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

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Summary:

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

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3. EXECUTIVE SUMMARY

The final version of THOMAS OPS includes all the components required for the realization of THOMAS vision to create dynamically reconfigurable shopfloor utilizing autonomous, mobile dual arm robots that are able to perceive their environment and through reasoning, cooperate with each other and with other production resources including human operators. Both versions of THOMAS Mobile Robot Platforms (MRP) final versions are integrated and tested in LMS and TECNALIA premises. In addition, the THOMAS Mobile Product Platform (MPP) which is able to cooperate with other mobile resource like the MRP has been successfully integrated in automotive use case's demonstrator (Figure 1).

The main outcome of this period concerning this WP is the updated design and manufacturing of THOMAS Mobile Robot Platform focusing on addressing the safety requirements of both end users.

Integration, testing and setup activities of the different prototypes and required peripheral hardware components (sensors, grippers, etc.) configure a common system that will allow the realization of the THOMAS target. This common system stands for THOMAS Open Production Station as a product (OPS) and this deliverable presents the final version of THOMAS OPS as developed until the end of M42 of the project.

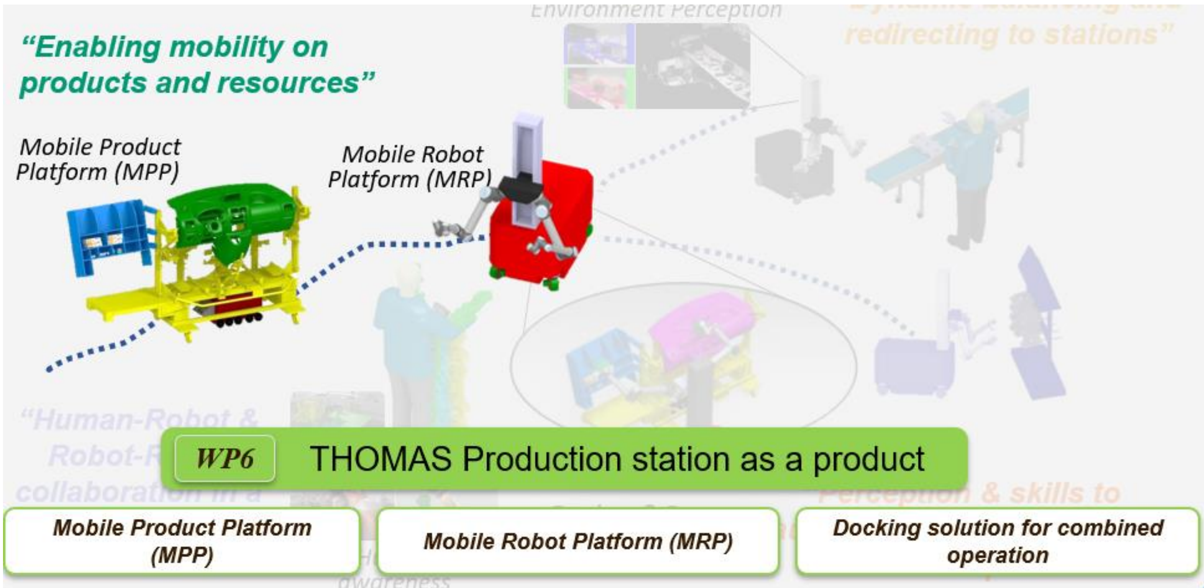


Figure 1: THOMAS Open Production Station (OPS) as a Product

THOMAS individual technologies developments have been driven from the early beginning of the project by the industrial use cases, namely the automotive and the aeronautics pilots. Thus, during the finalization phase of the OPS, testbed, integration and setup processes have been implemented at LMS and TECNALIA premises based on the automotive and the aeronautics use cases requirements respectively. An updated version of the mitigation plans for both use cases of THOMAS project are presented in this document too.

4. Introduction

The final version of THOMAS OPS, consists of the technologies developed inside WP2 to WP5 which have been integrated, tested and finally implemented in hardware and software dimension in the following way:

- WP2: THOMAS Initial Safety Concept and Human Robot Interaction (HRI) mechanisms
- WP3: Perception methods for multiple object detection as well as for accurate navigation
- WP4: Skills based robot programming
- WP5: Station Controller for Execution control and orchestration.

Details on the individual OPS n1 and n2 status can be found in the different WPs public deliverables available through THOMAS public website (http://www.thomas-project.eu/deliverables/).

As the main integration, DGH is responsible for majority of the hardware integration activities to provide the MRPs and MPP prototype and INTRASOFT is leading the packaging of software components.

In the period of the project (M36-M42), the tasks performed under the THOMAS OPS integration activities may be summarized as follows:

- Integration of the final version of MRPs.
- Sensors and tooling design and integration in each use case demonstrator.
- Docking mechanisms design and test for highly accurate cooperative assembly.
- Software modules integration and packaging. Integrating and implementing in final demonstrators use cases.

Objectives:

The objectives have already presented in deliverable D6.1 and the actual status of each objective on M42 of the project is presented below:

Table 1: Current status of WP6 objectives on M42

Objectives	Status
Increase reconfigurability. The mobile resource MRP will be able to change workstations based on production needs	
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.	
Increase Manufacturing Line flexibility. The MRP will be able to follow the mobile product (MPP) while operating.	
Support multiproduct Manufacturing Line. The MRP integrated with the perception modules will be able to dynamically detect and adapt in changes in the process.	
Increase ergonomy and safety conditions of human work. THOMA OPS, integrating the safety & interaction mechanisms will use the MRP for performing the difficult operations.	

5. THOMAS OPEN PRODUCTION STATION AS A PRODUCT OVERVIEW

THOMAS OPS consists of all the hardware and the software components required for all operations' execution inside both industrial use cases of THOMAS project. MRP version 1 and version 2 are the main components of THOMAS OPS based on the fact that the main solution introduced inside THOMAS project is the creation of re-configurable industrial shopfloors based on mobile robotic units. The software modules developed under the WP2-WP5 of the project and their implementation inside THOMAS use case for the execution of any operation are included inside the OPS. The content of THOMAS OPS may be summarized as presented in Figure 2.

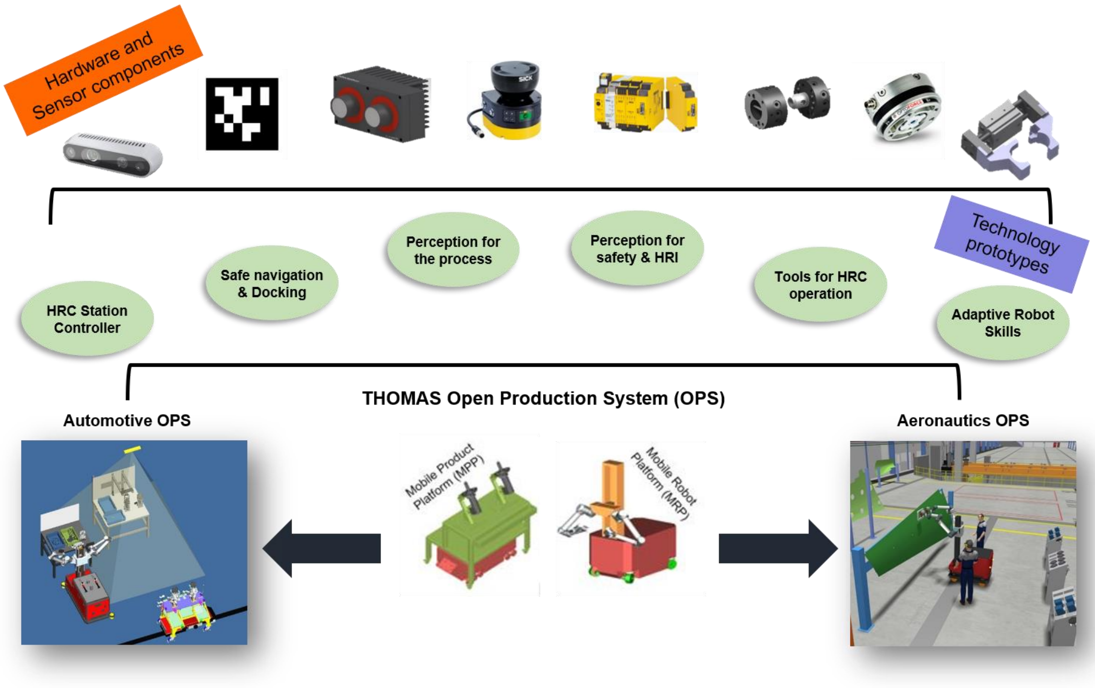


Figure 2: THOMAS Open Production Station as a Product Overview

5.1. THOMAS Mobile Resource

5.1.1. THOMAS Mobile Robot Platform (MRP)

As already presented in deliverable D6.2, until M42 of the project both MRP n1 and n2 have been tested inside LMS and TECNALIA premises and are fully functional. Both MRP versions have been tested in industrial use cases from the end users as presented in the deliverable of WP1. During these tests, both the hardware and the software components integrated into THOMAS industrial demonstrators. The intermediate version of THOMAS MRP has already be presented in deliverable D6.2 as the robotic resource of the automotive use case scenario demonstrated in TECNALIA's premises (Figure 3).

Figure 3: THOMAS MRP 1st version at TECNALIA premises

The 2nd version of the MRP at LMS premises used inside the automotive use case is presented in Figure 4.

Figure 4: THOMAS MRP 2nd version at LMS premises

The main components selected to be installed on the automotive use case's MRP for the testing and the realisation of THOMAS safety concept are presented in Figure 5. The safety concept has already detailly presented in deliverable D2.4 on M18 of the project. The hardware and software components required for the safety concept have been presented in deliverable 6.2 delivered on M18 of the project.

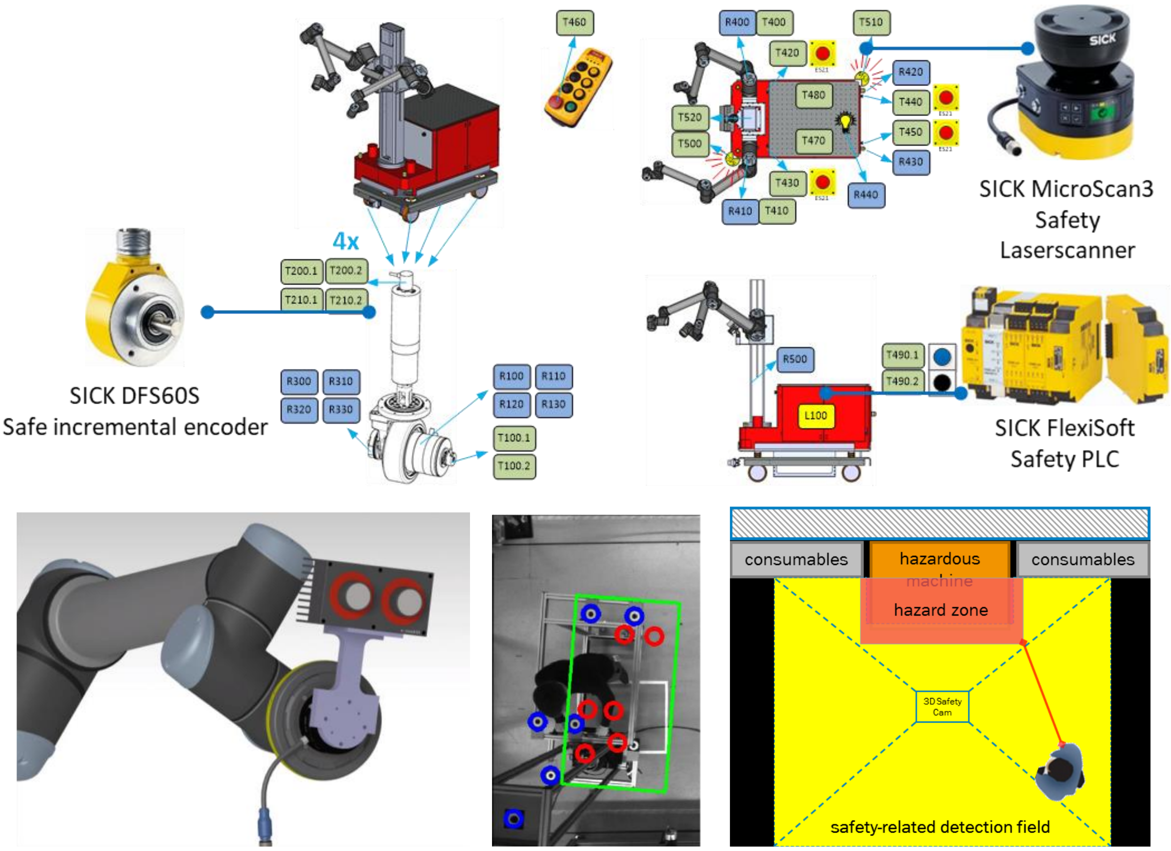


Figure 5: Safety concept design for the MRP (MRP_n2) and safety devices of THOMAS OPS

5.1.2. THOMAS Mobile Product Platform (MPP)

The final version of THOMAS Mobile Product Platform (MPP) has already be presented in deliverable D6.2 and no further updates need to be documented. The main use of THOMAS MPP inside the automotive use case is to transfer the assembled product between the workstations of the shopfloor enabling the parallel execution assembly and navigation operations. More details are presented in the following sections.

