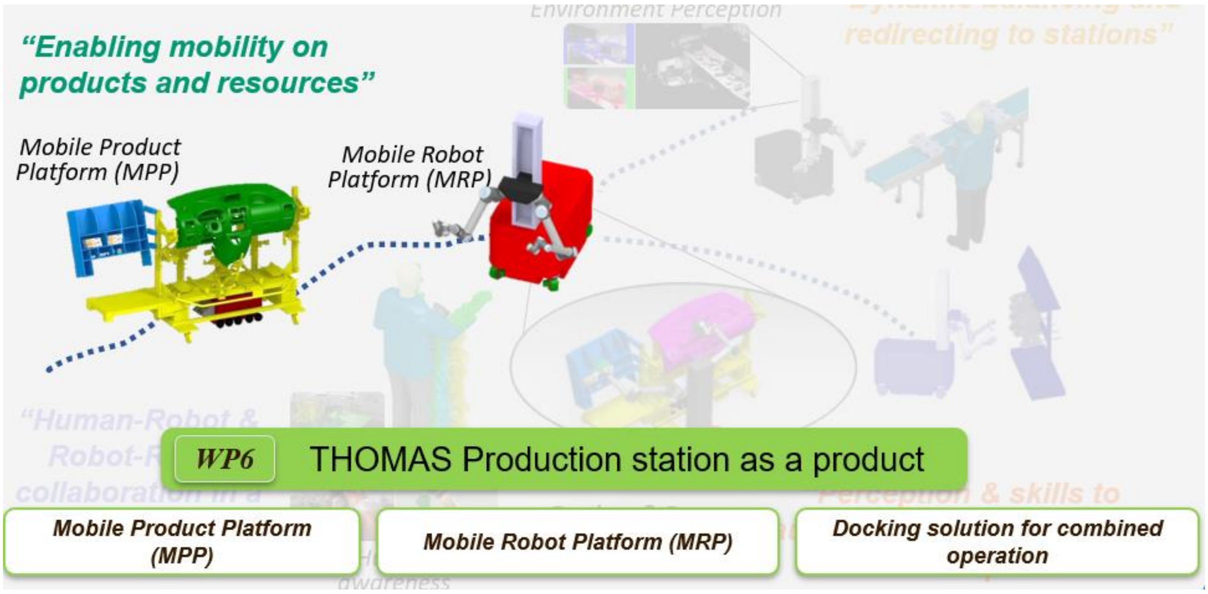


Figure 1: THOMAS Open Production Station (OPS) as a Product

THOMAS OPS is planned to be delivered in three versions. The first version was documented under D6.1 that was submitted on M24. The current deliverable presents OPS intermediate version of which is an enhancement of the initial one. The final OPS version will be reported on M42.

The main effort under this period (M24 – M36) was to finalize THOMAS MRP_n2 by integrating and validating the safety system included the hardware safety devices integration as well as the software safe logic deployment. In addition, the tools to support MRP operations have been designed, manufactured and tested in real operations. Finally, during this period: a) the static docking of THOMAS MRPs using physical connection as well as virtual localization has been achieved, b) the MRP-MPP co-navigation (mobile virtual docking) has been developed tested in the actual machines. The sensors that are required for supporting the THOMAS individual results (WP2-WP5) have been finalized and integrated in THOMAS MRP_n1 and MRP_n2. THOMAS OPS versions are being customized for the PSA and AERNNOVA use cases deployed at LMS and TECNALIA premises respectively. These demo areas are used for the testing and fine tuning of THOMAS OPS.

4. Introduction

THOMAS Open Production Station (OPS) aims to achieve the following benefits in modern manufacturing systems:

- **Increase reconfigurability**. The mobile resource MRP will be able to change workstations based on production needs. Time required to travel among the different workstations.
- **Reduction of programming efforts**. The MRP, integrated with skills, will be able to fast and easily learn new operations. Time to program and validate the assembly operation
- **Increase resource planning and optimization**. The MRP, integrated with the required tooling will be able to perform multiple operations. Number of different types of operations.
- **Increase Manufacturing Line flexibility**. The MRP will be able to follow the mobile product (MPP) while operating. Time save through operating while moving from one station to the next.
- **Support multiproduct Manufacturing Line**. The MRP integrated with the perception modules will be able to dynamically detect and adapt in changes in the process. Number of different product variants to be processed
- **Increase ergonomy and safety conditions of human work**. THOMA OPS, integrating the safety & interaction mechanisms will use the MRP for performing the difficult operations. Total weight handled by operator in a cycle.

The present deliverable presents THOMAS OPS intermediate version where the final versions of THOMAS individual technologies are being integrated. Details on the individual technologies may be found in THOMAS public website (http://www.thomas-project.eu/deliverables/) referring to WP2, WP3, WP4, and WP5 deliverables.

The activities performed under WP6, during the third year of the project may be summarized as follows:

- Finalization of MRP_n1 and MRP_n2,
- Finalization of the tools selection for supporting MRP multiple operations,
- Development of physical connection based as well as virtually static docking mechanisms,
- Development of MRP-MPP co-navigation module – mobile docking,
- Integration and testing of the above technologies under THOMAS OPS,
- Fine tune the individual technologies deployment under THOMAS OPS by considering the latest developments performed during the second period.

The performed integration and validation tests tool place at LMS and TECNALIA premises where the demonstrators for the PSA and AERNNOVA use cases have been set up. DGH has been leading the activities for the hardware integration and testing while INTRASOFT was responsible for the enhanced software components packaging.

5. THOMAS Open Production Station as a Product Overview

As described in the previous section, THOMAS OPS main to integrate the different hardware and software components that will allow the realization of THOMAS vision. The latter is oriented around THOMAS industrial pilot cases from the automotive (end user: PSA Group) and from the aeronautics sector (end user: AERNNOVA). Figure 2 visualizes the major components of THOMAS OPS that after customization derive the deployment and execution of the project's industrial use cases.

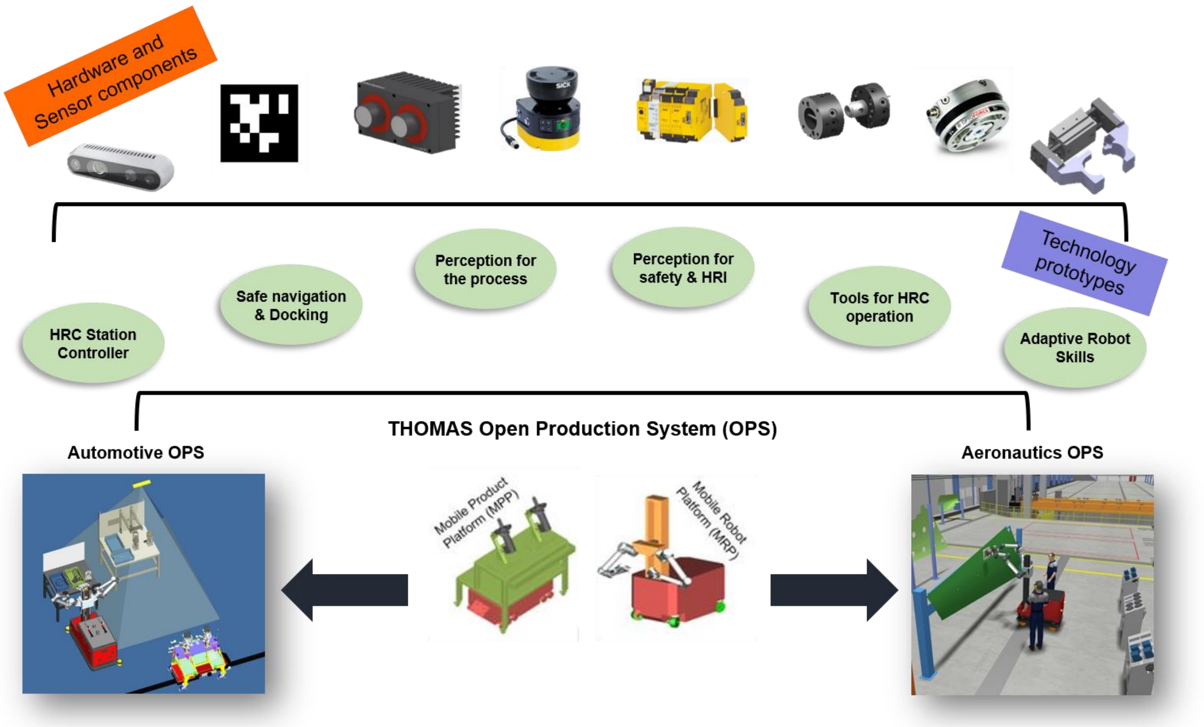


Figure 2: THOMAS Open Production Station as a Product Overview

5.1. THOMAS Mobile Resources

5.1.1. THOMAS Mobile Robot Platform (MRP)

THOMAS Open Production Station main resource is the Mobile Robot Platform (MRP) that will be used for the realization of THOMAS both industrial pilot cases. In more detail, THOMAS MRP is a mobile dual arm manipulator that may autonomously navigate in different workstations undertaking multiple operations using its 6 DOF robot arms (Universal Robot – UR 10). The main components of THOMAS MRP are visualized in the following figure.

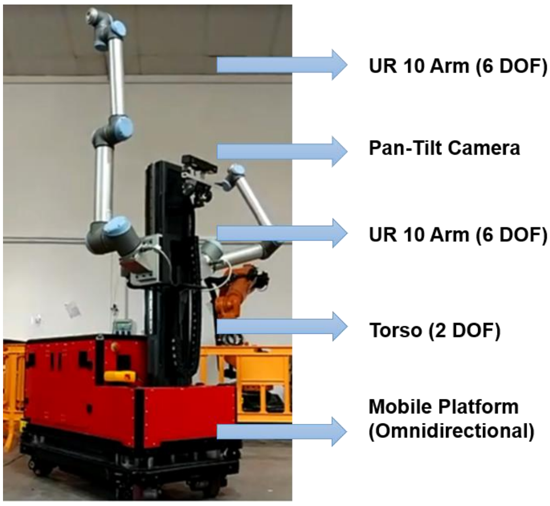


Figure 3: THOMAS MRP Main Components

Towards the effective design and development of THOMAS MRP a 2 – step approach has been following by the consortium. In the beginning of the project the MRP 1st version (Figure 4) was designed by the consortium with DGH and TECNALIA leading this activity. The manufacturing of the MRP has been undertaken by an external partner. This 1st version has been used for testing the different partner's developments during the first and second years of the project. Then, this robot focused more on the tests performed regarding the aeronautics case.

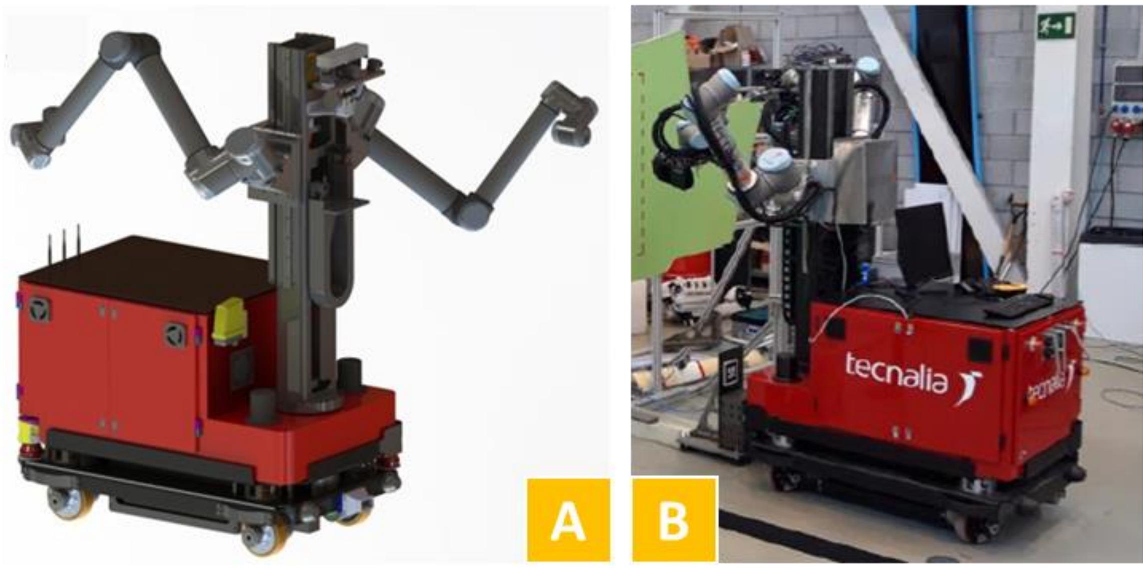


Figure 4: THOMAS MRP_n1 at TECNALIA premises A) 3D design, B) final MRP

This was feasible, since on M24 the second MRP has been delivered at LMS. After several iterations with the external partner, the robot has been re-designed and enhanced with several safety devices so to boost the hardware closer to certification. Then, on M24, after several functional acceptance tests that took place at the manufacturer premises, the robot was delivered at LMS. Since then, this robot is also used for testing the partners' individual developments while it is more focused on the automotive pilot case.

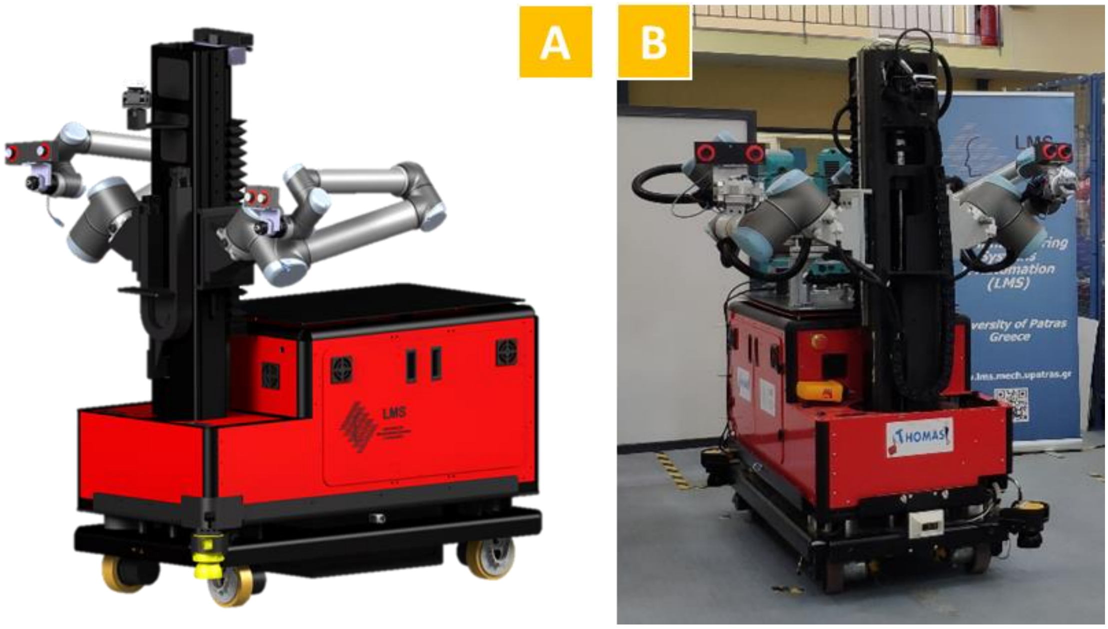


Figure 5: THOMAS MRP_n2 at LMS premises A) 3D design, B) final MRP

In this development period, THOMAS application safety setup has been tested and implemented in THOMAS MRP_n2. Figure 6 shows the main safety components selected to be added in the Mobile Robot Platform n2 as indicated by the safety setup done in this period. Under deliverable D2.4, submitted on M18 of the project, the detailed safety concept alongside with the technical specifications of the selected safety hardware have been documented. In D2.5, submitted on M36, the developed and deployed on the MRP_n2 safe logic is presented in detail.

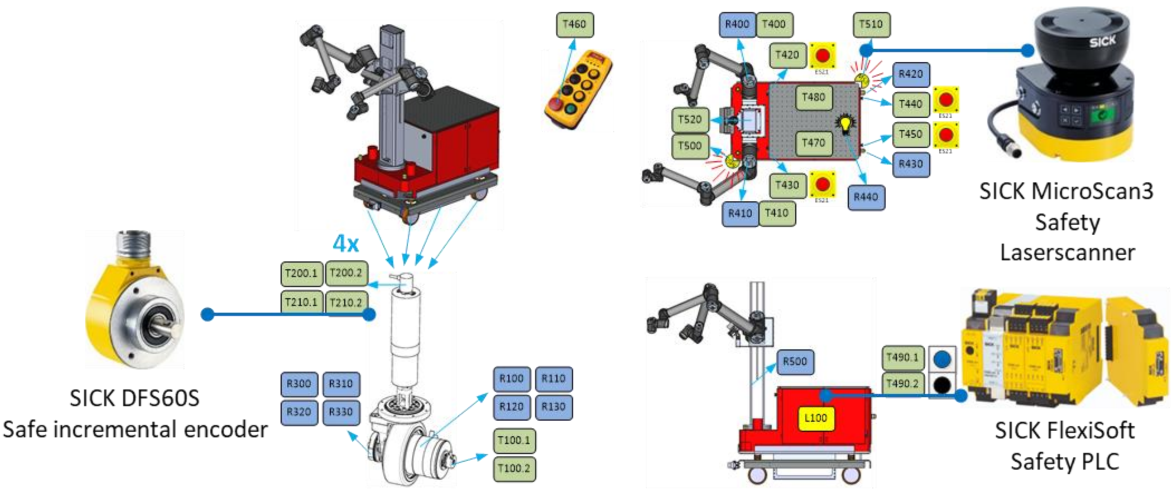


Figure 6: Safety concept design for the MRP (MRP_n2)

The main safety components are:

- two safety laser scanners on opposite corners of the MRP base (SICK microScan 3) [9] for environment perception and subsequent object detection and tracking (T500-T510)

Figure 7: SICK MicroScan3 safety laser scanner

- two safety encoders (SICK DFS60S Pro) [13] at each wheel to safely measure wheel orientation, wheel turning direction and wheel speed (T101-T208)

Figure 8: SICK Safety encoder DFS60S Pro

- an operation mode switch (T493), as well as a start and reset button (T491 and T492)
- several E-stop buttons on each side of the MRP (T420-T460)
- non-contact, inductive safety switches (SICK IN3000 Direct) [14] to monitor the safe retracted position of the robot arms (T470-T480) and of the torso (T520-T540).

Figure 9: SICK IN3000 Direct

- safety programmable logic controller (SICK Flexi Soft) [10] components to safely connect triggers to reactions

Figure 10: SICK FlexiSoft system

5.1.2. THOMAS MRP after 1st project's safety integration WS

THOMAS MRP_n2 main parts have already been presented in THOMAS deliverable D6.1. An updated version of THOMAS MRP was the result of THOMAS 1st safety integration workshop which took place in Greece on M30 of the project. During this workshop several changes took place on MRP_n2 body. Another safe proximity sensor was added in MRP's torso in order to control better MRP's motion (Figure 11) by adding safe MRP configurations for MRP navigation. LMS added one extra switch dedicated for the safety MRP's components and another one for both rc_visard cameras. Last but not least, new brake systems were installed inside MRP's wheels in order to increase mobile robot navigation action's accuracy (Figure 12) while ensuring safety.

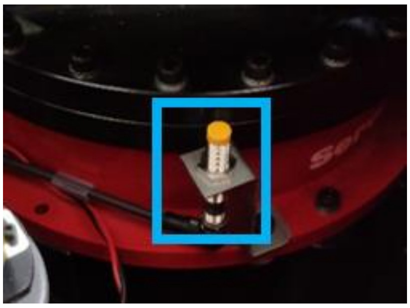


Figure 11: Second MRP torso safe rotation proximity sensor

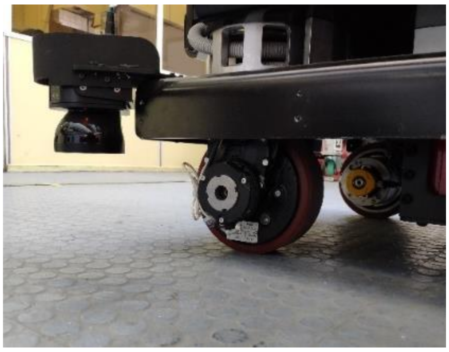


Figure 12: Updated brake model

5.1.3. MRP Updated Electrical diagram

Along with the integration of different devices, the documentation of the hardware connections established on the robot was very critical in order for the different partners to be able to work on the same system in parallel. In addition, the optimization of robot electrical and pneumatic connections was an important task in order to ensure that the robot complies in the relevant regulations. DGH supported by SICK and LMS compiled the MRP updated electrical diagram including all the hardware connections included on the MRP. In particular, the connection of the robot arms, platform's motors/encoders and sensors to the SICK Flexisoft were detailed on this diagram so for the safe logic deployment to be done efficiently and for the troubleshooting during deployment to be done easily. The full version of the diagram is available within THOMAS consortium. Indicatively, the connection of the Flexisoft to the UR10 robots and to some of the safety sensors can be visualized in Figure 13 and Figure 14.