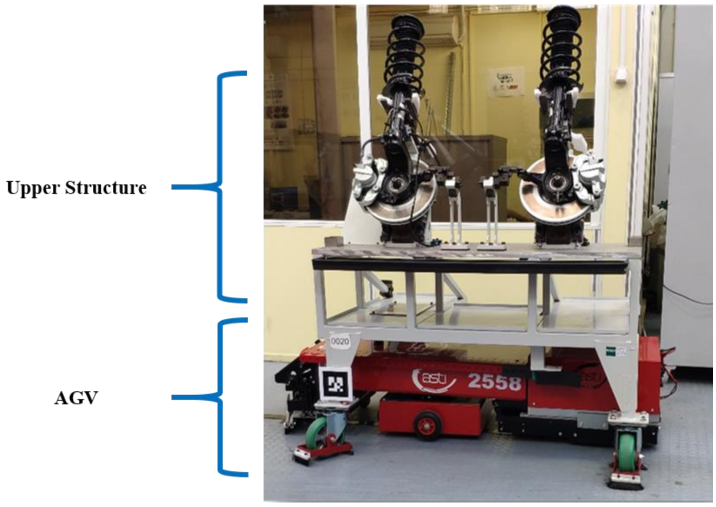


Figure 6: THOMAS MPP available in LMS premises

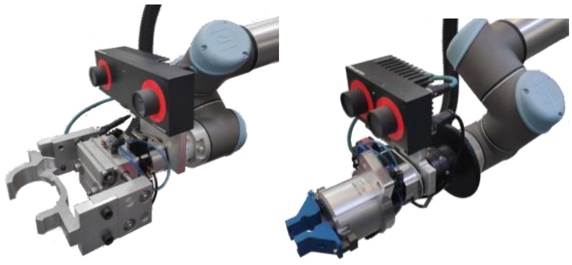
5.2. Selection of sensor and tooling for THOMAS OPS

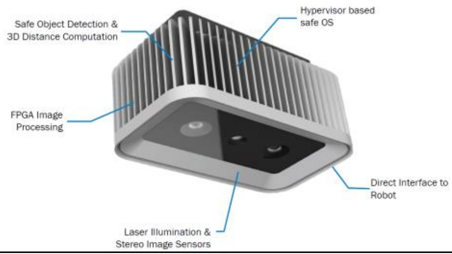
Sensors and tools of THOMAS OPS used under automotive and aeronautics pilot cases as already presented in previous deliverables of WP6, are listed in the following subsections of this document. New sensors added in THOMAS OPS for the successfully execution of all operations inside both use cases of the project during the last six months of the project are presented in sections 6 and 7 of this deliverable.

5.2.1. Selection and testing of tools for HRC operation

The final version of THOMAS OPS consists of several tools for enabling the safety and efficient cooperation of human and robot resources in the same shopfloor. These components which are listed in Table 2, have already presented in deliverable D6.2 and no further updates need to be documented.

Table 2: 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 [11],[5]	
RealSense 3D sensor for human detection and accurate navigation in 3D [6]	

2D cameras for localization and navigation [18],[19]	
Kinect 2 3D sensor for human detection and accurate navigation [7]	
SICK laser scanners for human tracking and safety zones implementation [8],[9]	
End-Effector Safeguarding sensor	
3D Safety Camera	
Microsoft HoloLens Augmented Reality glasses for human operator support during collaborative assembly [12]	

5.3. Software modules integration and packaging

In order to prepare the Open Production Station as a product, the software that has been developed and integrated needs to be packaged in a way that facilitates the deployment of the software to the related hardware as well as its future development, maintenance and integration cycles.

The integrated software includes the integration software as well as the software that implements different features, that is able to be deployed and work as a system.

In particular the packaging of the software includes all required message exchanges definitions between the different resources that are used for the collaborative tasks' execution, and the data stored in the repository. Furthermore, it includes the information that will be used for the scheduling and task planning, and the data structures needed by the digital instances of the production devices. For instance, the digital World Model and the skills definition.

In the next sections the different packaging formats used are explained and detailed lists are provided with the packaged software.

1.1.1. Packaging Practices

1. ROS Packages

As ROS is the platform used by many the state-of-the-art robotics software and also by THOMAS, the majority of the developed software modules has been developed in ROS and is packaged in the form of Software packages. Software in ROS is organized in packages. A ROS package can contain ROS nodes, ROS-independent libraries, datasets, configuration files, third-party software, or anything else that logically constitutes a useful module.

ROS packages provide useful functionality in an easy-to-consume manner so that software can be reused.

2. Docker Container

   In order to be able to easily deploy the software the different ROS Packages have been packaged in Docker Images. Docker Images are used to store and ship applications. They not only include the required ROS Packages but also contain and replicate the environment needed by all contained ROS Packages.

   Docker is a set of platform as a service (PaaS) products that uses OS-level virtualization to deliver software in packages called containers. Containers are isolated from one another and bundle their own software, libraries and configuration files; they can communicate with each other through well-defined channels. A Docker image is a read-only template used to build containers.

3. PLC programs

   A PLC (Programmable logic controller) is an industrial digital computer which has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, or robotic devices, or any activity that requires high reliability, ease of programming and process fault diagnosis. Software that runs in PLCs is packaged in the format required by each PLC vendor.

4. C# Solution

   The software deployed in the HoloLens hardware is contained in a C# Solution. A solution combines multiple projects, which are usually related to each other. A solution can contain different projects. For instance, a single solution could be used to package

   - A project containing common interfaces, producing a DLL
   - A project containing database definition, producing an RDBMS deployment script
   - A project containing server-side API implementation, producing an executable

1.1.2. Packaged Software Modules

The packaged software is listed below grouped per functionality. In particular the following lists are provided:

1. The Software Modules offering HRI and Safety functionalities, developed in WP2. These are listed in Table 3.
2. The Software Modules offering Environment and Process Perception functionalities, developed in WP3. These are listed in Table 4.
3. The Software Modules offering functionalities for Simplified robot programming and skills programming, developed in WP4. These are listed in Table 5.
4. The Software Modules offering functionalities for the integration (network of services), task planning and work balancing, developed in WP5. These are listed in
5. Table ***6***.

For each developed module the packaging method as well as the responsible partner have been included.

Table 3: HRI and Safety (WP2) Modules Packaging

HRI and Safety (WP2) Modules	Responsible	Packing
End-effector Safeguarding	SICK	ROS Package
3D Safety Camera	SICK	ROS Package
Safe logic	SICK	ROS Package, PLC
2D human detection	SICK	ROS Package
PCA Predictive Collision Avoidance	LMS	ROS Package, Docker Image
Gestures Recognition	LMS	ROS Package, Docker Image
Manual Guidance	LMS	ROS Package, Docker Image
AR App	LMS	ROS Package, C# Solution , Docker Image
HHRI	LMS	ROS Package, Docker Image

Table 4: Environment and Process Perception (WP3) Modules Packaging

Environment and Process Perception (WP3) Modules	Responsible	Packing
2D navigation	TECNALIA	ROS Package
3D localization - virtual docking	TECNALIA	ROS Package
April tag detection	ROBOCEPTION	ROS Package, Docker Image
Object pose estimation - CAD matching	ROBOCEPTION	ROS Package
Virtual docked moving	TECNALIA	ROS Package, Docker Image

Table 5: Simplified robot programming and skills (WP4) Modules Packaging

Simplified robot programming and skills (WP4) Modules	Responsible	Packing
Skills Library	TECNALIA	ROS Package
Execution Engine	TECNALIA	ROS Package
Cad Based Programming	TECNALIA	Microsoft Installer (CATIA Plugin)

Table 6: Network of services and work balancing (WP5) Modules Packing

Network of services and work balancing (WP5) Software Modules	Responsible	Packing
3D Environment constructor	LMS	ROS Package, Docker Image
Digital Twin	LMS	ROS Package, Docker Image
Robot program generator	LMS	ROS Package, Docker Image
Task Planner	LMS	ROS Package, Docker Image
Station Controller	INTRASOFT	ROS Package, Docker Image

6. OPS AUTOMOTIVE USE CASE

6.1. General Overview

As has already be presented in previous deliverables of THOMAS project, the main target of the project was to introduce a flexible dual arm robot-based system for executing assembly operations inside industrial shopfloor. In order to achieve its target, the assembly process of the front axle of a vehicle car by a dual arm mobile robot unit and a human operator is investigated in one use case of the project. The required hardware and software components of THOMAS automotive OPS for the successfully execution of the required assembly tasks but also for ensuring the safety co-existence of human and robot resources in the shopfloor are presented in the following sections.

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

The final version of the automotive use case simulated environment has been detailly presented in deliverable D6.2 and no further updates took place during the last 6 months of the project (Figure 7). The main purpose of building this environment was to validate the updated software components of THOMAS OPS before their implementation in the physical environment but also to evaluate the different task sequences of THOMAS task planner module.

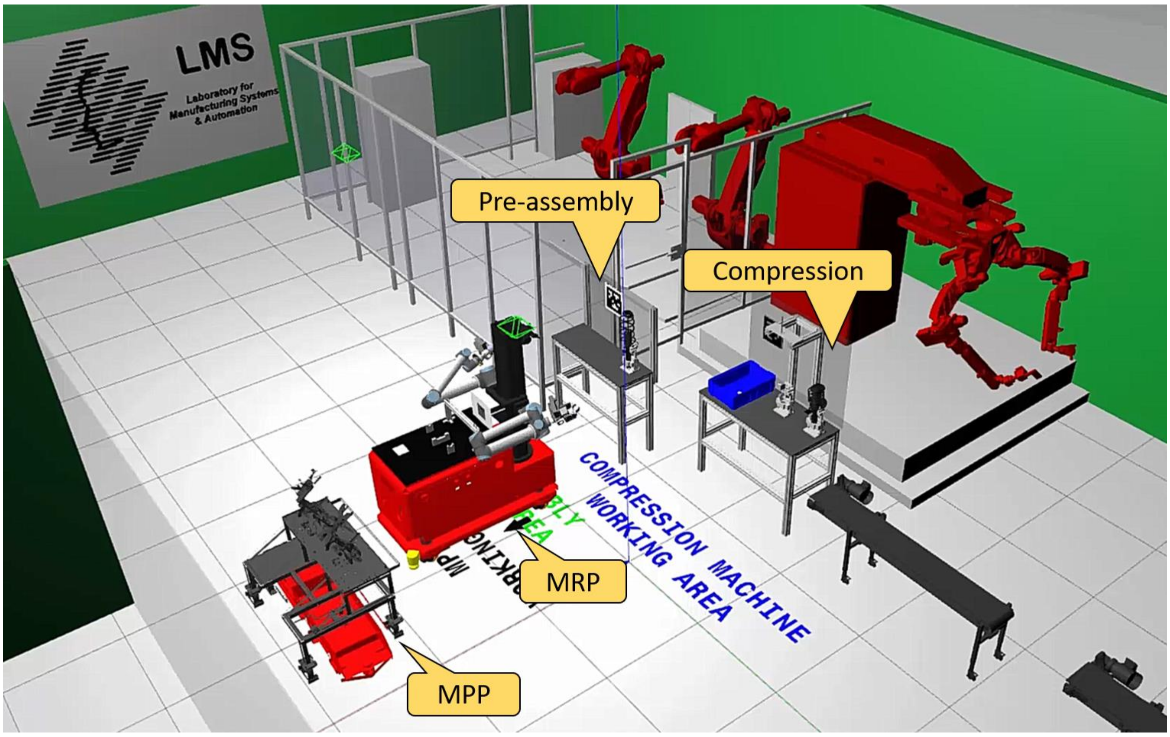


Figure 7: Simulation environment of THOMAS automotive pilot case scenario

All THOMAS OPS components required for the successfully execution of all operations inside the automotive pilot (Figure 8) have been detailly presented in deliverable D6.2.

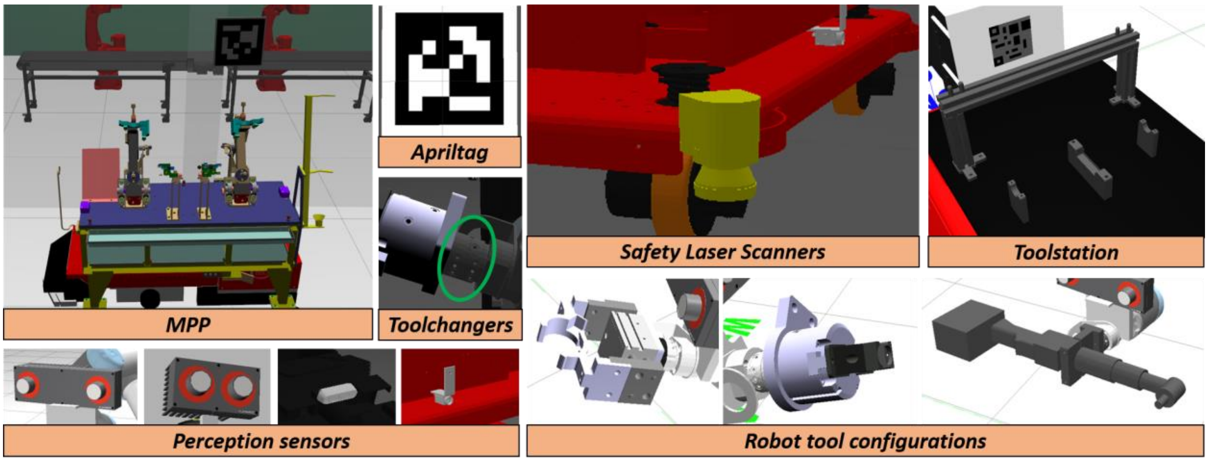


Figure 8: Hardware components in THOMAS Automotive pilot case

6.3. Physical set up of the automotive OPS at LMS

As has already been documented in deliverable D6.2, the automotive demonstrator setup has been prepared at LMS during the 2nd period of the project. Having available all the hardware components of the physical demonstrator, the software components and the technologies prototypes have been deployed inside automotive use case's physical environment. The main updates on the physical demonstrator of the automotive pilot took place on the MPP for the successfully execution of the screwing operation.

6.3.1. Automotive pilot set up at LMS

Until M42 of the project, the automotive pilot case demonstrator has been set up at LMS to test the complete workflow of the automotive use case. The final version of the demonstrator has already been documented in deliverable D6.2 and no further updates need to be presented.