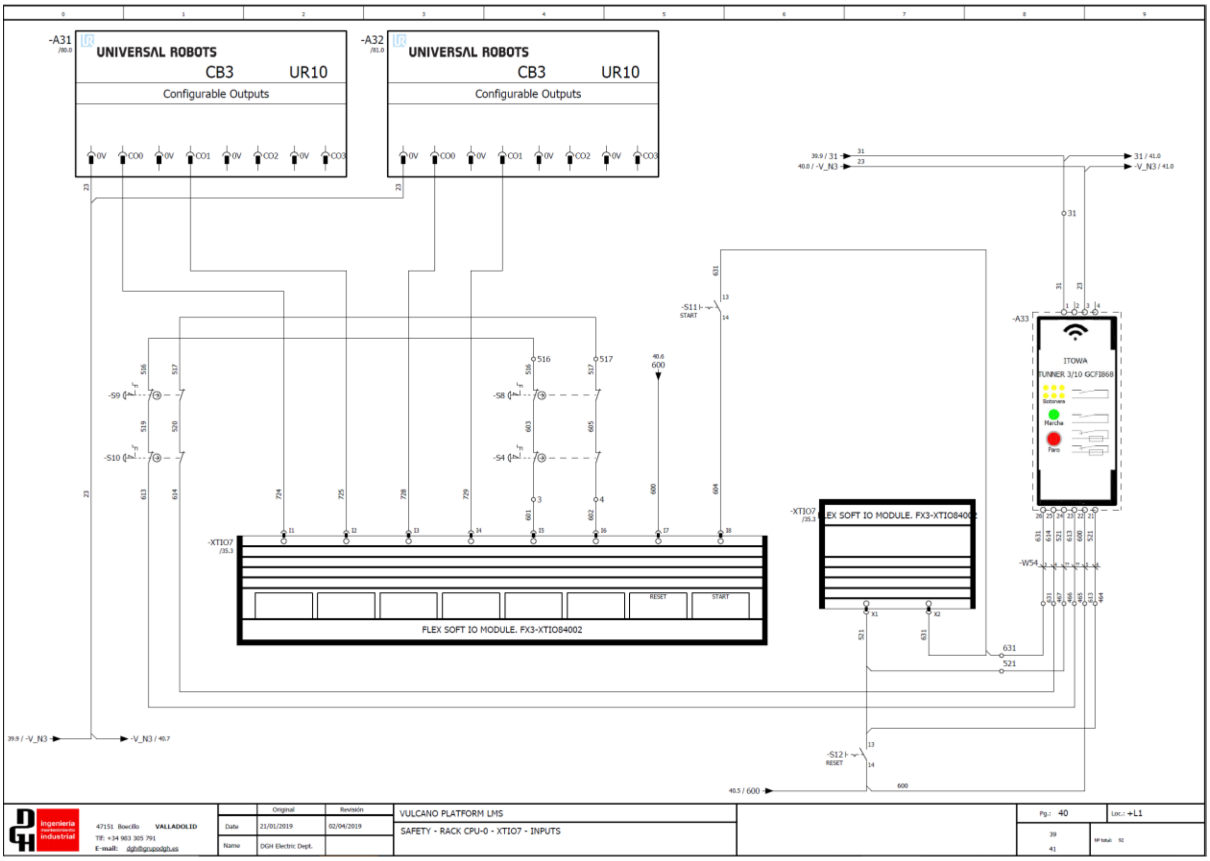


Figure 13: THOMAS OPS - SICK Flexisoft - UR10 connection

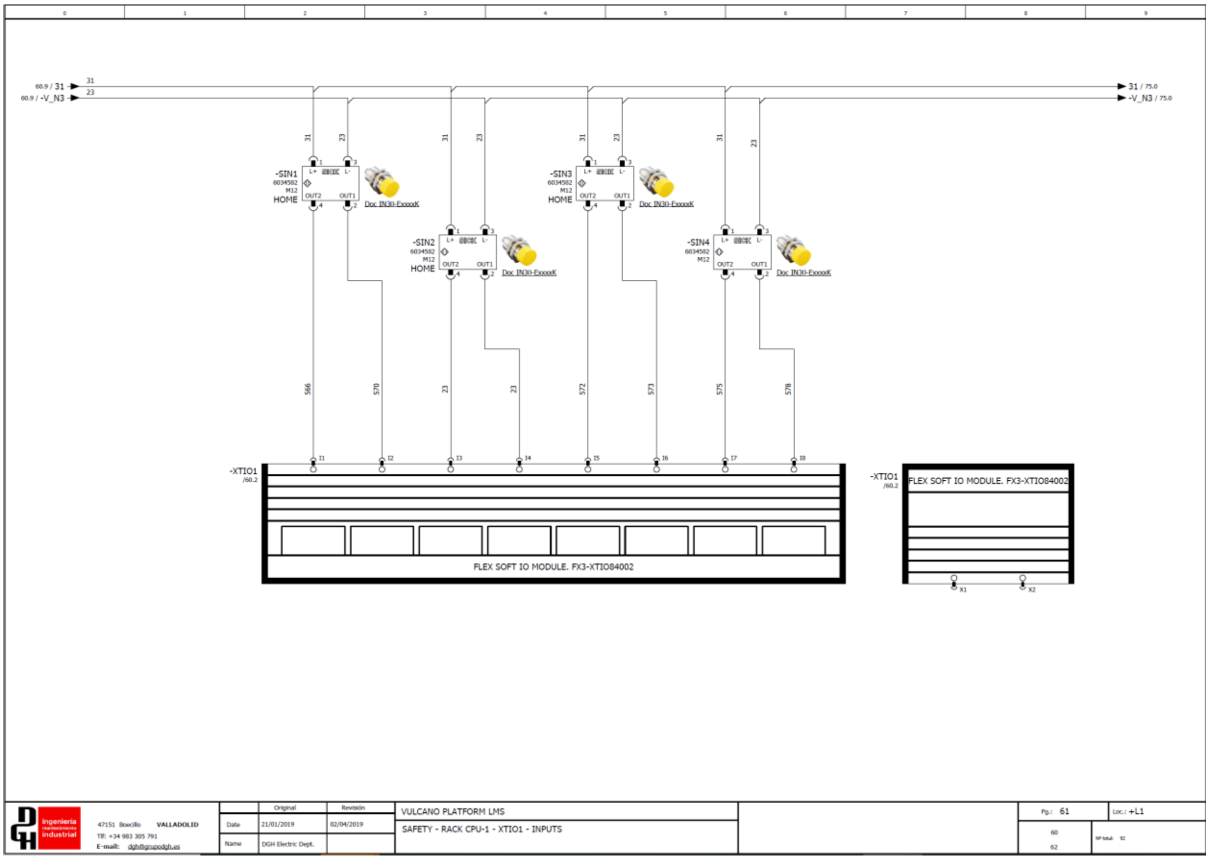


Figure 14: THOMAS OPS – Flexisoft - safe inductive sensors connection

5.1.4. THOMAS Mobile Product Platform (MPP)

As documented in deliverable D1.1, a Mobile Product Platform (MPP) is included in THOMAS OPS able to autonomously navigate and transfer the final product inside THOMAS shopfloor. THOMAS MPP consists of an Automated Guided Vehicle (AGV) and a custom upper structure model (Figure 15). This AGV is capable to execute navigation actions guided by a magnetic line installed inside THOMAS shopfloor. On the other hand, the upper structure model consists of custom fixtures for objects' temporary storage during AGVs' navigation.

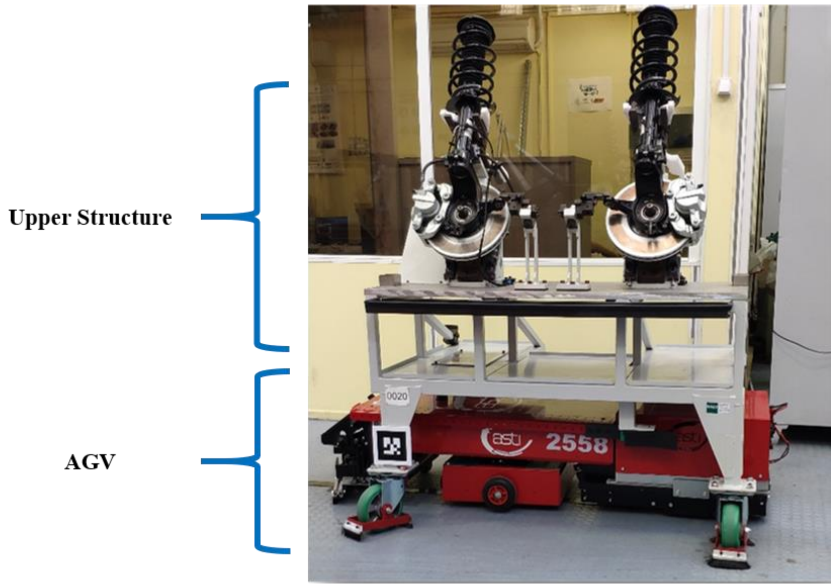


Figure 15: THOMAS MPP available in LMS premises

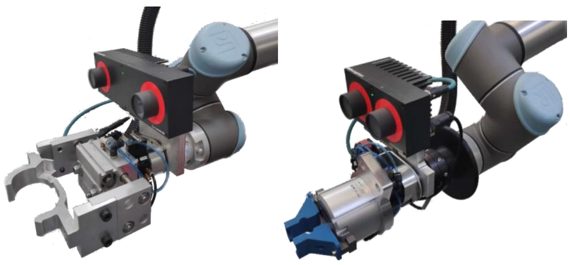
5.2. Selection of sensor and tooling for THOMAS OPS

Inside THOMAS project, mobile robots are able to navigate and perform manipulation actions with respect to other employee's safeness in the production line. Sensors and tools using under automotive and aeronautics pilot case are be listed in the following subsections.

5.2.1. Selection and testing of tools for HRC operation

Different kind of sensors and hardware components are required for both use cases of THOMAS project. Table 1 lists the major components selected for the THOMAS OPS.

Table 1: Selected tools for HRC operation

ROBOCEPTION rc_visard 65 and rc_visard 160 stereo cameras for multiple objects detection [1]	
Pneumatic grippers for multiple parts manipulation [2],[3]	
Automated drilling / Screwing machines machine	

SCHUNK Tool changers for automated tool changing [4]	
OptoForce / ROBOTIQ Torque and force control device [5],[11]	
RealSense 3D sensor for human detection and accurate navigation in 3D [6]	
2D cameras for localization and navigation [18]	
Kinect 2 3D sensor for human detection and accurate navigation [7]	
SICK laser scanners for human tracking and safety zones implementation [9],[8]	
End-effector Safeguarding sensor	
3D Safety Camera	
Microsoft Hololens Augmented Reality glasses for human operator support during collaborative assembly [12]	

6. OPS AUTOMOTIVE USE CASE

6.1. General Overview

Under the automotive pilot case, THOMAS aims to implement a flexible robotic assembly system where mobile robots as assistants to human operators. The selected scenario concerns the assembly of the suspension system in the front axle of a passenger vehicles involving three different steps: a) damper pre-assembly, b) damper compression and c) the damper assembly on the brake disks. Starting from this scenario and its requirements, in the following sections, the automotive THOMAS OPS current status is documented.

6.2. Simulated set up of the automotive OPS at LMS simulated layout

During the second period of the project, the simulation environment for the automotive OPS has been fine tuned and updated hosting all the changes in the 3D design of grippers, mechanical supports, working tables etc. indicated by the needs of the use case (Figure 16). The GAZEBO simulation environment was used in that period as well to validate the updated software components of THOMAS OPS before the physical commissioning at LMS premises.

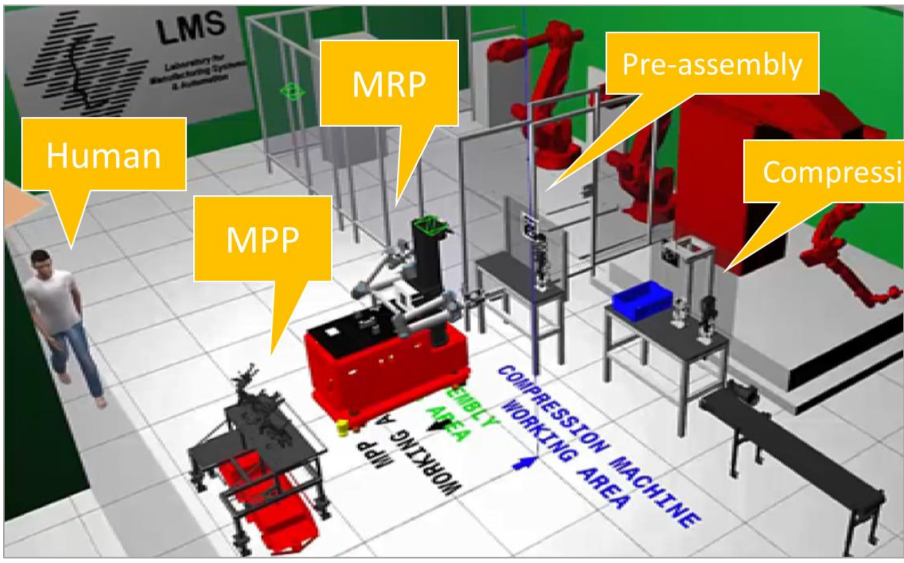
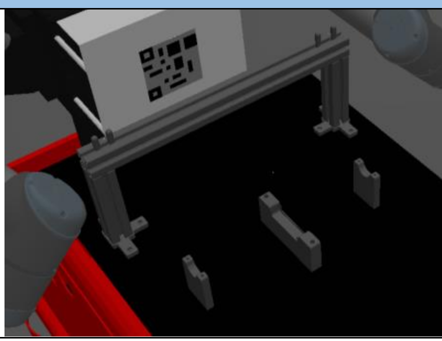
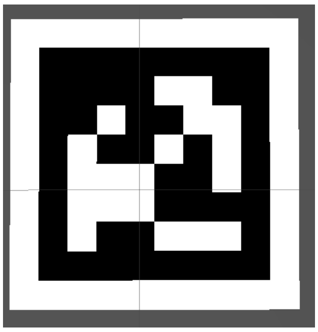
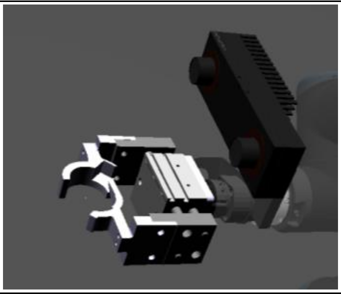
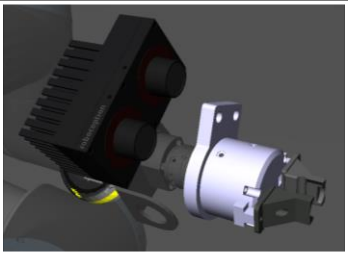
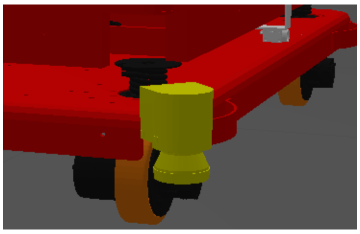
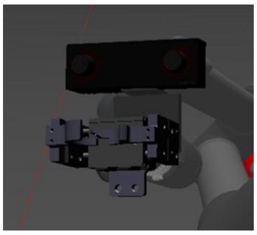
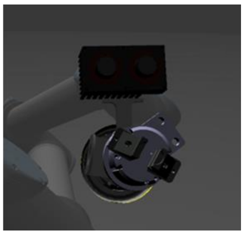
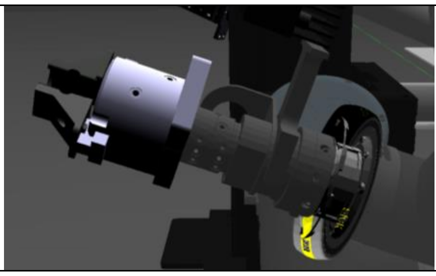


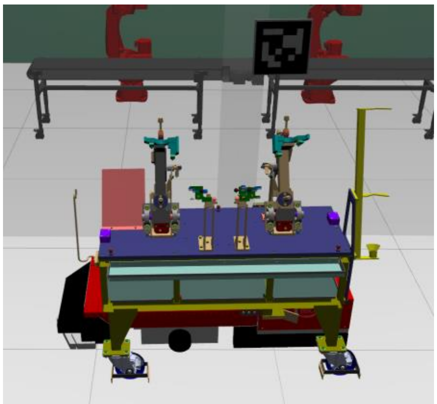
Figure 16: General Overview of THOMAS automotive pilot case scenario

In table 2 the THOMAS OPS components that have been added / updated to match the needs of the automotive pilot are listed in the table below.

Table 2: Hardware components in THOMAS Automotive pilot case

Hardware Components	Simulated model
Tool change stand on the MRP	

Hardware Components	Simulated model
April tags	
Pneumatic gripper for damper's manipulation	
Pneumatic gripper for nut's and alignment rod's manipulation	
SICK MicroScan 3 sensor	
ROBOCEPTION rc_visard 65 and 160 stereo cameras	 
Tool changers	

Hardware Components	Simulated model
Mobile Product Platform (MPP) with fixtured model	

6.3. Physical set up of the automotive OPS at LMS

In parallel with the GAZEBO simulation environment finalization, the automotive demonstrator setup has been prepared at LMS. Having available this demonstration area, during the 2nd period of the project, the software components / individual technologies prototypes have been deployed in the physical environment.

6.3.1. Automotive pilot set up at LMS

In the development period, the automotive pilot case demonstrator has been set up at LMS to test the complete workflow of the automotive use case including tasks such as detection and manipulation of the damper, positioning in compression machine and manipulation of the compressed damper to the MPP. This setup is visualized in Figure 17 having MRP_n2 as robot resource.

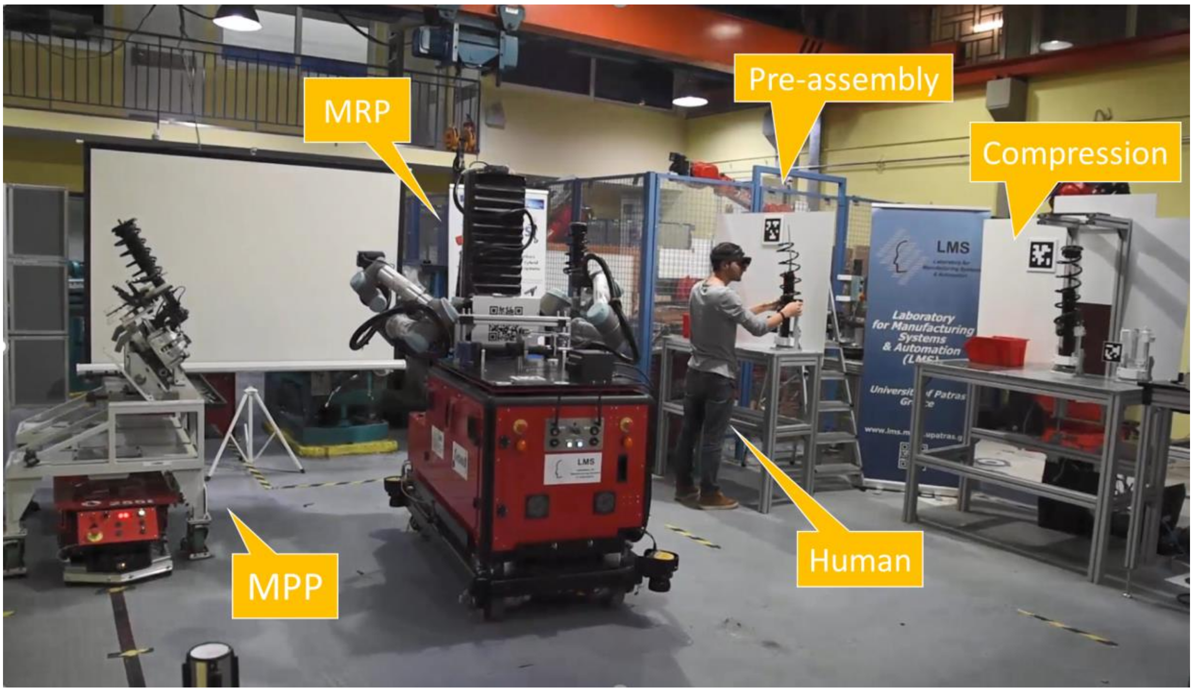


Figure 17: Automotive pilot intermediate test bed at LMS premises

Two pneumatic grippers, integrated on the MRP's arms, has been used for testing all the operations in the automotive use case, optimizing their design to be used in the final demonstrator. The selected and manufactured fingers, and tools used in these grippers are visualized in Figure 18. Two rc_visard

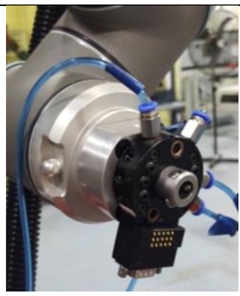
cameras have been deployed for testing the Apriltag and object detection modules achieving the accurate damper pose estimation for grasping.