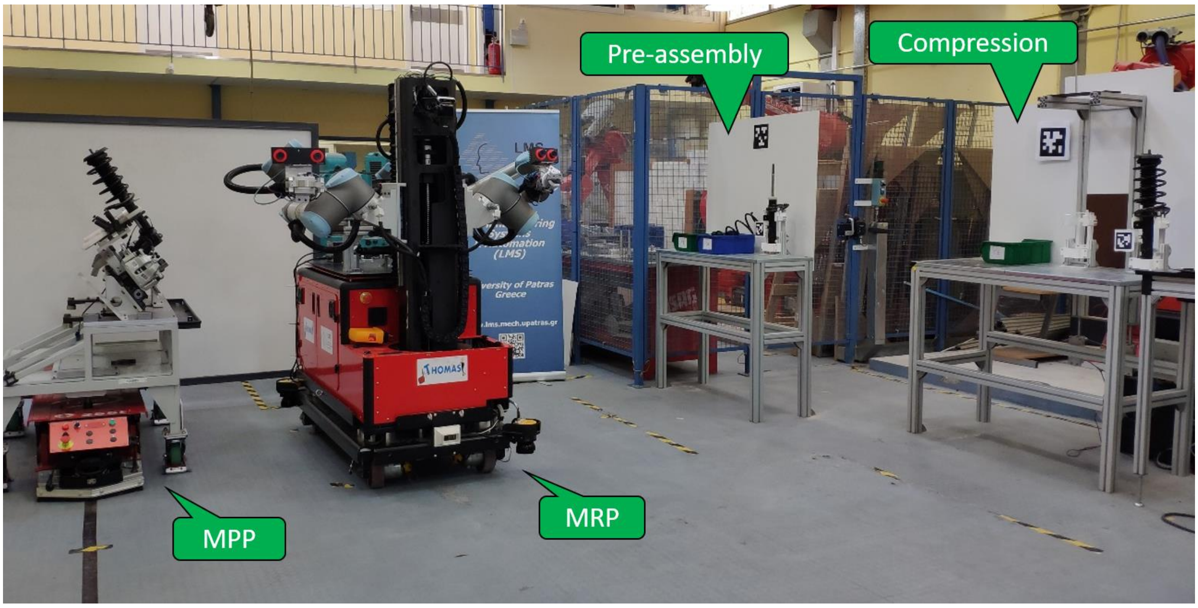


Figure 9: Automotive pilot case final test bed in LMS premises

6.3.2. Hardware components of the automotive OPS at LMS

The hardware components of THOMAS automotive OPS have been detailly presented in deliverable D6.2.THOMAS OPS consists of several components installed either inside the robot platform or inside the physical layout of the environment to ensure the safety collaboration of human operators and mobile platforms in the shopfloor (Figure 10).

Figure 10: Safety components of THOMAS Automotive use case OPS

Multiple sensors are included inside THOMAS automotive OPS for the perception of the environment. These sensors used either for different object's 3D detection process or for the detection of multiple sensors installed inside the physical layout of the demonstrator (Figure 11).

Figure 11: a) ROBOCEPTION rc_visard 65, b) ROBOCEPTION rc_visard 160, c) RealSense camera, d) Basler camera

Figure 12: Apriltags inside the physical layout

Based on the type of the operation performed by the mobile robot during the workflow of this demonstrator, two types of robotic configuration are used inside THOMAS project (Figure 13). The required components of each configuration have already presented in deliverable D6.2.

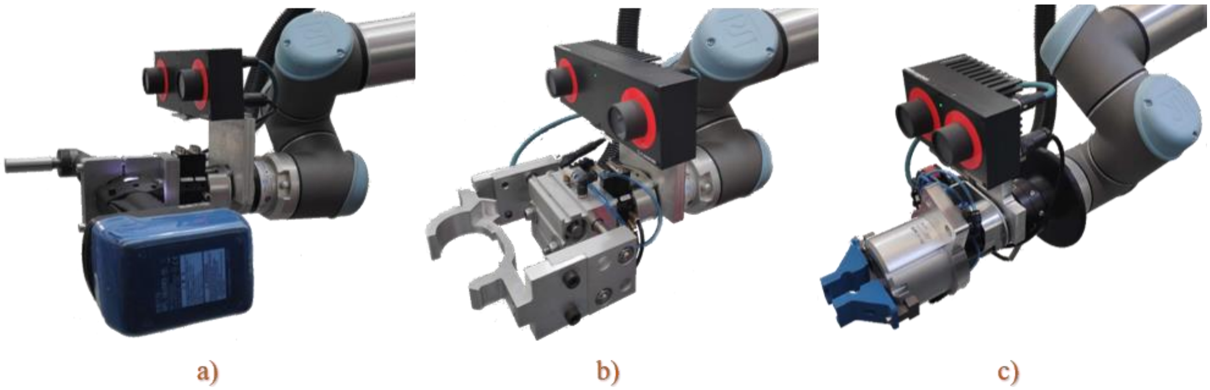


Figure 13: a) Screwing, b) Right arm handling and c) Left arm handling configurations

A toolchange system is implemented inside the demonstrator also for a quick exchange of robotic tools during workflow of the demonstrator. For the successful execution of all required operation inside the demonstrator different force sensors have been installed on the MRP arms (Figure 14).

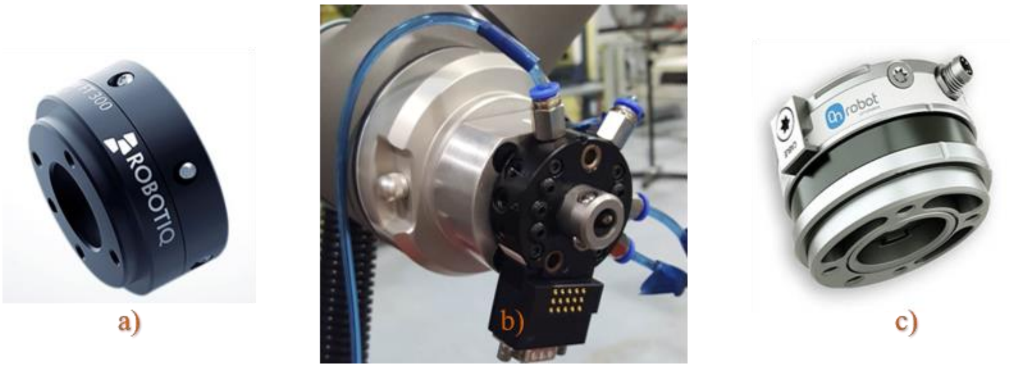


Figure 14: a) ROBOTIQ, c) OnRobot force sensors and b) SCHUNK toolchange system

6.3.2.1. Automotive use case tool exchanging system

The Mobile Product Platform included inside the automotive use case has already presented in deliverable D6.2. This platform used for damper's transportation between the last two workstations of the workflow.

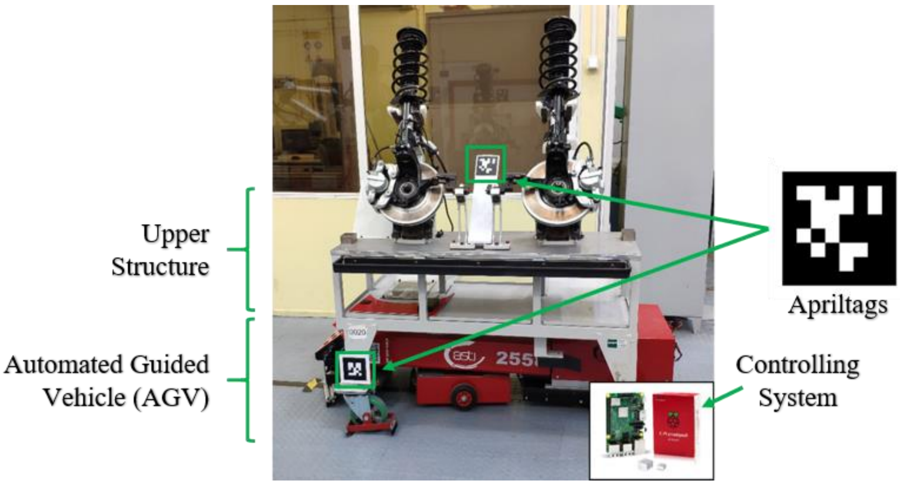
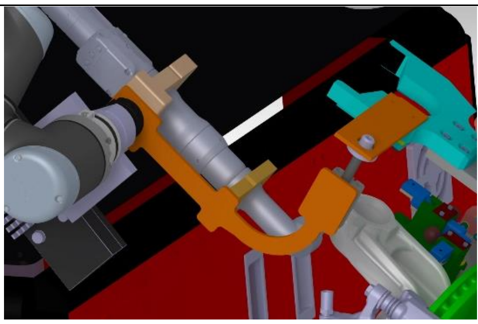
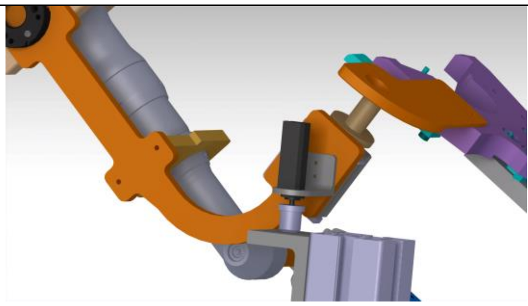
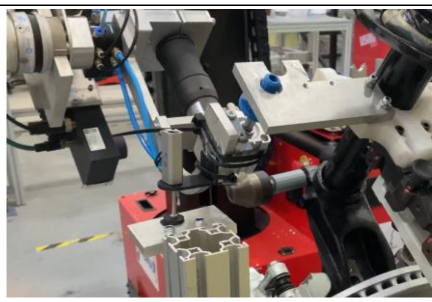


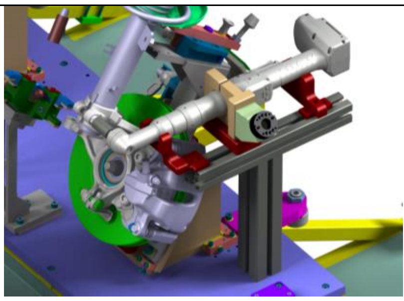
Figure 15: THOMAS Mobile Product Platform and controlling system

6.3.2.2. Screwing operation

Being one of the most challenging tasks of the automotive use case, the screwing operation has been considered and modified a lot during the project. The tested configurations of the screwing procedure are shown in Table 7.

Table 7: Screwing configuration of THOMAS OPS

1st configuration	**Description**	
	The co-navigation error is compensated by a mechanical clamping mechanism included a pneumatic actuator and a 3D printed pin. A custom device added in the upper structure mechanism for the clamping operation. After the screwdriver's alignment, the pneumatic actuator pushes the pin into the device mounted on the upper structure that lays on the MPP's upper structure.	
	CAD Model	**Physical View**
		
2nd configuration	**Description**	
	A second pair of actuator and pin added in the 1st configuration in order to reduce screwdriver's degrees of freedom during the execution of the screwing operation.	
	CAD Model	**Physical View**
		
3rd configuration	**Description**	
	Screwdriver component is released before the co-navigation of MRP and MPP platforms begin. This configuration based on a custom base installed on the MPP upper structure to support the screwdriver during the screwing during MPP's moving procedure.	
	CAD Model	**Physical View**

The first two configurations require small error values in the co-navigation of the MRP and MPP, for the screwdriver to remain in place, without applying exaggerated strain on MRP's arms. A lot of testing and tuning has been performed in the control loop of the co-navigation module, in the context of reducing this error. However, with the given hardware, the produced deviation is larger than the desired one. Thus, the best solution seems to be the 3rd, namely the detachment of the screwdriver during the movement and following. Screwdriver's re-attachment on MRP's arm take place at the end of the co-navigation process.

6.3.2.3. Automotive use case tool exchanging system

In order to perform all the required operations inside the automotive use case, different type of tools need to be mounted on the robotic arms. However, due to the maximum payload of each robotic arm these tools could not be always mounted on the robotic arms. For this reason, a tool station has been designed, produced and installed on the body of the mobile robot platform (Figure 16). This toolstation has already presented in deliverable D6.2.

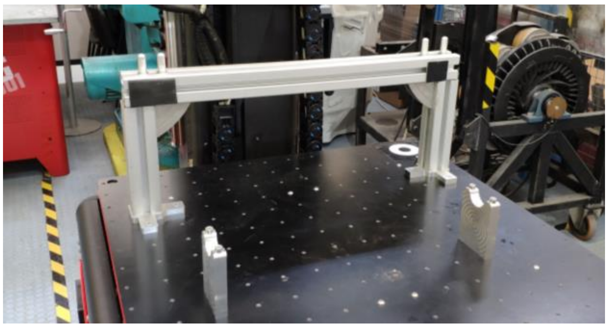


Figure 16: Toolstation of THOMAS Automotive use case OPS

6.3.3. Software components of the automotive OPS at LMS

6.3.3.1. 2D laser scanner-based navigation

As already presented in deliverable D6.2, the 2D laser scanner-based navigation of THOMAS automotive use case based on the data received by the two SICK MicroScan3 laser scanner installed on MRP n2 body. Based on these data and a navigation planner, the MRP n2 is capable to navigate between all the workstations of automotive use case's layout.

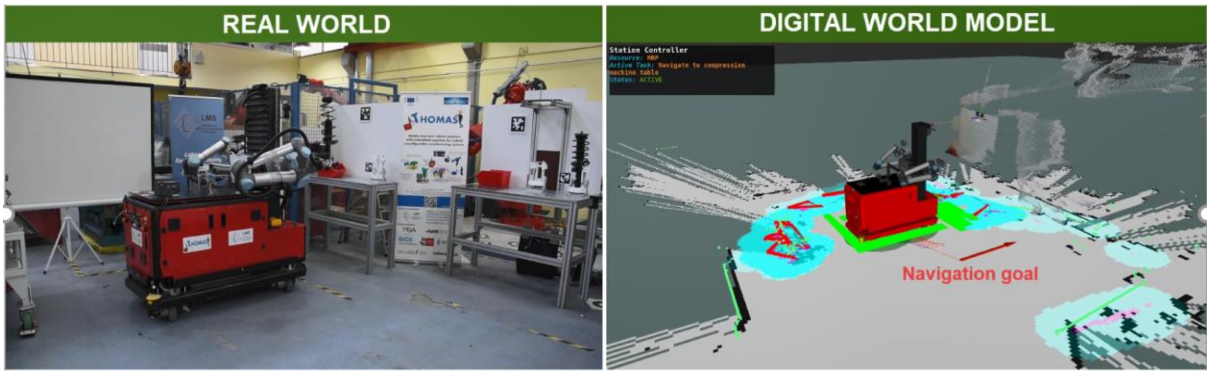


Figure 17: Navigation action in the real world

6.3.3.2. April tag detection using 3D sensor data for accurate navigation

The apriltag detection process has been successfully integrated inside Automotive use case demonstrator. This module's integration has already presented in deliverable D6.2. Apriltags' detection module is required for the in-cell navigation inside THOMAS project. The in-cell navigation module based on a detected Apriltag inside a 3D sensor's field of view. This module has been detailly documented in D6.2 and no further updates needs to be reported (Figure 18).