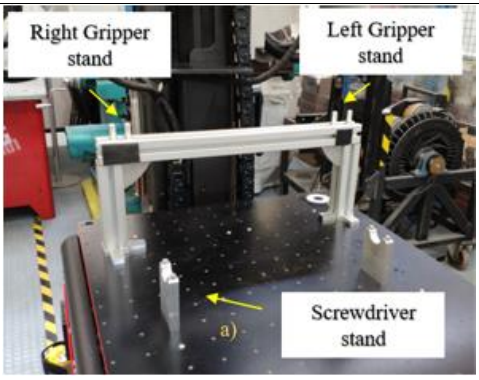
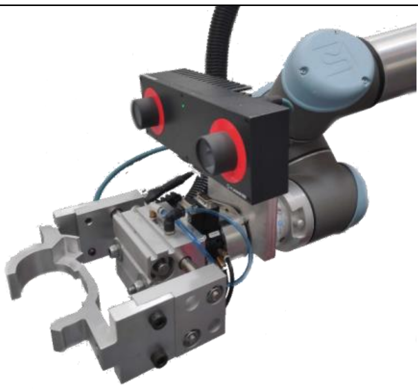
Figure 18: Damper's Manipulation

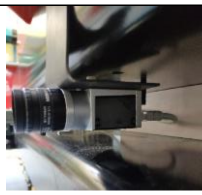
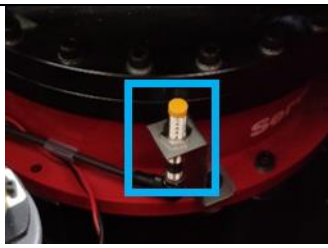
6.3.2. Hardware components of the automotive OPS at LMS

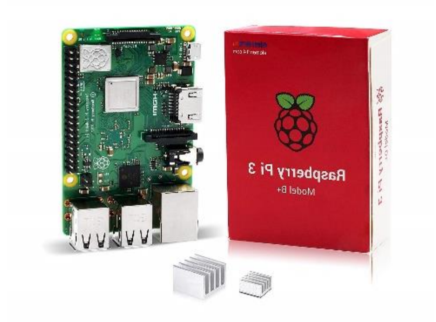
The existing components of THOMAS automotive OPS are listed in the following table (Table 3):

Table 3: Available components in LMS premises for THOMAS automotive pilot case

Hardware component	Description	Physical
April tags	April tags are used for objects' detection process and MRP platform's localization.	
Tool changers	A SCHUNK SWK 011 male tool changer is installed on each robot's arm in order to automate robot's tools change (grippers and screwdrivers). Each tool uses one SCHUNK SWA 011 female tool changer to be attached in robots' arm.	
Screw Machine	ESTIC electrical screwing machine is attached on the OPS right arm and is used for the connection of one damper and one disk model.	

Tool change Station	The tool change station is placed on a plate at the back side of the MRP_n2. It is consisted of a mounting base for the two grippers and one for the screwdriver.	
SICK MicroScan 3 sensor	Two SICK MicroScan 3 sensors are installed on MRP's platform in such a way so to cover the complete perimeter of the robots.	
Pneumatic gripper for nuts / alignment rod's manipulation and ROBOCEPTION rc_visard 65 stereo camera	rc_visard_65 camera is responsible for detecting the nut and alignment rod and publishing the detected grasping point on the THOMAS world model. The MRP uses the SMC MHS 2 63D pneumatic gripper with one pair of custom designed fingers to grasp and manipulate both the nut and alignment rod.	
Pneumatic gripper for damper's manipulation and ROBOCEPTION rc_visard 160 stereo camera	rc_visard_160 camera is responsible for detecting the uncompressed / compressed damper and publishing the detected grasping point on the THOMAS world model. The SMC MHL 2 25D pneumatic gripper and another pair of fingers is capable to grasp and manipulate each damper's model.	
Real Sense Sensor	Real Sense sensor is used in THOMAS automotive pilot case in order to detect human motion and Human Robot Interaction (HRI) through gesture's recognition but also for the in-cell navigation.	

2D camera	This camera is used for MRP's localization inside the MPP working area.	
Microsoft HoloLens AR glasses	AR glasses used as the human side interface allowing the human to provide feedback on the Station Controller.	
Safe Incremental Encoders	Automotive pilot case's MRP is equipped with one safe incremental encoder per each motor inside the robot. MRP includes 2 motors for each wheel. In this case, MRP consist of 8 encoders responsible for the motion of the robot in a safety certified way.	
Emergency buttons	Four safety buttons have been installed around the MRP in case of malfunction.	
Remote Emergency button	One remote safety button has been integrated in MRP's controller allowing operator to stop MRP's navigation and its arms motion without approaching the mobile platform.	
Safe position sensor	Used for monitoring position in a safety certified way.	

End-effector Safeguarding (EES) sensor	EES system will be installed on the final version of OPS arms providing safeguarding services	
3D Safety Camera	3D safety camera will be mounted above the compression machine working area to monitor the 3D volume. Moving obstacles will be detected inside of field of view of camera	
SICK FlexiSoft safety PLC	This safe PLC is used for integrating the inputs / outputs from all the involved safety related hardware on the robot. The safe logic configuration will be deployed on this PLC so to regulate the safety functions during execution.	
Force and Torque Control Device	On each of the OPS arms there is mounted a force sensor which is 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	 
Mobile Product Platform (MPP) controller interface	THOMAS MPP control based on a Raspberry Pi3 single board computer connected with MPP's controller.	

6.3.2.1. Mobile product platform implemented in LMS Facilities

As previously commented in paragraph 5.1.3 of this document, Mobile Product Platform (MPP) is included in THOMAS OPS able to navigate and transfer the final product inside THOMAS shop floor. THOMAS MPP consists of an Automated Guided Vehicle (AGV) and a custom upper structure model (Figure 19). Additional AprilTags have been added on the MPP so to facilitate the process perception tasks such as detection and pose estimation of assembly parts, detection of MRP – MPP distance to achieve static and mobile docking.

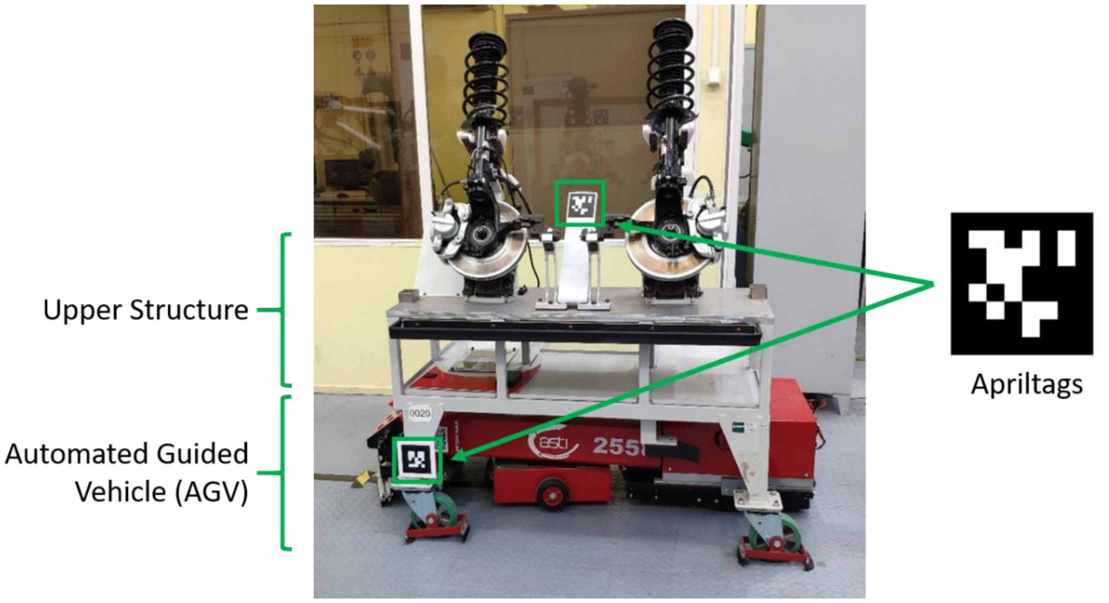


Figure 19: THOMAS Mobile Product Platform

6.3.3. Software components of automotive OPS at LMS

6.3.3.1. 2D based SLAM navigation

Under the first implementation of the automotive scenario the conventional 2D laser scanner based navigation using the SICK S300 laser scanner simulated data was tested (Figure 20). The deployment of a dedicated navigation planner, the MRP was able to reach the final goals though optimized and collision free trajectories. In this way, MRP's reachability in scenario's workstations but also object's manipulation has been successfully tested. Planned navigation trajectory can be visualized using ROS RViz.

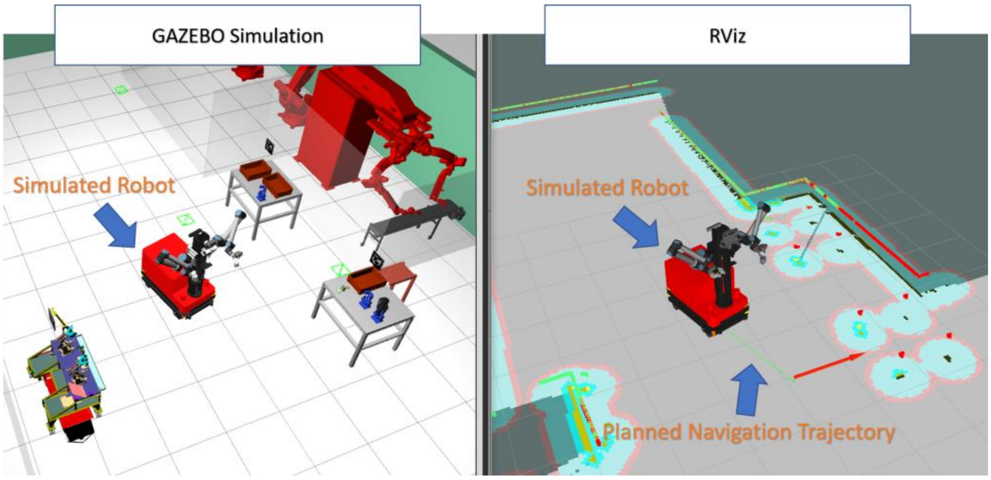


Figure 20: Navigation action using simulated MRP model

Following this virtual validation, during the second period of the project, the 2D based SLAM navigation has been tested with the physical MRP at LMS set up. The navigation planned used the information from the Digital world model, published from SICK MicroScan3 laser scanner and the visualization of the planned trajectory can be seen in Figure 21. The accuracy achieved was around 5-10 cm.

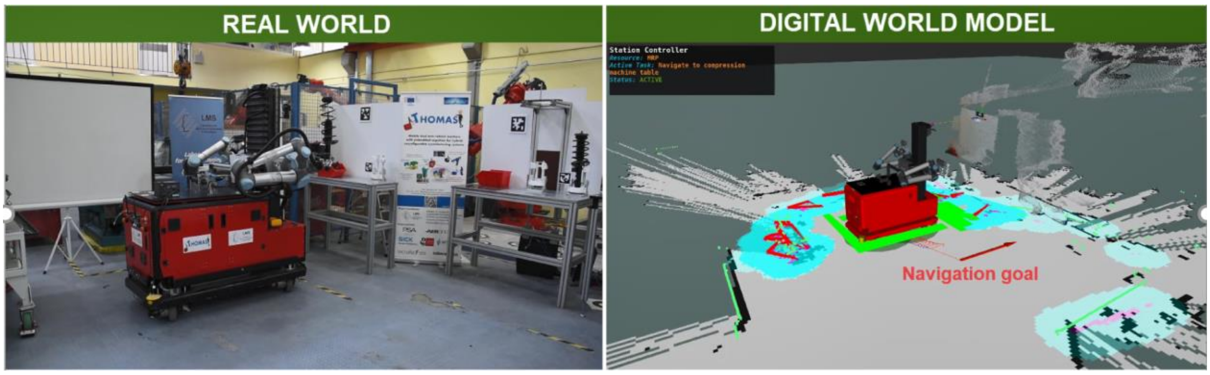


Figure 21: Navigation action in the real world

6.3.3.2. 3D sensor data based accurate localization

As mentioned in the previous sub-section, during the testing of the conventional navigation algorithm several navigation errors were detected not allowing the robot to reach with accuracy its final goal. A strategy for compensating these errors were needed concluding in the usage of 3D sensor data and the localization based on apriltag detection. Apriltags have been placed inside the simulation environment, on each of the three working areas. In this way it is ensured that the MRP will reach the final navigation goal without any navigation errors. The only requirement is that after each navigation action, the respective apriltag needs to be inside robot camera's view (Figure 22). A 3D sensor has been used for the implementation of this module.

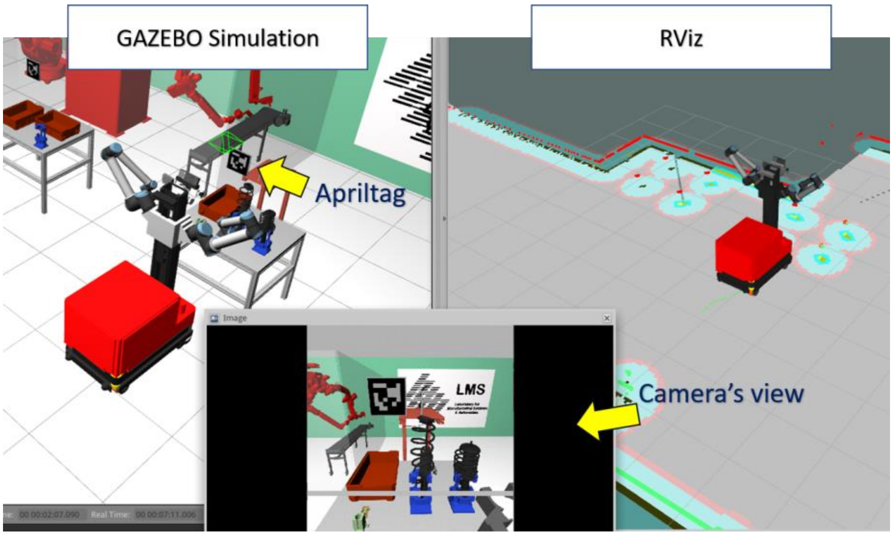


Figure 22: MRP accurate localization process in simulation

Following the same principles, the localization module developed for the simulation has been adjusted so to much the requirements of the real world. The Intel Realsense 3D camera that is placed on the MRP torso was used for the detection of the apriltags. After several testing, it is concluded that through this localization strategy the navigation error is reduced to around 1 cm. This error is in the acceptable range considering that further localization takes place in the robot arm level so to estimate the poses of the parts to be assembled. This virtual docking is supplemented by the safety system that detects the working tables using the laser scanner information. When the table is detected in the expected proximity the safety system verifies that the virtual docking has been performed successfully (Figure 23).

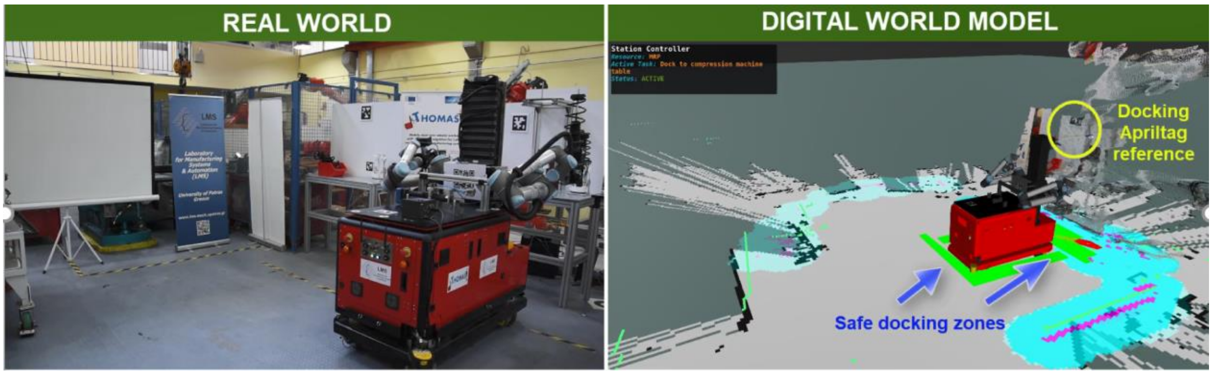


Figure 23: MRP accurate localization process in real world

6.3.3.3. System for enabling docking and collaborative operation of mobile units

THOMAS project introduces a new perception system for virtual docking and co-navigation processes of two mobile platforms. As presented in deliverable D3.4, this mechanism is based on an Apriltag's detection process using one 2D camera sensor placed on the MRP. The MRP executes navigation actions in order for the MRP's camera frame to reach a predefined distance value from Apriltag's down left corner. In parallel with MPP's navigation action, the MRP starts to execute navigation actions in order to maintain the distance between MPP's Apriltag and MRP's 2D camera (Figure 17).

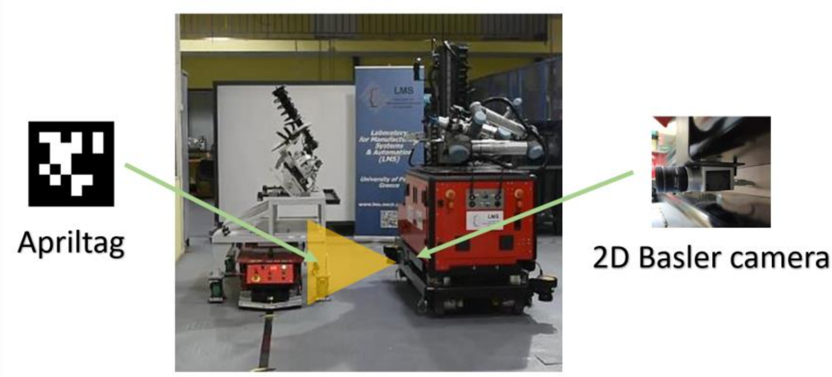


Figure 24: Mobile platforms co-navigation inside THOMAS shop floor

MRP's motion is going to be either decelerated or stopped in case the active safety fields are infringed by an operator or any other resource. As presented in deliverable D2.3, THOMAS safety system includes 2 types of safety fields. Protective field used to stop MRP's motion in case of moving obstacles detection inside this field (field in green colour around MRP's platform). On the other hand, detection field used to identify that MRP is docked with the MPP (field in red colour). Mobile platforms' co-navigation can't be executed if MPP's body doesn't recognized by the safety system.

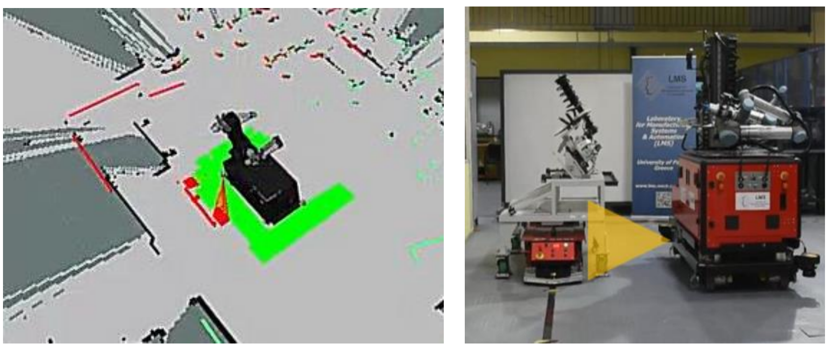


Figure 25: THOMAS Mobile Product Platform

6.3.3.4. Deployment of THOMAS Station Controller intermediate prototype in LMS premises.

THOMAS Station controller is a high-level mechanism responsible for the communication between all sensors and hardware components included in the execution (Figure 26). In this way, station controller is able to send commands regarding navigation, object detection and robot arm motion actions relative to the detected models. Under the station controller the human operator is also integrated through specially designed human side interfaces. In the current set up, the HOLOLENS AR glasses has been used as the human side hardware device.

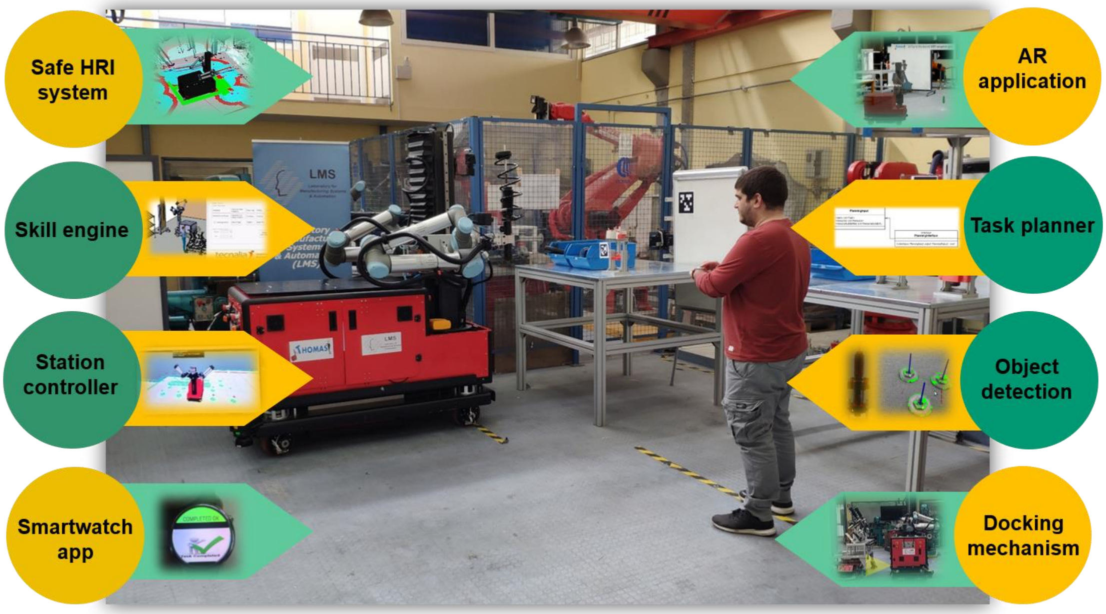


Figure 26: Station Controller developed under THOMAS project

7. OPS AERONAUTICS USE CASE

Under this section, the aeronautics OPS is presented providing details on the deployment of the navigation, static docking, automatic tool changing and perception modules.

7.1. General Overview

Three aeronautics processes have been addressed at this use case, two mainly processes, drilling and sanding processes, and with minor priority level the riveting inspection operation.