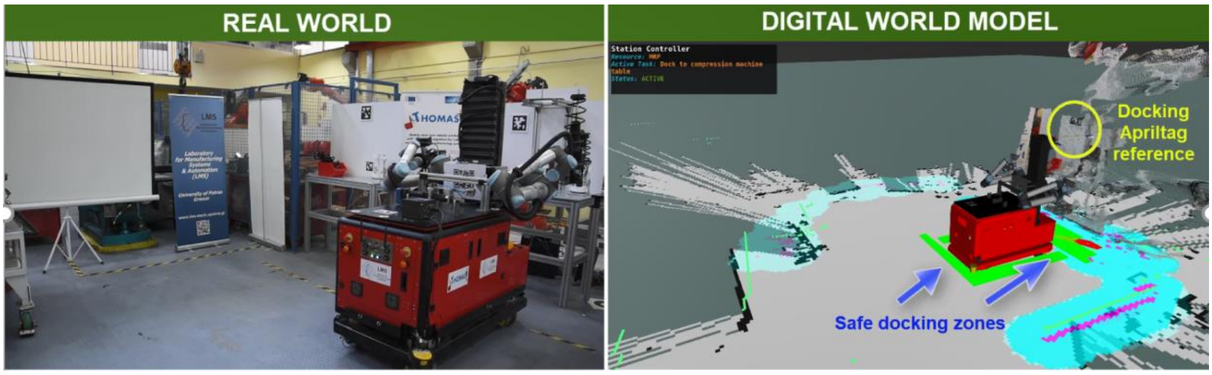


Figure 18: MRP accurate localization process in real world

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

The cooperation of two mobile resources is required for the execution of all processes inside the automotive use case of THOMAS project. The co-navigation of these resources has already presented in deliverable D6.2 and no further updates need to be documented in this deliverable. The cooperation of MRP n2 and MPP but also the safety system developed for this operation inside the automotive use case set up in LMS facilities is presented in Figure 19.

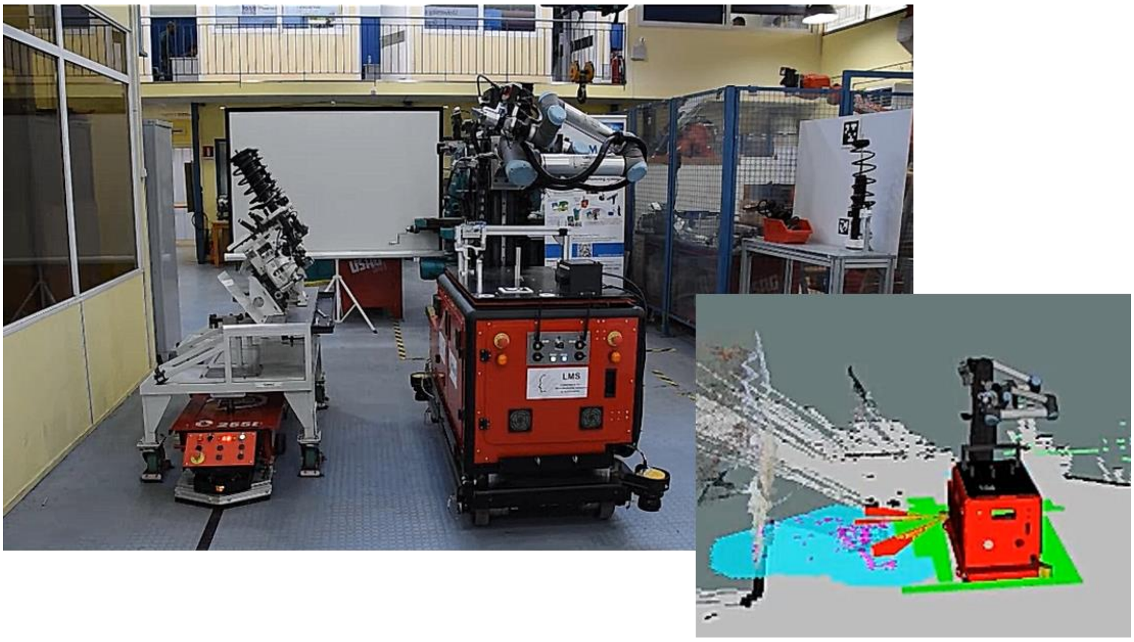


Figure 19: Mobile platforms co-navigation and safety architecture inside THOMAS shop floor

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

The Station Controller has been packaged in a Docker Image and is deployed in a physical computer that is stationary in the LMS premises. A screenshot of the execution of a schedule is shown in Figure 20.

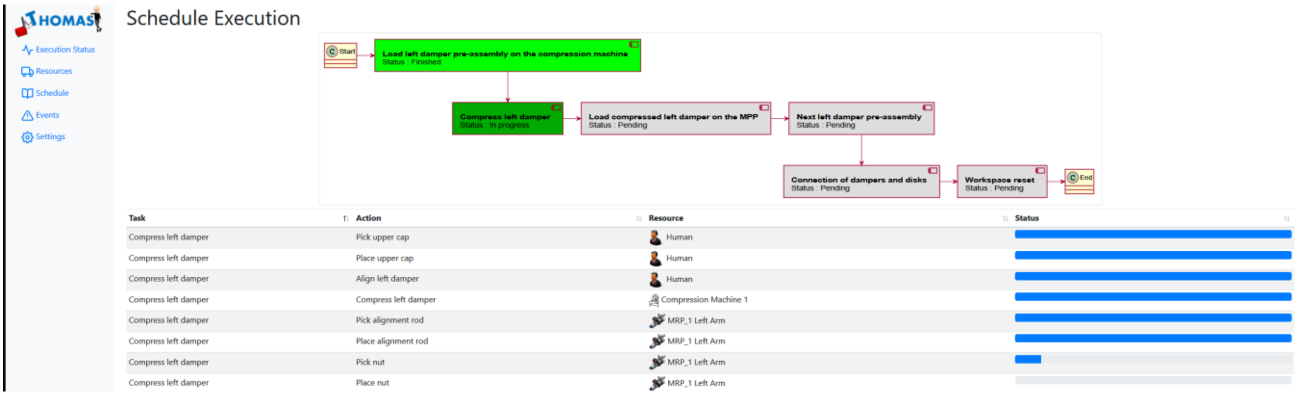


Figure 20: Station Controller Schedule Execution User Interface

The Station Controller provides an intuitive User Interface that can show the overall Collaborative Task Schedule, detailed information about each Task and Action Usage as well as how shop floor events are managed. Some details of the UI functionality are presented in more detail hereafter.

6.3.3.4.1. Schedule Execution Status Visualization

The schedule execution diagram, that is depicted in the Station Controller Execution screen (shown also in Figure 20) is a dynamic visual representation of the that visually represents:

1. Known pending tasks, in particular the whole Schedule Execution is automatically designed as a graph of tasks as shown in Figure 21.
2. The dynamic, current execution status. In particular each rectangle is changes color in order to indicate the current status. The following status encoding is used:

a. Yellow dashed rectangles: Represent Station Controller related commands, such as:
   i. The start of the Collaborative Execution Schedule
   ii. Events that appear dynamically
   iii. The end of the Collaborative Execution Schedule

   In the top left of Figure 21 the "Start" of the Collaborative Schedule Execution can be shown. Where on the top right of Figure 21 a Battery Event that has dynamically appeared can be shown.

b. Gray rectangles: These represent inactive tasks. Inactive tasks are the tasks whose execution has not been started yet.

   In the bottom right of Figure 21 there are two inactive tasks shown.

c. Light Green rectangles: These represent successfully completed tasks.

   In the top left of Figure 21 there are two completed tasks shown.

d. Dark Green rectangles: These represent tasks that are under execution and are proceeding OK.

   In the top right of Figure 21 there are two completed tasks shown.

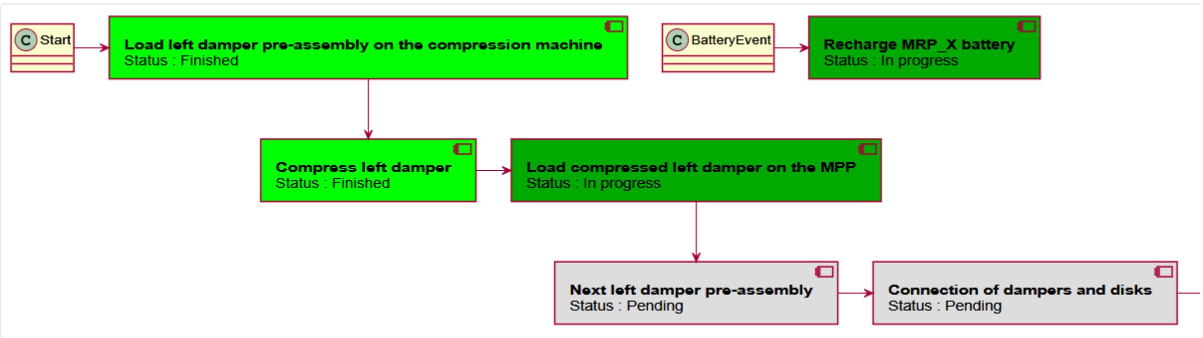


Figure 21: Collaborative Schedule Execution

6.3.3.4.2. Task Execution Details

The Station Controller Execution screen, that is shown in Figure 20, includes a detailed Task - Action Execution Status Matrix. An example of the Task-Action Execution Status Matrix is shown in Figure 22.

Task	Action	Resource	Status
Compress left damper	Pick upper cap	Human	
Compress left damper	Place upper cap	Human	
Compress left damper	Align left damper	Human	
Compress left damper	Compress left damper	Compression Machine 1	
Compress left damper	Pick alignment rod	MRP_1 Left Arm	
Compress left damper	Place alignment rod	MRP_1 Left Arm	

Figure 22: Task - Action Execution Status Matrix

In every Collaborative Execution Schedule, a Task contains one or more Actions. The Task – Action Execution Matrix shows in detail the execution status of each Action for every Task. For each action the Task – Action Execution Status Matrix shows:

1. The Task that the Action belongs to.
2. The name of the Action
3. The Resource that is currently planned to execute the Action
4. The actual Status completion percentage of the Action.

For instance in Figure 22, the first four Actions are already completed, the 5th action is currently under execution while the 6th action execution has not been started yet.

6.3.3.4.3. Station Controller Deployment and Integration

The Station Controller use the ROS Master of the MRP PC and is connected with other software in the LMS premises. These interconnections are presented in a deployment diagram that is show in Figure 23. This diagram shows software modules that are connected with the Station controller. Furthermore, this deployment diagram highlights the main interconnections between the software modules shown.

The THOMAS Station controller is responsible to invoke and monitor the execution of all Actions to complete the Tasks of the Collaborative Schedule. Each of the connections shown in Figure 23 are used for this reason.

The THOMAS Station Controller needs to notify and be notified by both human and machine resources. The interaction with humans is managed by the Augmenter Reality Application while a set of different connections manages the interaction with other robotic and sophisticated machinery systems.

In particular the THOMAS Station Controller is connected with the Augmenter Reality Application in order to to provide production and process related information and get information from the human. Augmented Reality based designs have been successfully demonstrated for the provision of production and process related information as well as to enhance the operators' immersion in the safety mechanisms, dictated by the collaborative workspace. [20]

The collaboration between human operators and industrial robots phases several challenges in assembly operations in terms of safety and simplified interaction. A case study involving perception technologies for the robot in conjunction with wearable devices used by the operator has been presented in [21].

However modern research has demonstrated that wearable devices such as Augmented Reality glasses and smartwatches can be used for closing the communication loop between operators and robots under a service-oriented architecture. [22]

The THOMAS Station Controller connects with the Augmented reality tool that is used for supporting operators in a shared industrial workplace where humans and robots coexist. Information related to the development of the smartwatch application and its integration with the network of resources under the ROS framework is also available in [23].

For the interaction with different robotic and machine systems the THOMAS Station Controller is connected with:

- The MRP and its connected equipment for the execution of robotic actions such as:
    - The navigation of the MRP
    - The execution of the MRP skills
    - April Tag Detection that uses 2D cameras
    - Object Pose Estimation that uses 3D cameras
- The compression machine for the execution of the compression actions
- The MPP for the execution of MPP actions

Finally, the THOMAS Station Controller is connected with the THOMAS Task Planner that allows it to reschedule the allocation of Tasks to Resources in order to address shop floor events, such as for instance a machine malfunction or the rescheduling of activities in case of an MRP battery needs to be recharged.

The THOMAS Task Planner is also connected with the THOMAS Digital Twin and THOMAS World Model information and simulation systems that provide a realistic modeling of the shopfloor and support the Task Planner and Station Controller in the scheduling and execution of a dynamic, collaborative production plan.

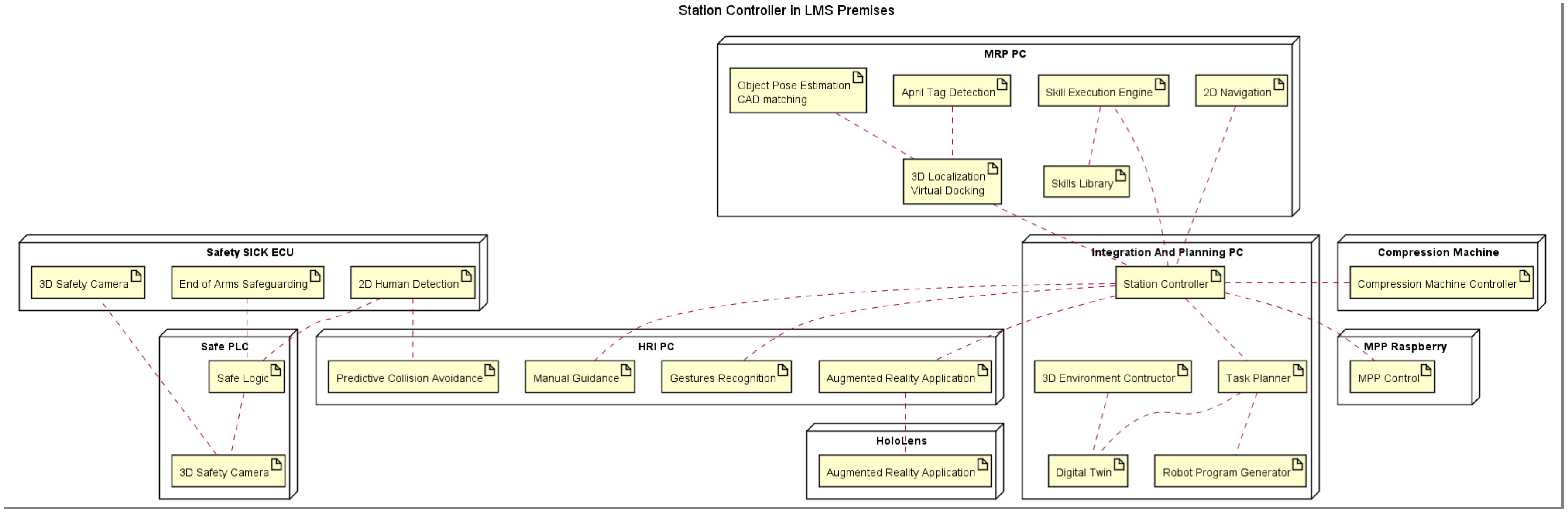


Figure 23: Software Deployment Diagram

6.3.3.5. Task planner module

The Task Planning framework is responsible for the fast and effective reconfiguration of operation assignments within the workcell. Its main goal is to orchestrate the sharing of task execution between all available resources, be-it humans or robots.

To achieve that, the workload needs to be modelled according to a set of database entities. These entities correspond to the tasks, resources and task-resource suitabilities that collectively construct the workload information in a well-defined manner.

The tasks' model contains all tasks comprising the assembly sequence, the precedence constraints between them, any used parts and their respective weight, their position on the workshop grid map, etc. The resources' model contains all resources available at a given moment. Properties such as linear/angular speed, resource type, weightlifting capabilities and limits, etc. determine the way the resources are being assigned to any pending tasks. Finally, the task-resource suitabilities' model, entails all information needed to determine which resources can carry out which tasks. Details such as process time and sensors needed are also provided. In the case of the precedence constraints, the planner uses the relations between the tasks, so as to examine rational sequences depending on the tasks already assigned and scheduled.

As a consequence to the above structure, the automotive case study was broken into said collections of data and stored in a database. Following the retrieval of these stored data, the software was designed to transform all gathered information into the model utilized by the task allocation algorithm. To perform the required transformations, a specific construct of Java classes was created, the Model Conversion Utilities Interface (MCUI), which is responsible for feeding the planner with deciphered data.

As the planning input is formed and fed to the algorithm, a process of iterative search methods takes place. The algorithm runs through the pending operations and creates batches of tasks to resources allocations, referred to as alternatives, that abide by precedence constraints and task-resource suitabilities. Each alternative is, then, processed by the evaluation criteria mechanisms and a utility score is extracted. This score depends on the metrics of said alternative, such as flowtime, distance covered, human ergonomics and feasibility. The alternative with the highest score is chosen to be extended and to produce child-alternatives that aim to complete the plan, while maximizing their utility value. Thus, the output of the Task Planner is highly dependent on the weight that each criterion is assigned, as different alternative operations sequences result in different evaluation scores. It is important to note here, that the terms 'task' and 'operation' are used interchangeably and do not directly adhere to the hierarchy defined for THOMAS. Detailed information about the Task Planner criteria is provided in D5.5 "THOMAS Station Controller – Final Version", but a summarized overview, along with minor additions, is useful to be described. After careful consideration of the use-case requirements and assembly targets, the list of evaluation criteria devised contains the following:

- **Total flowtime:** The total plan execution duration.
- **Payload handled by human:** The total weight lifted by the human workers, while they execute tasks with parts of non-trivial payload.
- **Human busy time:** The amount of time that human resources were utilized to execute tasks.
- **Utilization of resources:** The percentage of time that each resource is being utilized to help complete the plan.
- **Distance covered:** The total distance that all resources collectively traversed through the workcell.
- **Non-adding values activities time:** The total time of non-adding values activities, such as moving and changing tools.

During the planning, some of the criteria responsible for evaluating the sequences generated need to get access to actual simulation data. This way, they can provide better estimations on the evaluation scores of each alternative. These simulation data are acquired by the designed transcription interface

between the Task Planner, the Station Controller and the Gazebo digital twin implementation. The data are either gathered from an existing simulation database, or directly acquired from a new simulation. The Task Planner first converts the batch of tasks to be simulated into Station Controller actions. This translation takes place frequently, so the Java framework needed to be optimized for speed and simplicity. The converted batches are sent to the Station Controller to request for execution metrics and, then, the Station Controller propagates the request to the Gazebo digital twin implementation.

The simulated environment of THOMAS automotive use case is used for the evaluation of the different generated task sequences. The station controller module is responsible to distribute tasks to simulated models inside the simulated environment. Using custom ROS nodes, the station controller is capable to receive several information regarding the type of the task executed inside the simulated environment. Based on the type of the resource (Human, MRP_base, MRP_arm) used for the execution of each task, different kind of information sent to the station controller. The following kind of information received by the station controller based on the type of the resource executed each task:

- MRP_arm
    - Arm Motion Duration: The time required for the execution of an MRP’s arm or torso motion measured in milliseconds.
- MRP_base
    - MRP Navigation Duration: The time required for the execution of an MRP’s navigation task measured in milliseconds.
    - MRP Navigation Distance: The length of the path that the MRP needs to follow in order to execute the navigation task calculated in meters.
- Human
    - Human Navigation Duration: The time required for the execution of a simulated human model navigation task measured in milliseconds.
    - Human Navigation Distance: The length of the path that the simulated human model needs to follow in order to execute the navigation task calculated in meters.

After the execution of the required simulations, the Task Planner uses the received data to validate the alternatives and store them in its database for future use (Figure 24). That way, future plan generations become faster and more reliable, as more simulation data are already available for utilization.

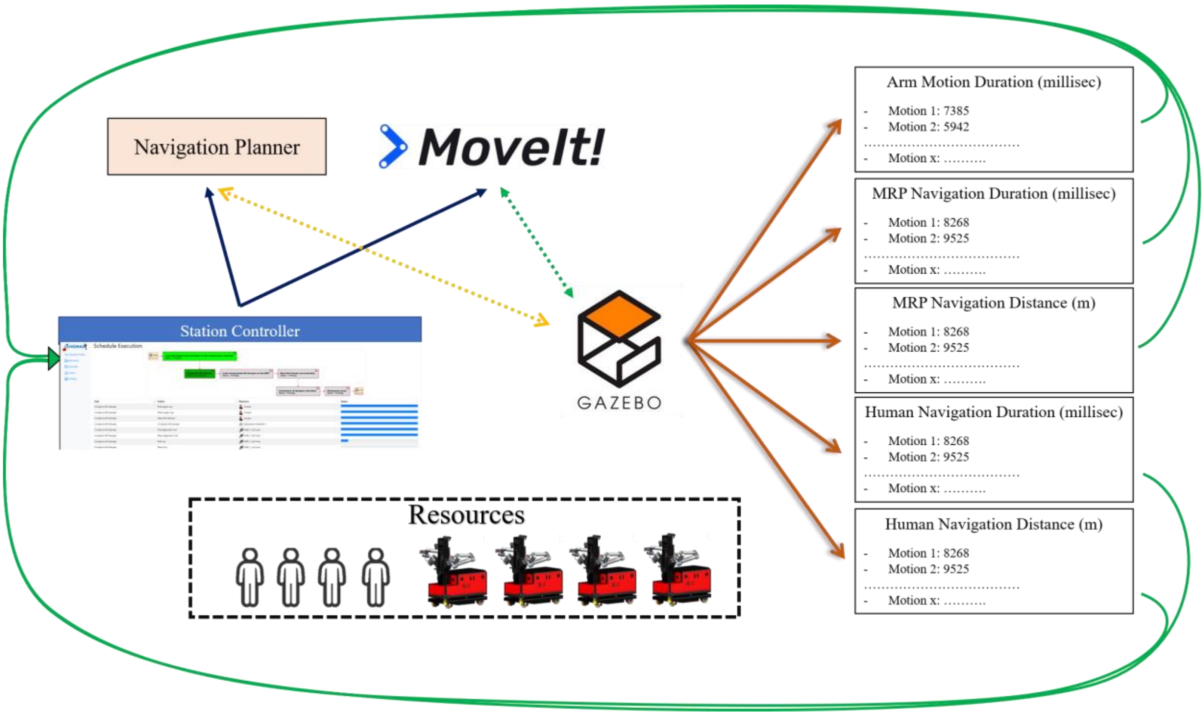


Figure 24: Alternative task sequence evaluation based on simulated execution of tasks

In order to provide an overview over the planner's functionalities and access to the planning input data, there is an option to control and use the framework with an added Graphical User Interface (GUI). This addon is designed to offer the user with a simplified interface so as to perform the task scheduling. The main window (Figure 25) offers the option to either view the workcell information or a prompt to configure and run the task scheduling algorithm. The workcell information contain the workstations (Figure 26), resources (Figure 27) and tasks (Figure 28) that comprise the planning input.

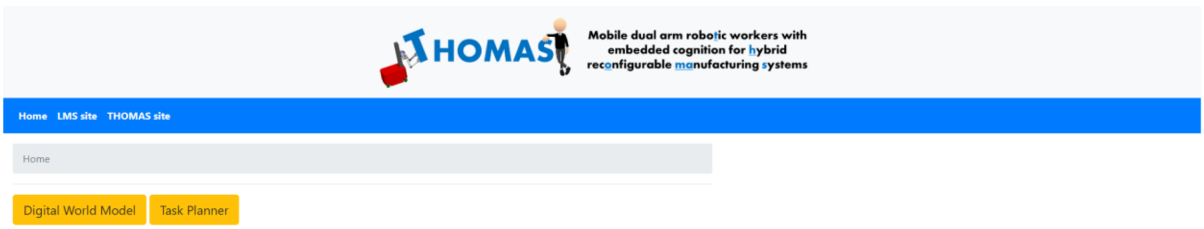


Figure 25: Task Planner GUI home window

Workstations

Workstation	Working Area	Abbreviation
General Assembly Station	MPP	MPP
MRP Recharge Station	Battery Recharger	BR
Left Damper Assembly Station	Pre-Assembly Table 1	PT_1
	Compression Machine 1	CM_1
Right Damper Assembly Station	Pre-Assembly Table 2	PT_2
	Compression Machine 2	CM_2

Figure 26: Workstations overview

Available Resources

#	Name	Speed (m/s),(deg/s)	Max Payload (kg)
0	Human	1.4	5.0
1	MPP	0.5	0.0
2	MRP_1 Base	0.5	100.0
3	MRP_1 Left Arm	150.0	10.0
4	MRP_1 Right Arm	150.0	10.0
5	MRP_2 Base	0.5	100.0
6	MRP_2 Left Arm	150.0	10.0
7	MRP_2 Right Arm	150.0	10.0
8	Compression Machine 1	1.0	0.0
9	Compression Machine 2	1.0	0.0

Figure 27: Resources overview

Assembly Tasks

Choose a sequence to view:

(•) Normal Execution

( ) Battery Low Event

#	Name	Part	Position
0	Pick stopper	stopper	(1337.0, 3551.0, 1700.0)
1	Insert stopper	stopper	(1337.0, 3451.0, 1700.0)
2	Pick dust cover	dust cover	(1337.0, 3551.0, 1700.0)
3	Insert dust cover	dust cover	(1337.0, 3451.0, 1700.0)
4	Pick spring	spring	(1337.0, 3551.0, 1700.0)
5	Insert spring	spring	(1337.0, 3451.0, 1700.0)
6	Pick alignment rod	alignment rod	(1337.0, 3551.0, 1700.0)
7	Insert alignment rod	alignment rod	(1337.0, 3451.0, 1700.0)
8	Pick cap	cap	(1337.0, 3551.0, 1700.0)
9	Insert cap	cap	(1337.0, 3451.0, 1700.0)
10	Pick pre-assembled left damper	left damper	(1337.0, 3451.0, 1700.0)
11	Place pre-assembled left damper	left damper	(1335.0, 3642.0, 1700.0)
12	Pick upper cap	upper cap	(1337.0, 3551.0, 1700.0)
13	Place upper cap	upper cap	(1335.0, 3642.0, 1700.0)
14	Align left damper	upper cap	(1335.0, 3642.0, 1700.0)

Figure 28: Tasks overview

Considering the above as the starting point, the user can afterwards open the task scheduling window. After choosing the desired search parameter values and the criteria weights (Figure 29) to use, the algorithm can be launched. After the execution, which typically takes about 2-3 minutes depending on the options set and number of Gazebo simulations requested, the planner presents the user with the best plans it could devise, concerning the criteria set (Figure 30). The user can, then, choose any plan to view its task-resource assignments, its execution metrics, its Gazebo simulation or send it for execution to the Station Controller (Figure 31).