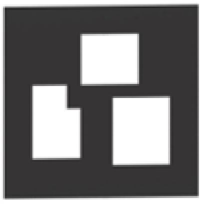
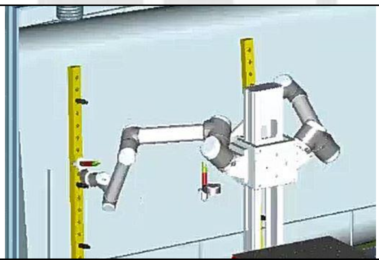
7.2. Simulated set up of the aeronautic OPS at TECNALIA simulated layout

For testing the THOMAS OPS in aeronautic use case, the three processes have been developed on different parts of the same wing. In order to perform one process, THOMAS MRP will navigate to the tool station and will get the required tool to perform this process. When the task is finished it will move again to the tool change table in order to change its tools and perform another process. Then these actions will be repeated in order to perform the new process. Figure 27 shows a drawing of the aeronautic use case layout.

Figure 27: Simulation of Layout of the final use-case at AERNNOVA

Table 4 lists in detail all the hardware components that are included in THOMAS OPS for supporting the aeronautic use case scenario and are required for all required processes execution.

Table 4: Hardware components in THOMAS Aeronautic pilot case

Hardware Components	Simulated model
Drilling Template	
AprilTag	
IDS CAMERA	
Pneumatic Drilling Machine SETITEC ADU	
Pneumatic sanding machine	

7.3. Physical set up of the aeronautic OPS at TECNALIA

THOMAS aeronautics pilot case preliminary setup has started to be constructed in TECNALIA and DGH premises based on the simulated layout presented in previous figure. The 3D simulation layout will be constantly updated alongside with physical layout's updates.

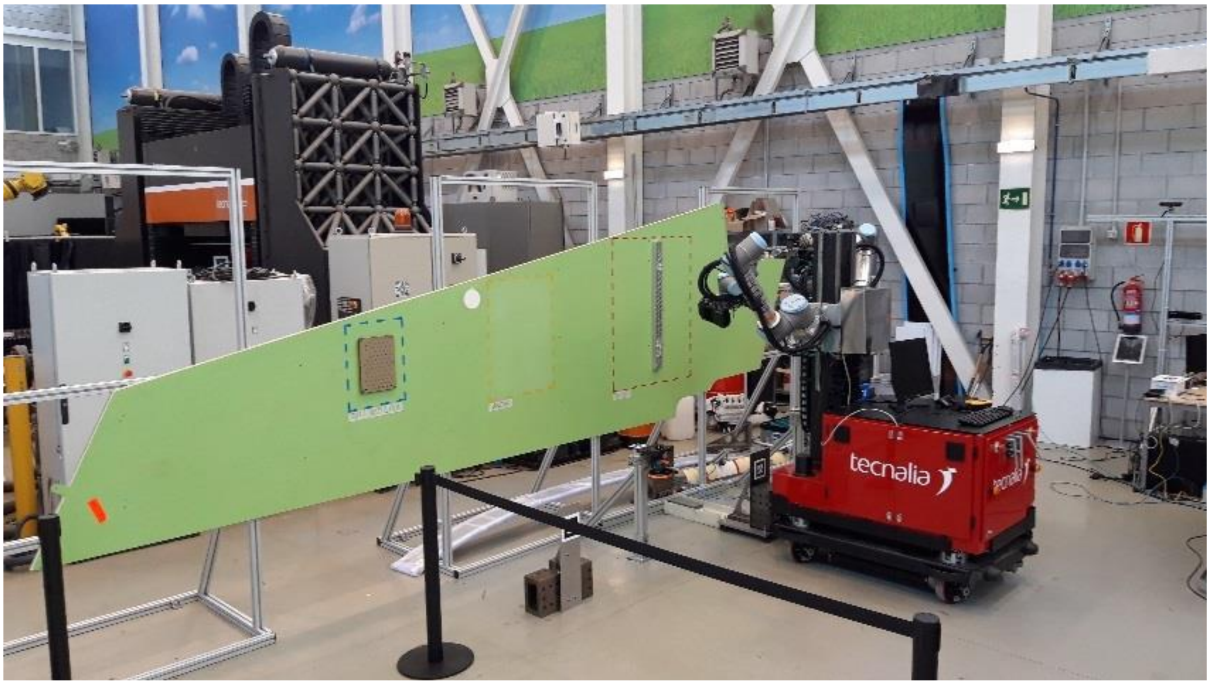
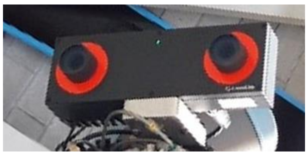
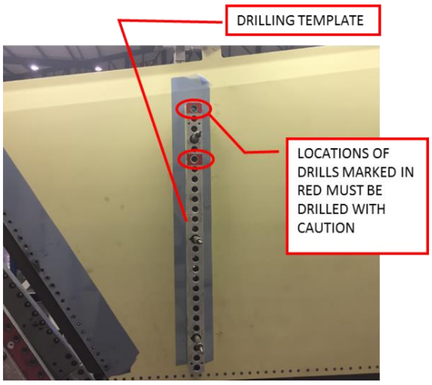
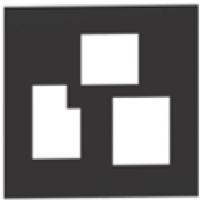


Figure 28: Actual demonstrator of THOMAS Aeronautics use case in Tecnalia laboratory

The already existing components are presented in the following table (Table 5):

Table 5: Available components in TECNALIA premises for THOMAS aeronautic pilot case

Hardware component	Use	Robot Configuration	CAD model OR real picture
ROBOCEPTION rc_visard 160 stereo camera	Template's detection	Right arm configuration	
ROBOCEPTION rc_visard 65 stereo camera	Detailed hole detection	Left arm configuration	
Drilling Template	Template for drilling	Human	

Hardware component	Use	Robot Configuration	CAD model OR real picture
AprilTag	In-cell navigation to drilling area	In from, and arms of OPS n1	
IDS CAMERA [19]	AprilTag detection for static docking	Front of the robot	 
Real Sense Sensor camera [6]	Used for adding the 3D dimension to the navigation system	On robot Torso	
Pneumatic Drilling Machine SETITEC ADU [17]	Preform drillings	Right arm	

Hardware component	Use	Robot Configuration	CAD model OR real picture
Pneumatic sanding machine [15]	Sanding surface	Installed in both arms for to reduce the cycle time	
Rivet detection camera (to be decided if Gocator 3D Smart Sensor or Structure light cameras are used)	Rivet detection	Right arm	 
Force and Torque control Device [11]	These sensors provide information about the forces and torques applied to the tools as well as useful information for programming the arms	Depending the number of pneumatics machines	

7.4. Navigation

Cell to cell navigation is required inside the aeronautic use case scenario as well as the static docking capability of in cell navigation. The THOMAS navigation system intermediate prototype is presented in the D3.6 where cell-to-cell navigation modules are presented.

7.4.1. 2D Navigation on working area

Figure 29: MRP Cell to cell navigation

MRP_n1 navigation is composed of standard 2D laser-based planer. Besides the navigation and localization methods implemented, some other actions were necessary to improve navigation efficiency and safety, namely the improvement of the wheel low level management and the use of dynamically adaptable robot's footprint to take into account the robot's arm configuration while navigating.

7.4.2. 3D Perception based navigation

The laser-based navigation has its limitations. The main limitations are: robot re-localization problems (robots must start navigation always at a known point in their map) and the limited 2D information about the obstacles inside MRP's working area. To address these problems 3D perception is integrated inside THOMAS navigation module (Figure 30). In addition, the viability of using 3D semantic maps have been developed in this period and validated using MRP_n1.

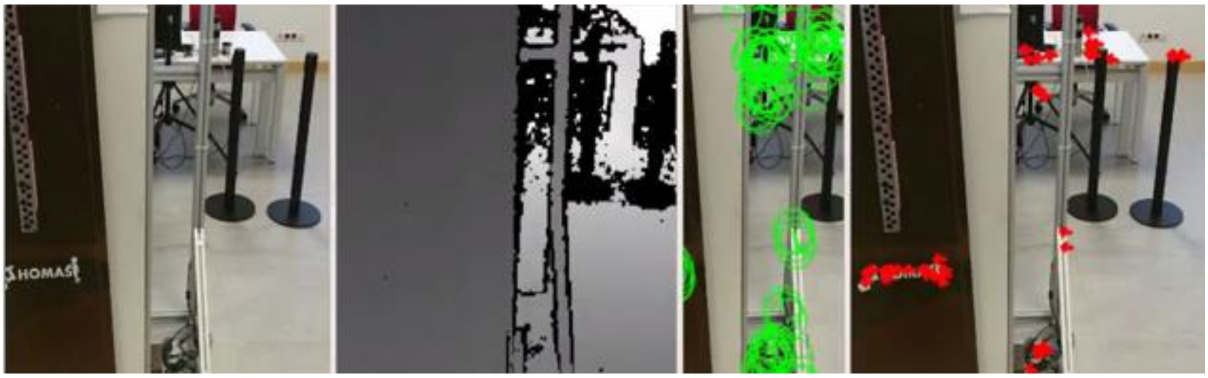


Figure 30: Initialization view

Figure 31: Final 3D map of the environment and robot trajectory

7.4.3. Static Docking: Accurate positioning with respect to a static reference

The static docking is achieved using a vision system and one reference marker. The system is based on a proportional control that maintains and ensures, with the desired tolerance, the position of the robot with respect to the marker. Static docking is done in a specific module which can provide both compressed air than electrical power (Figure 32).

Figure 32: Final docking system with charge station and marker installed

7.5. Processes

7.5.1. Tool exchanging system

One of the main features of the aeronautics case is the ability of THOMAS MRP to travel to different workstations for performing different type of operations. In this particular use case, three different use cases are investigated: a) drilling, b) inspection of rivers and c) paint sanding. To enable this flexible behaviour from a hardware and tooling point of view, a tool exchanging system is being designed to enable tool exchanging at the AERNNOVA use-case. Figure 33 presents the mechanical structure of the tool exchanging table.

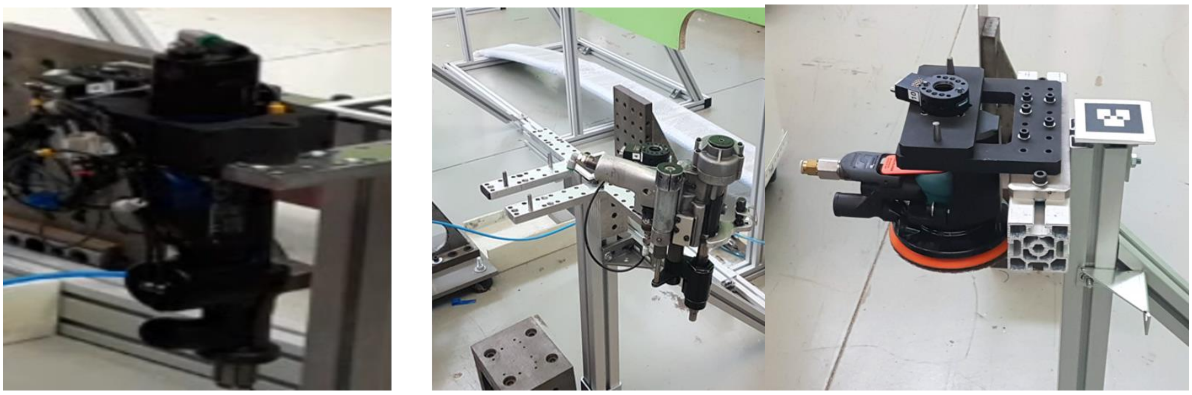


Figure 33: Mechanical design of the tool exchanging table

7.5.2. Drilling

An intermediate prototype of the drilling process has been developed and is demonstrated at TECNALIA's premises. This intermediate version of THOMAS OPS solves the problem of navigation to the operation station, drilling template detection using ROBOCEPTION rc_visard stereo cameras and drilling machine insertion at the template holes.