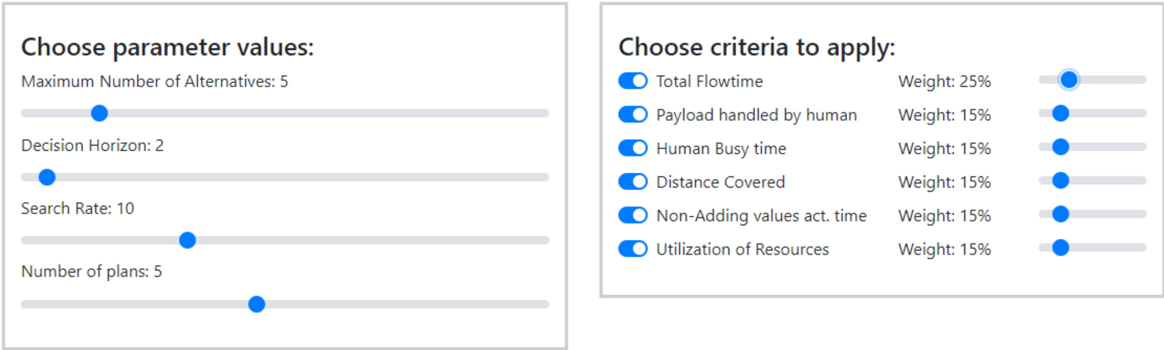


Figure 29: Search parameters and evaluation criteria

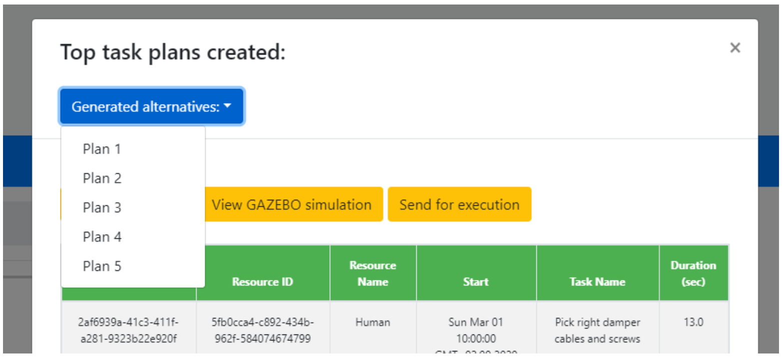


Figure 30: Plans generated

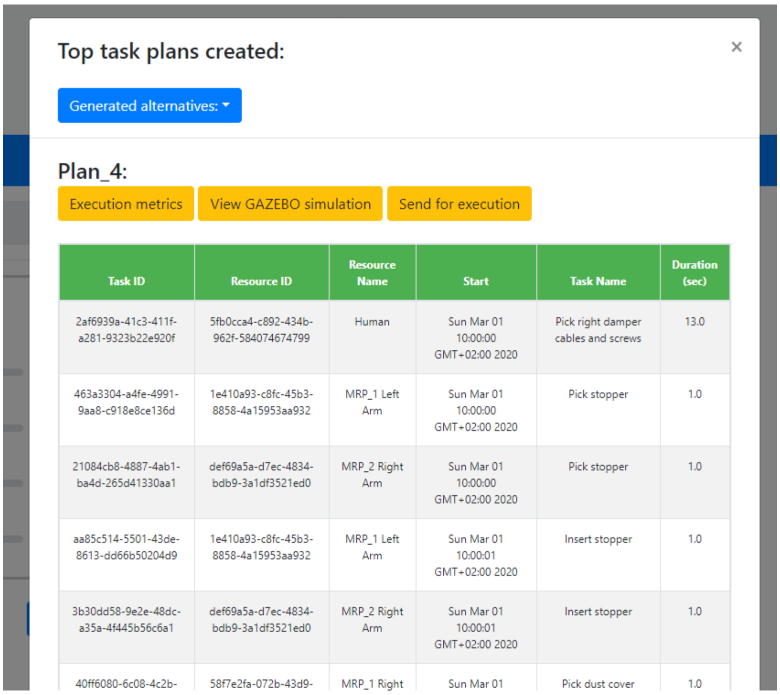


Figure 31: Chosen execution plan

6.3.3.6. Augmented Reality Application for operator support

The augmented reality application, running on the Microsoft HoloLens Mixed Reality Headset (Figure 32), provides handful of utilities to the human operator of the automotive use case demonstrator.

Figure 32: Microsoft HoloLens Mixed Reality Headset

These utilities can assist the operator's work during the setup of the system, during the execution of the work cycle as well as at failure and emergency handling. With this application, the worker can be informed in real time about the state of the robot and his current task. The operator can also get provided with detailed information about the way they can resolve any issues or emergencies that may take place during the execution. Moreover, the operator gets supplied with tools that utilize the direct instruction and programming of the robot.

Figure 33: AR Application main menu

In more detail the AR application provides the following functionalities:

- **Information about the current operator task**: The operator gets informed about the task assigned to him with instructions on how to perform this specific task which are displayed over the correct workstation (Figure 34).

Figure 34: Popup messages informing the operator about the current task

- **Task Completed Button**: When the operator completes the assigned task, he can press the "Task Completed" button to inform the system that the task has been successfully performed (Figure 35).

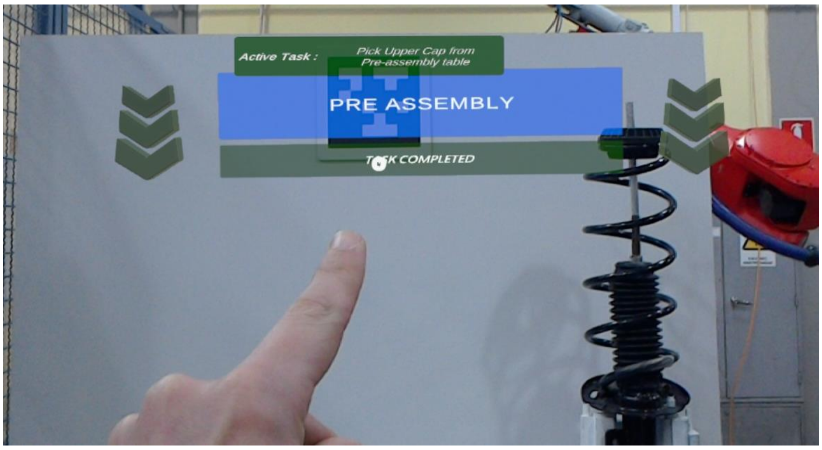


Figure 35: The operator informs the station controller that the task is completed

- **Monitoring of the robot's status**: The operator is informed though popup notifications inside the application by the time MRP is moving, in order to be aware and to avoid blocking its navigation path. Additionally, in the case that the robot goes in emergency state, the operator will be again informed with a popup message which describes the type of emergency and gives instructions on how to overcome the specific failure. When the required steps get performed, the operator is able to resume the execution by clicking on the "OK" button. Lastly, if the safety zones of the robot get violated by any obstacles, a safety field violation message will be displayed and the fields will be visualized around the real robot to help the operator understand where the obstacle is and remove it. Finally, the worker can resume the execution by clicking on the "OK" button (Figure 36).

Figure 36: Station controller gives information about the system's recovery

- **Visualization of the safety fields**: As mentioned above, the developed AR application gives the ability to the operator to visualize in real time the safety fields produced by MRP's laser scanners (Figure 37). This feature is enabled automatically when a safety field violation exception is detected, but also the user can enable and disable it at his will.

Figure 37: The safety fields' visualization feature

- **Ability to navigate the robot to each workstation**: Using visual panels displayed over each working area of the automotive use case layout human operators are capable to instruct the robot to navigate into the selected workstation (Figure 38). This feature can be very useful in emergency handling, as the operator can reset the emergency and immediately send the robot to the needed workstation to resume the cycle execution, drastically minimizing the overall idle time.

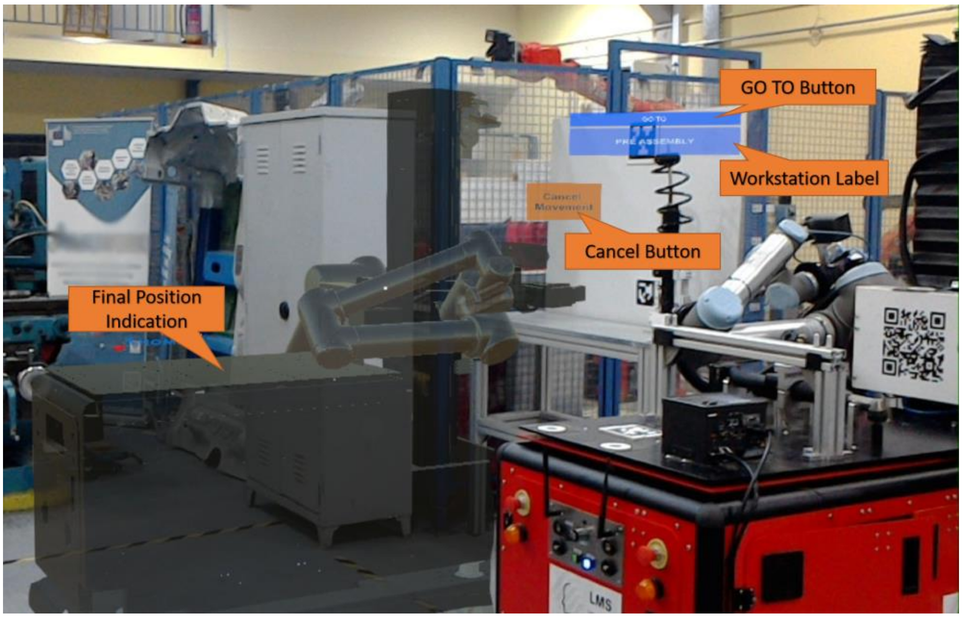


Figure 38: The operator can move the robot to each workstation with the press of a button

- **Ability to teach new navigation goals:** In addition to the previous feature, the operator can click to any point inside the shopfloor to navigate the MRP there. This is again of great use in emergency and failure handling, as the operator can manually disengage the robot out of a problematic position. Additionally, this feature can be used in the setup of the system for teaching new positions to the robot.

With all the above features, we achieve a bidirectional communication between the station controller and the human operators. Thus, the station controller can treat all the resources of the system (both robotic and human) in a uniform way, by sending specific tasks and waiting for the outcome. At the same time, the operator is offered an easy and intuitive way of understanding the state and the intention of the system.

6.3.4. Safety concept

The automotive use case of THOMAS project consists of both human and robot tasks. For this reason, several safety modules have been developed and implemented inside the automotive use case demonstrator to guarantee the safety motion of human operators inside the working area of the MRP. Several modules have been developed for the safety of human operator either MRP is performing navigation actions or not.

6.3.4.1. On-board safety

The most important safety module of THOMAS automotive use case based on the data come from the two SICK MicroScan3 sensors placed on MRP n2 body. Based on these data and the safety fields configurated through the safety system of MRP n2, human operators standing close to MRP may be detected and trigger the MRP motion to stop. Different configurations of safety fields are used during the workflow based on the type of the operation executed by the MRP (objects' manipulation, navigation, screwing etc.) and mobile robot's location inside the shopfloor. This module and its integration inside the automotive use case demonstrator are presented in deliverables D2.6 and D7.3 respectively and no further updates need to be documented.

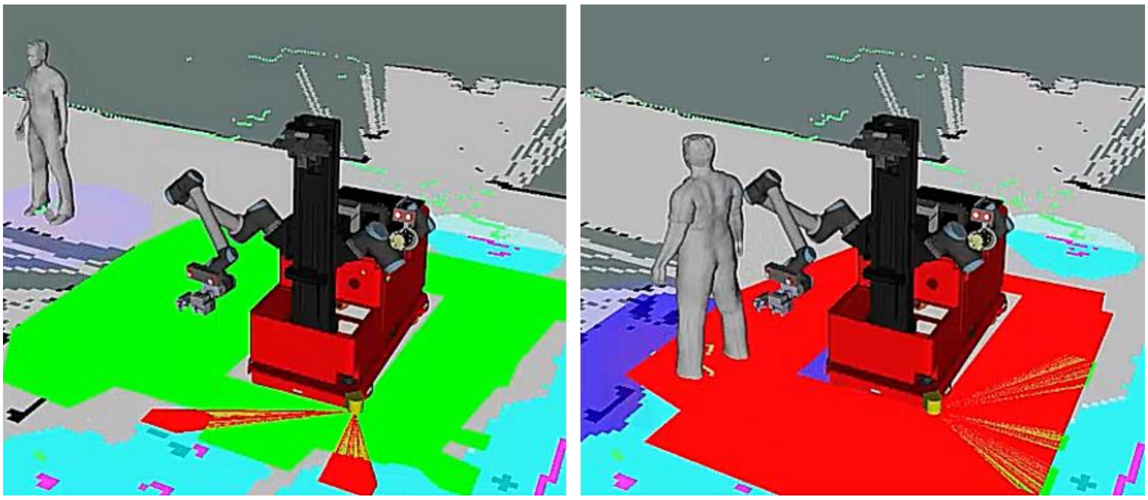


Figure 39: Protective fields with and without human intension during pre-assembled damper's manipulation

6.3.4.2. On-Robot-Arm safety

Another safety module introduced inside THOMAS project is developed by SICK partner. This module targets the safety at the end of the robot arm. This module based on a custom component built by SICK and is scheduled to be delivered in LMS premises during the following months (Figure 40). More information regarding this module's functionality are documented in section 4 of THOMAS deliverable 2.6.

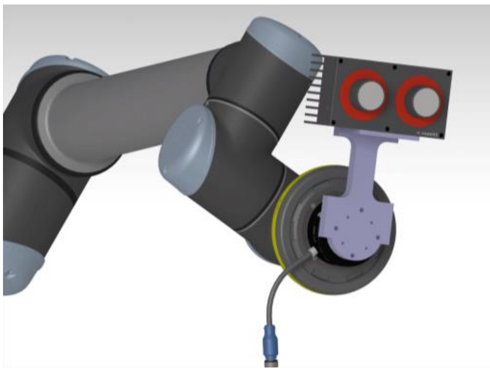


Figure 40: End-Effector safeguarding prototype

6.3.4.3. On-site safety

Inside THOMAS project, SICK partner targets to introduce a new 3D safety camera to secure the human operator while performing several actions close enough to the MRP. The 3D safety camera and the detection module based on its functionality are presented in deliverables D2.6. This module's integration inside the automotive use case demonstrator is also presented in deliverable D7.3 and there are no further updates need to be documented.

7. PILOT CASE MITIGATION PLAN & ECONOMICAL / TECHNICAL GAINS

Upon the completion of the first period of the project (M18), THOMAS consortium supported by the Expert reviewer have identified the need to incorporate a strategy to address the following issues:

- Ensure that the use cases meet the requirements of the end users at the end of the project (M48). To this direction, a mitigation plan ("Plan B") has been set up for aiming to ensure internal exploitation capabilities and attractiveness of the results by the industrial end users. The current version of the plan documented in this document is the second version (M42) that will be regularly updated (in a 6-month basis) during the project.
- Perform an initial analysis of the economic and technical gains for the end users aimed through the implementation of THOMAS results. This cost – benefits analysis will be kept up to date along with the evolvement of the project's developments in a 6-months basis. Along with the business plan implementation a market and competitors' analysis will be performed and updated along with the cost – benefit analysis in the next period of the project.

The last version of THOMAS automotive use case mitigation plan has been detailly presented in THOMAS deliverable D7.3 and there are no further updates until the M42 of the project.

7.1. Automotive Pilot Case – End User: PSA

The following sub-sections are focusing on the mitigation plan and the cost – benefit analysis performed for the automotive pilot case of the project.

7.1.1. Automotive pilot case mitigation plan

The basis of the mitigation plan for the automotive use case was to investigate the different internal exploitation capabilities of PSA group for THOMAS solution. Proving the applicability of the project solution to multiple production plants of PSA strengthens the argued interest of PSA for THOMAS Operation Production Station. Following, in the next figure summarized the high-level workflow of the production of vehicles throughout the manufacturing lifecycle. This particular lifecycle concerns seven mechanical manufacturing plants that are located in France, 7 plants that are located in the rest of Europe and 5 plants that are located outside Europe. As pointed out in this figure, the assembly lines of these plants are the targeted application are of THOMAS provided solution.

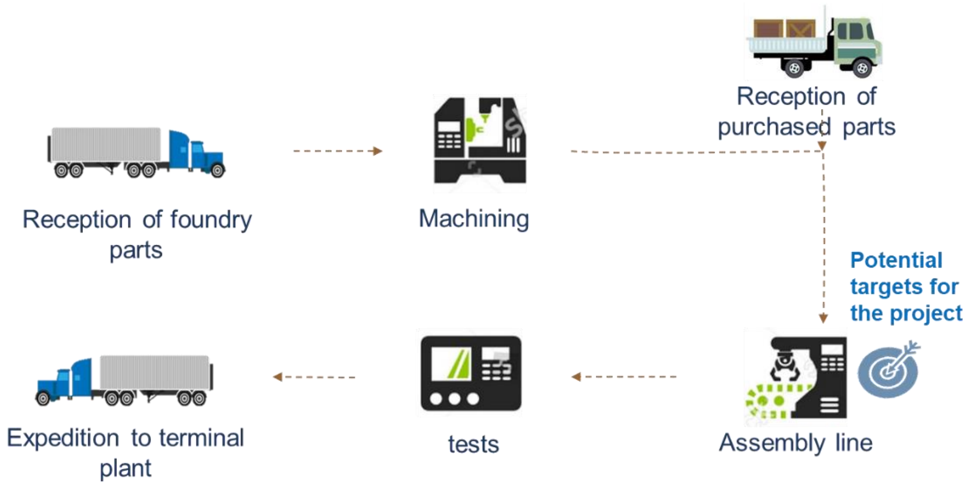


Figure 41: PSA Group production system workflow

Next figure zooms in the workflow inside PSA's assembly plants aiming to identify the specific workshops where production could be benefited by THOMAS Open Production Station (OPS) implementation. After an extensive investigation of PSA supported by the rest of the partners, it was concluded that project objectives may meet the requirements of the processes performed in the:

- **Intra factory logistic** applications where the THOMAS MRPs may be used for kitting and transferring consumable parts (clips, screws, tools etc.) in the different assembly lines ensuring that no stoppages of production will take place due to lack of consumable materials.

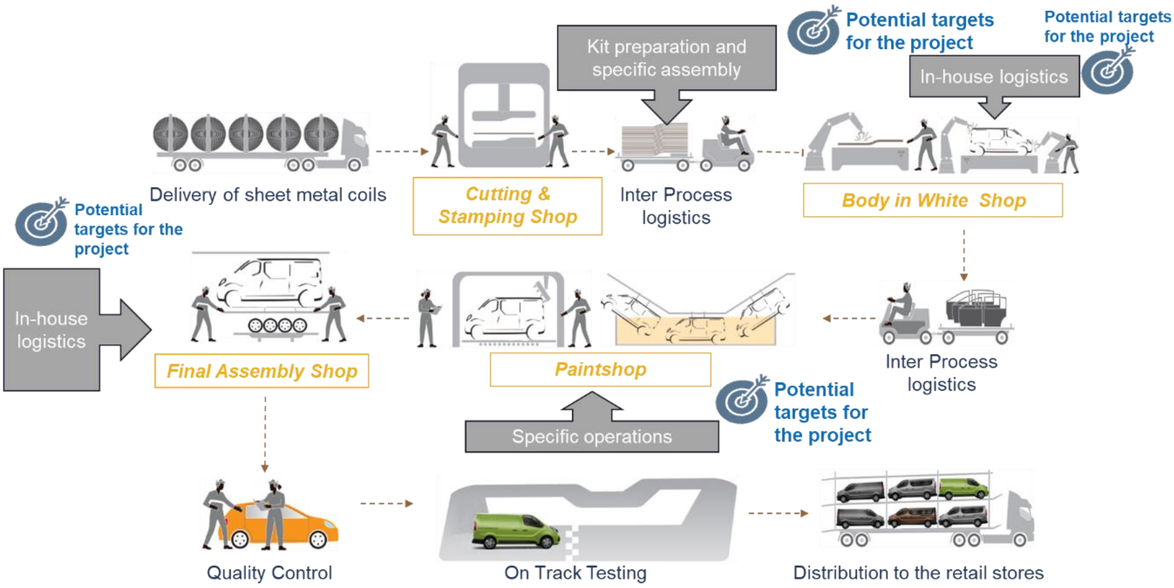


Figure 42: PSA vehicles assembly lifecycle

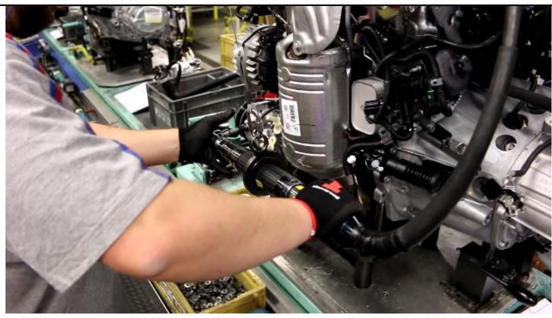
- **Body-In-White (BiW)** shop. This workshop refers to the stage where the car's body sheet metal (including doors, hoods, trunks, bumpers and deck lids) assembly operations are taking place. THOMAS MRP versatility allows its usage into various applications involving different assembly operations in this stage, given that the robot resources are equipped with the appropriate tools. Thus, it is expected THOAMS MRP to be able to manipulate the different part of the car body and assemble them so for the welding operations to follow. An identified restriction in this workstation is that some of the parts involved in the assembly may be overweighed compared to the MRP robot arms (UR10) allows payload: 1 arm may lift to 15 kg, using dual arm manipulation the maximum payload can reach up to 30 Kg.

- **Paint** shop. This workshop concerns the vehicle's outer part surface preparation and painting activities. THOMAS skill-based programming enables THOMAS MRP to perform these kinds of operation as well in complementarity with the assembly tasks. Prototypes of these robot skills have been developed towards addressing the requirements of the automotive pilot case being generic enough so to be re0used in different environments if needed.

- **Final assembly** shop is the workstation that demonstrates the most exploitation capabilities given the nature of the assembly process performed there. The dual mobility concept may also be exploited in these workstations since the base part for assembly is placed on moving tracks/ Automated Guided Vehicles (AGVs) that the MRP may follow and work on them in parallel. Thus, at this stage, the mitigation plan identifies as a Plan B the following use cases where PSA is interested to apply THOMAS solution (further to the selected use case) in M42:

Table 8: PSA Final assembly shop – "Plan B"

Description	Descriptive Image

Description	Descriptive Image
Door assembly Manual clips and cables in the final assembly of the door – door is located in a moving crane while clips and cables are stored in trays	
Engine assembly Manual assembly of multiple parts into the engine base part – screwing operations	
Pipe and heat shield assembly Manual screwing and mounting of flexible parts into the down side of the car	

It is important to mention, that the use case related to the front axle assembly is still up – to – date concerning the interest of PSA group. This first mitigation plan analysis supports the argument that PSA group has a variety of use cases where they can use THOMAS application to advance their production system, that is also one of the targets in their innovation and technical advancement roadmap.

During 2017 and 2018, THOMAS participated in PSA Booster Day. This is an internal event, organized by the PSA innovation and technology department where PSA personnel from all the production plants some together so to be introduced in new technologies that are under development from PSA and their technology providers collaboration network. In this event, both times attended, THOMAS had the chance to present the project concepts and results capturing a lot of attention from the PSA personnel occupied in the different assembly plants (production managers, designers etc.), verifying the interest of PSA on the dynamic reconfigurable assembly systems enabled by flexible dual arm robots that act as assistants to humans. In the second event (October 2018), after PSA and OPEL merging activities, representatives from OPEL attended the event as well. These representatives also were introduced to THOMAS concept and aspiration showing high interest on the profits that such an application may provide. This enables the extension of THOMAS OPS exploitation capabilities in OPEL plans as well. A further investigation towards this direction is expected to be done in the last period of the project.

7.1.2. Automotive pilot case technical / economical gains

7.1.2.1. Technical gains – Key Performance Indicators (KPIs)

The technical gains targeted by the implementation of THOMAS OPS in the automotive industry, and in PSA in particularly, have been quantified through the definition of the Key Performance Indicators (KPIs) listed in the following table. These KPIs were presented in D7.3 in M36.

The status of these KPIs not change in last 6 months until M42 because all integration tasks on the demonstrator inside the automotive use case layout in end user's premises (PSA Factory Mulhouse (France)) have been delayed for several medical reasons (Covid19 virus Pandemic).

Table 9: Automotive pilot case - Current validation status [M42]

KPI	Baseline	THOMAS solution – Current status of validation	Target
Maximum mass handled by the operator	5Kg	0.275 Kg	1 Kg
Number of models/ Diversity	3	6	6
Activity of operator	60%	70%	70%
Production throughput	60 Veh/h net	41 Veh/h net	60 Veh/h net
Number of operators	3	1	1
Robustness and repeatability	95%	To be validated by M48	99%
Quality	95% Direct run	To be validated by M48	99% Direct run
Flexibility of the line	Not relevant	Flexible MRP capable of performing various operations (handling, assembly, screwing)	Same as human workers
Safety	TF1(**) = 1,37	To be validated by M48	TF1(**) < 1
Cost	• 3 human operators (annual salary) • Equipment for station 5 & 6	• 1 human operator (annual salary) • Peripheral equipment (safety, perception, grippers etc.) • 2 MRPs (~ 280 Keuros)	ROI < 12 months

**TF1 - Lost-time accident frequency rate. It measures the number of accidents resulting in more than 24 hours of time off work. Accidents that occur when traveling to and from work, or to and from the location where employees normally eat their meals during the work day are not included.*

7.1.2.2. Economic gains – Cost benefit analysis

Concerning the economic gains an initial analysis has been performed towards the calculation of the return of investment for the current set up at PSA as well as the THOMAS OPS implementation case.

Given that at this stage of the project M42, THOMAS OPS is not yet completely set up, two cases in terms of cost have been considered the optimistic and the pessimistic.

To make a more completed analysis two group of costs have been considered for each of the cases: a) the investment cost which involves the costs for equipment acquisition and commissioning of the workstations – before starting the operation of the process and b) the operating cost which involve the annual required costs for the operation of the workstation.

Next table analyses the investment cost that was required for the current set up at PSA as well as the for the two cases of THOMAS OPS implementation.

Table 10: Investment cost of Current PSA state vs THOMAS OPS (2 cases)

	Current PSA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Equipment Cost	155.000€ (10.000€ ASTI AGV, 51.987,5€ for automated screwing machine, 40.000€ for compression machine, 20.000€ for screwdrivers, 5.000€ for tables / fixtures)	220.000€ (20.000€ for MPP, 140.000€ for MRP, 40.000€ for compression machine, 18.000€ for screwdrivers – grippers, 2.000€ for tables / fixtures)	301.000€ (35.000€ for MPP, 200.000€ for MRP, 40.000€ for compression machine, 20.000€ for screwdrivers – grippers, 6.000€ for tables / fixtures)
Consumables / sensors cost	2.000€	5.000€	5.000€
Commissioning labour cost	8.000€	4.000€	12.000€
Energy lines (Electric, Pressurised air etc.)	5.000€	7.000€	14.000€
Total investment Cost (€)	**186.987,5 €**	**236.000 €**	**332.000 €**

In the following table, the operating costs of the above cases has been estimated by the consortium based on current values from the end user and experience of the technology providers and the system integrators.

Table 11: Operating cost of Current PSA state vs THOMAS OPS (2 cases)

	Current PSA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Engineering cost (per year)	1.000€	2.000€	2.000 €
Maintenance cost (per year)	1.000€	4.000€	4.000 €
Operation cost – Electricity, pressurized air (per year)	1.000€	2.000€	2.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	90.000€ - (3 operators - **2** for the right&left damper assembly – **1** for the cabling / screwing)	30.000€ (1 operator)	45.000 € (1,5 operator)
Cost for quality defects (per year)	3.000€	100€	600 €
Cost due to MSD[1] (per year)	3.240€	650€	650 €
Total Running Cost (€)	**99.240€**	**38.750€**	**54.250 €**

[1] MSD: Musculoskeletal Disorders. These are caused due to the non-ergonomic nature of human operators' tasks. This leads in injuries of humans and thus their unavailability for specific period.

Based on the above analysis, the payback Head To Head Point (HTHP) has been calculated for both the optimistic and pessimistic case of cell deployment. As illustrated in Figure 43, in the optimistic case the HTHP is in 10 months, while for the pessimistic case is in 43 months.

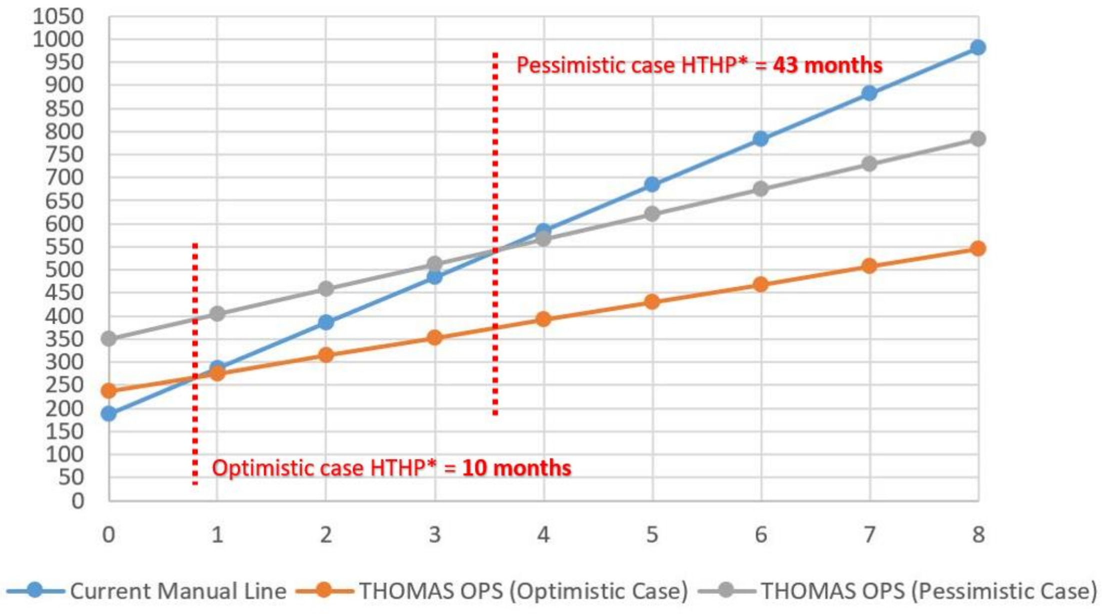


Figure 43: HTHP2 after THOMAS OPS deployment

- Strategic impact
  - increasing quality,
  - improve future vision of company,
  - safety required investment,
  - ergonomic improvement,
  - more than one task in the same station (pre-assembly of damper + compression of damper + assembly of damper on the disk).