Figure 34: Drilling process demonstrator at TECNALIA facilities

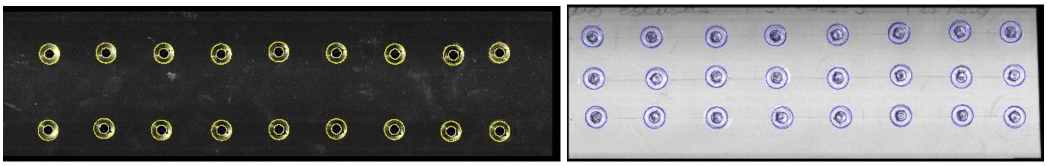
For making possible to get the 0.3mm precision of the vision-based CAD matching system, one projector has been installed on the MRP's torso are shown in next figure.

Figure 35: Projector integration for increasing CAD matching system accuracy

Last but not least, drilling quality tests must be done to validate the drilling process. Also, robustness for the vision system must be demonstrated for multiple template detection.

7.5.3. Inspection of rivets

A bunch of tests has been done with different types of sensors to select the one that best fits the THOMAS project's goals in terms of cost, reliability, precision and connectivity with the overall THOMAS system. The figures present the final status of the tested structure light camera (Photoneo and Zivid). Precision and reliability of these tests show that the structured light camera is the correct alternative for to execute this process. The Profilometer solution presented in deliverable D6.1 is the best option to measure rivets in precision but it is required to have relativity movement with the inspected part. For this reason, it would be better to use a structure light vision camera.



	height_difference		clasificacion
0	-0.081285	0	'OK'
1	0.0434306	1	'OK'
2	0.0104713	2	'OK'
3	0.0181832	3	'OK'
4	-5.83577e-005	4	'OK'
5	0.00657069	5	'OK'
6	0.00272402	6	'OK'
7	0.0339279	7	'OK'
8	0.013254	8	'OK'
9	0.0816296	9	'OK'
10	-0.00484887	10	'OK'
11	0.00472943	11	'OK'
12	0.0177129	12	'OK'
13	0.0173603	13	'OK'
14	0.00692154	14	'OK'
15	0.00998979	15	'OK'
16	0.00696357	16	'OK'
17	0.0301805	17	'OK'
18	-0.00537547	18	'OK'
19	0.0315945	19	'OK'
20	0.0120088	20	'OK'
21	0.011421	21	'OK'
22	-0.0232455	22	'OK'
23	0.02213	23	'OK'

Figure 36: Measurement tests with Structure light camera

Independently of the sensor selection, the skill system that will make the robot able to integrate the rivet inspection process at the aeronautic use case will be developed in the following period.

7.5.4. Paint sanding

The development of this process is in progress during this period of the project. The tool which is going to be used by the robot to perform the paint sanding operation has been selected and it is visualized in the following figure.

Figure 37: Sanding device used in Aeronautic use case

Currently, this pneumatic device is used by human operators to manually perform the sanding process. Under the scope of THOMAS project, a mounting system will be design and integrated towards the automatic use of the device by the THOMAS MRP_n1. In particular, THOMAS MRP_n1 will be equipped with a gripping system for sanding device's mounting at the end of MRP's arms.

Sanding process has been tested on the real parts of the aeronautic pilot case after its successfully test over metallic curved surfaces. As presented in following figures, the shape of the actual parts is more challenging, however, thanks to the optoforce force/torque sensor installed on the left arm of the robot, MRP's arms are able to follow the surface of the parts assuring a constant pressure and contact.

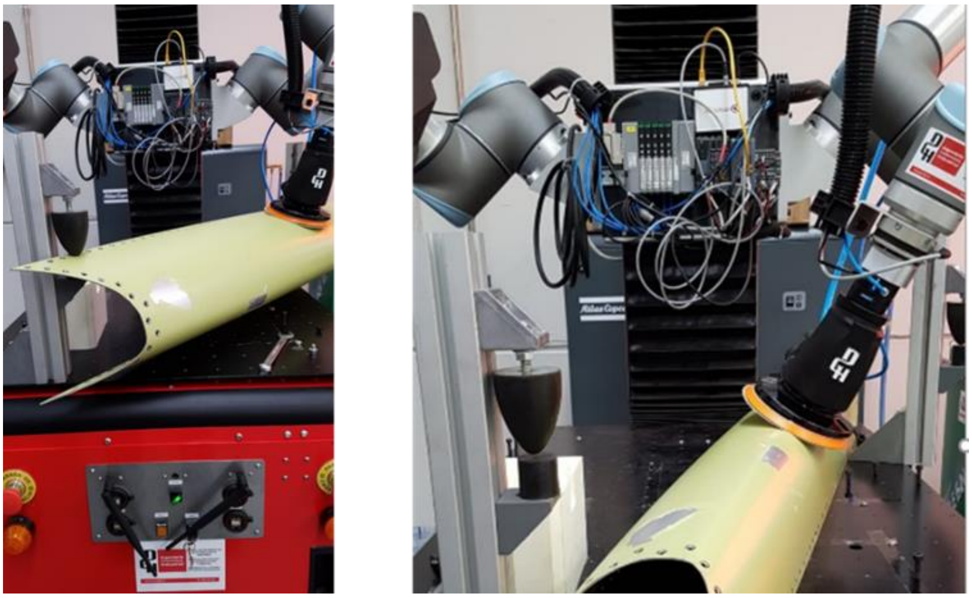


Figure 38: Sanding Test on curved parts

After the experiments performed at DGH's premises for validating the feasibility, the technology has been transferred to THOMAS MRP_n1 inside TECNALIA's premises.

Figure 39: Sanding operation in TECNALIA demonstrator

7.6. Safety concept

Aeronautic use case will be used to partially demonstrate the safety modules installed on the MRP_n1.

7.6.1. Safety during operation

Aeronautic use case's MRP is equipped with two safety laser scanners (SICK S300 laser scanners) targeting to change to Microscan 3 laser scanners by the end of the project. They provide a field of view of 360º together. They are connected to a general safety relay that can switch the robot down on person detection.

No humans will be able to work near the robot during operation. If a person enters the security limit of safety fields of the robot the system will stop in an emergency stop.

7.6.2. Safety during navigation

Given the safety configuration of the robot hardware. Navigation, from the point of view of safety, is restricted to open areas where humans are a fair distance far from the moving area of the robot.

For practicality reasons inside the aeronautic use case. Navigation safety fields will be modified by software following the dynamic safety zone paradigm where the zones are made wider in the direction of movement of the robot and dependent on the speed of the robot and narrower in the rest of the directions. This makes the robot able to navigate in workshop areas of Aeronautic safely for the demonstration purposes of the project, but this is not a certifiable solution. For being certifiable the robot should have safe encoders added to the laser system and the dynamic safety zone paradigm would need to be programmed on a safe PLC device. This will be demonstrated at the MRP.

8. CONCLUSIONS

This document summarizes all the developments of the enhanced version of THOMAS Open Production Station (OPS) until the M36 of the project. At this latest version, THOMAS OPS includes all the hardware and sensor components required for the execution of all processes inside both use cases of THOMAS project. The use of these components in each of the pilot cases has been documented in D7.3 (1st version automotive pilot) and D7.4 (1st version of the aeronautics) that were submitted on M36.

Following the presented results for THOMAS OPS, the project partners have achieved the defined technical milestones concerning the expected features to be implemented by M36 as listed following table.

Table 6: Technical Milestones for THOMAS OPS.

Project Technical Milestones	M36
Mobile dual arm manipulator for flexible operations – **1st and 2nd prototype**	■
System for enabling docking and collaborative operation of mobile units – **1st and 2nd prototype**	■
Generic Perception skill library providing Application-ready solutions for flexible robotics guiding: **a) Object & Process, b) Navigation, Human Detection**	■
Mobile platform navigation software library, complementing the traditional SLAM with vision-based accurate localization – **1st prototype and 3nd prototype**	■
Fenceless environment monitoring and robot control software library: **Human Tracking, and HI Interaction**	■
Automatic programming software library providing an easy operation programming for product-variants – **1 framework prototype and final version (FP, FFV)**	■
Global communication & synchronization framework - Network of services **a) Resource Shared Perception, b)Resource Level Reasoning, c) Workload Balancing**	■
Dual arm robot autonomy and cooperation level: **a) Navigation, b) Static Operation, c) Operation while moving, d) Cooperation with other robot**	■
Task sharing level between human and robot in the same workspace: **Separation And Common workspace**	■

THOMAS consortium will continue working on the optimization and the fine tuning of all technologies inside THOMAS OPS by integrating the final results delivered by the individual technologies WPs. The updated and final version of THOMAS OPS is scheduled to be presented in the deliverable D6.3, 6 months before the end of the project (M42).

9. GLOSSARY

MRP	Mobile Robot Platform
OPS	Open production Station
MPP	Mobile Product Platform
ROS	Robot Operating System

10. REFERENCES

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

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

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

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

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

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

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

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

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

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

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

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

[13] URL SICK Safety Encoder DFS60S https://www.sick.com/ag/en/encoders/safety-encoders/dfs60s-pro/c/g309664

[14] URL SICK Non-contact safety switches IN3000 Direct https://www.sick.com/ag/en/safety-switches/non-contact-safety-switches/in3000-direct/c/g207151

[15] URL Dynabrade Orbital Sander https://www17.dynabrade.com/view-product.php?mn=59014

[16] URL HSTOOLING Spacematic M1000 https://www.hstooling.com/spacematic.html

[17] URL Desoutter drilling tool ST1200 In line https://www.desouttertools.com/tools/7/advanced-solutions-for-aerospace-applications-seti-tec-line/70/pneumatic-advanced-drilling-units-adu/702/adu-heads/p/STSE1263/st1200-in-line

[18] URL Basler camera https://www.baslerweb.com/en/embedded-vision/embedded-vision-portfolio/embedded-vision-cameras/

[19] URL IDS sensor https://en.ids-imaging.com/store/ui-5240cp-rev-2.html