8. OPS AERONAUTICS USE CASE

8.1. General Overview

THOMAS Aeronautics OPS has been particularized with the required hardware and software for facing some of the most common processes in the aeronautic industry (template drilling, surface sanding and rivet installation quality check).

The simulated set up of the aeronautic use case is presented in the following subsection. Based on the fruitful results of the simulation, the actual hardware have been integrated and the cell has been constructed in TECNALIA’s premises. Then in section 7.3.2, the required hardware components for the execution of all processes in the aeronautic demonstrator are presented. Section 7.3.3, focuses on the developed software of the aeronautic OPS. Finally, the safety concept as implemented inside the aeronautic use case is explained in section 7.3.4.

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

For testing the THOMAS OPS in aeronautic use case, the three processes (template drilling, surface sanding and rivet installation quality check) have been demonstrated on different sections of the same wing. In order to perform one process, THOMAS MRP approximates the tool station and gets the required tool for performing corresponding process. When the task is finished it returns the tool to the tool station and navigates to other section of the wing for completing the rest of the processes. Figure 44 shows a drawing of the aeronautic use case layout.

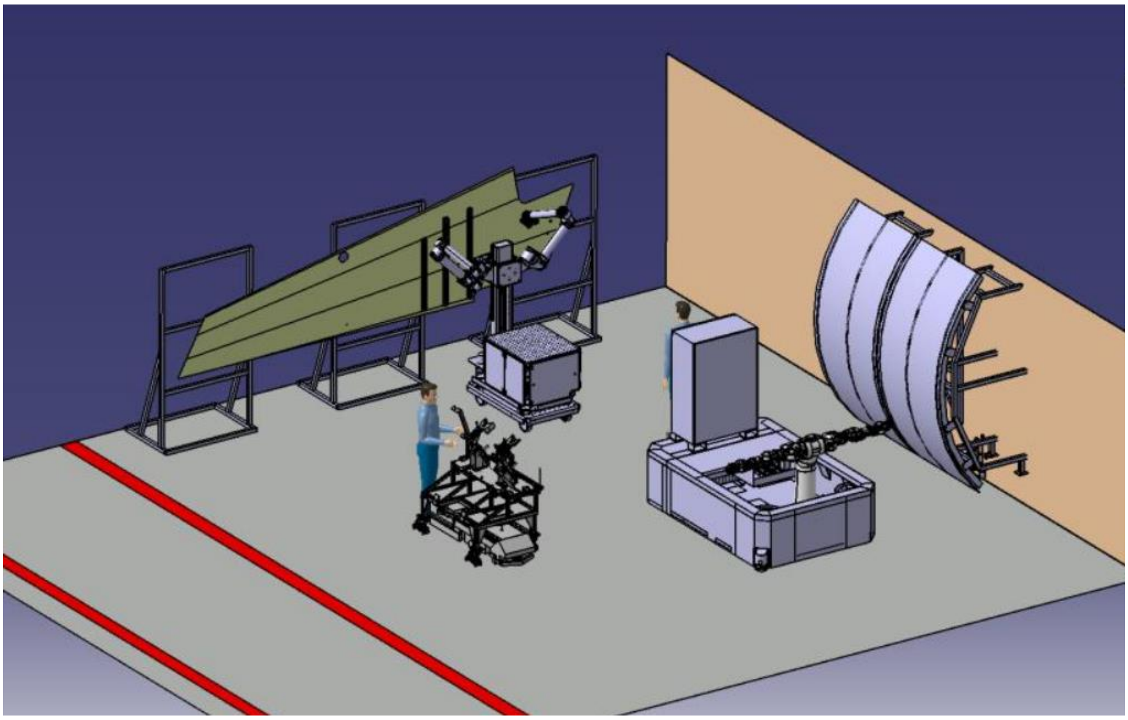
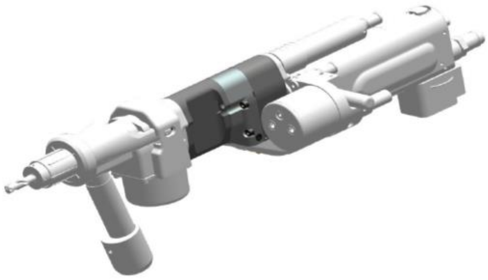
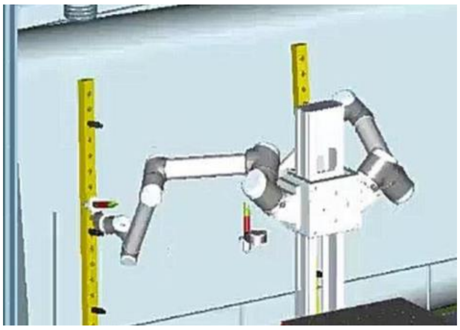
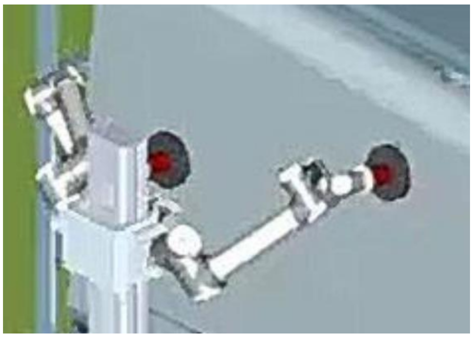
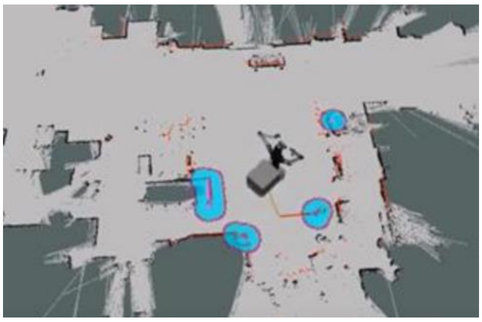


Figure 44: Simulation of the aeronautical layout use case at TECNALIA

In the Table 12, the simulated elements that have been used for testing and validating the developments before implementing in the actual robot can be found.

Table 12: Simulated components and processes of THOMAS aeronautics pilot case

Component	Simulated model
Pneumatic Drilling Machine SETITEC ADU	
Drilling simulation	
Sanding simulation	
Navigation	

8.3. Physical set up of the aeronautic OPS at TECNALIA

For the THOMAS aeronautics pilot case, a preliminary setup has been constructed and implemented at TECNALIA (Figure 45) and DGH premises, based on the simulated layout presented in previous figure (Figure 44).

8.3.1. Aeronautic pilot set up at TECNALIA

The aeronautic pilot set up prepared at TECNALIA premises contains three of the most usual and not automated processes of the aeronautic industry: aircraft skin drilling through templates, surface sanding and rivet installation quality check. These processes are no more than practical examples

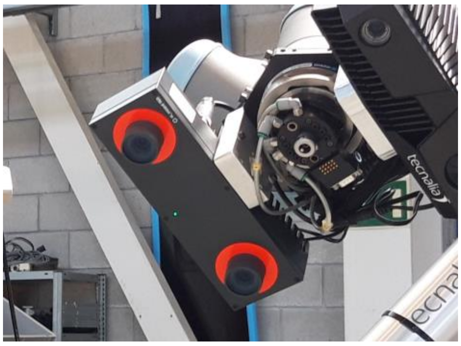
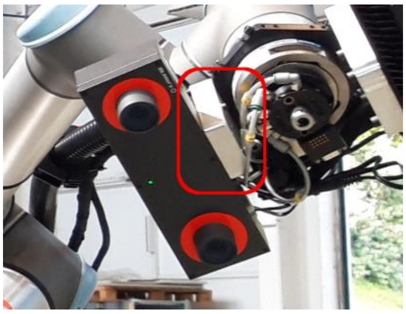
where the THOMAS aeronautic OPS can be applied. In the following sections the specific hardware and software that have been integrated in the THOMAS OPS.

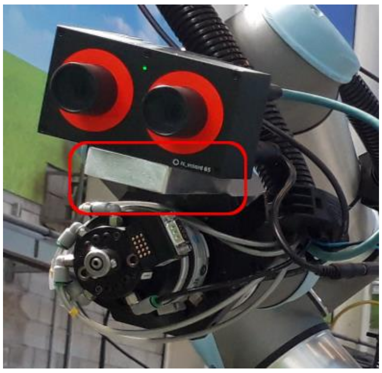
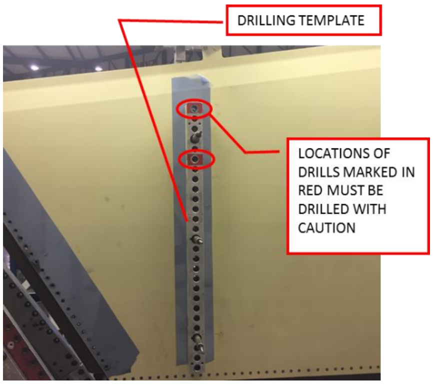
Figure 45: Aeronautic pilot set up at TECNALIA

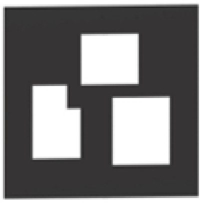
8.3.2. Hardware components of the aeronautic OPS in TECNALIA

The aeronautic THOMAS MRP have been equipped with the hardware compiled in Table 13.

Table 13: 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 [1]	Template detection. With the help of a texture projector can detect drilling templates installed in a flat wing surface	Left arm / drilling operation	
ROBOCEPTION rc_visard 160 stereo camera flange	Mount of ROBOCEPTION rc_visard 160 stereo camera	Left arm / drilling operation	

Hardware component	Use	Robot Configuration	CAD model OR real picture
Texture projector	Allow reducing lighting issues for ROBOCEPTION rc_visard 160 when operating	Pan/tilt of the MRP	
ROBOCEPTION rc_visard 65 stereo camera [1]	Detailed hole detection. After template is detected the holes are detected in sections of 8-10 holes for improving precision	Right arm / drilling operation	
ROBOCEPTION rc_visard 65 stereo camera flange	Mount of ROBOCEPTION rc_visard 65 stereo camera	Right arm / drilling operation	
Drilling Template	Template for drilling. Usually with quadrangular prismatic shape with a set of drill holes of the same diameter (at least most of the holes)	Human	

Hardware component	Use	Robot Configuration	CAD model OR real picture
AprilTag	In-cell navigation for different areas Tool exchanging station referencing	Located in each process area. Located in each tool exchanging station	
IDS CAMERA [19]	AprilTag detection for static docking. Allows a precise static docking through visual servoing techniques	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]	Preforming drillings. This tool can be considered semi-automatic, after insertion in the hole the concentric collet (tip of the tool) must be expanded for fixing into the template and then the drilling cycle must be triggered. Then the machine start drilling	Right arm / drilling operation	

Hardware component	Use	Robot Configuration	CAD model OR real picture
Pneumatic sanding machine [15]	Sanding surface. When the machine is provided with compressed air starts turning.	Right arm	
Rivet detection camera (to be decided if Gocator 3D Smart Sensor or Structure light cameras are used)	Rivet installation quality check	Left arm	 
On-Robot/Optoforce Force and Torque control Device [5][11]	These sensors provide information about the forces and torques applied to the tools. It allows maintaining the sanding machine in whole contact with the surface of the wing	Sensors are equipped alongside the drilling and sanding machine (right arm of the MRP)	

8.3.3. Software components of the aeronautic OPS in TECNALIA

The base software architecture, where all the developments have been implemented for the aeronautic OPS, is the THOMAS skill engine (more details can be found at D4.5). The skill engine provides mechanisms for creating, modifying, and composing skills using existing primitives. The skills allow the adaptation into different environments and situations configuring some key parameters. Available skills are stored in a skill library which can be interfaced from different modules, and finally are executed by the Execution Engine, which is the responsible of managing the execution flow, communication between skills, error handling, etc (see Figure 46).

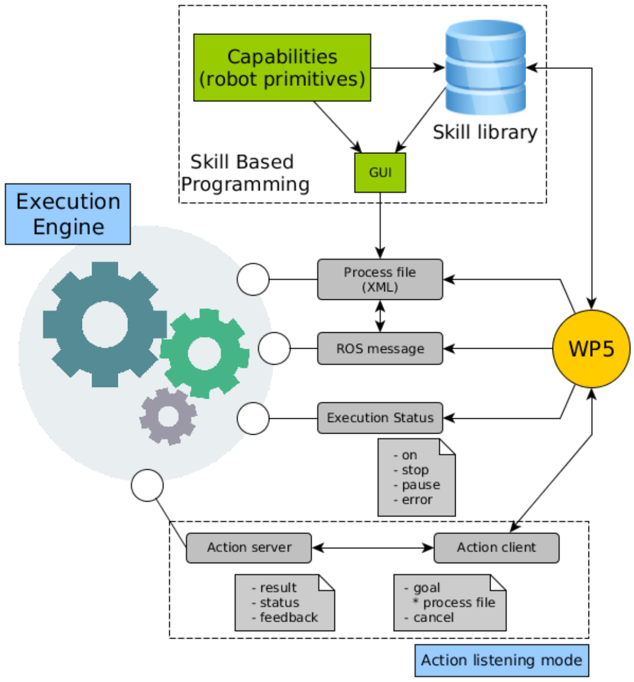


Figure 46: Summary of Skill Engine and its interfaces

On top of the Skill Engine the CAD Programming module can be found. It consists of an interface developed in Visual Basic that take advantage of the CAD information provided by Catia for configuring pre-programmed skills. From Catia software, operators can configure skills and generate the required XML files for the Execution Engine (more details can be found at D4.4). In the following figure (Figure 47) the main GUI of the CAD Programming module is presented.

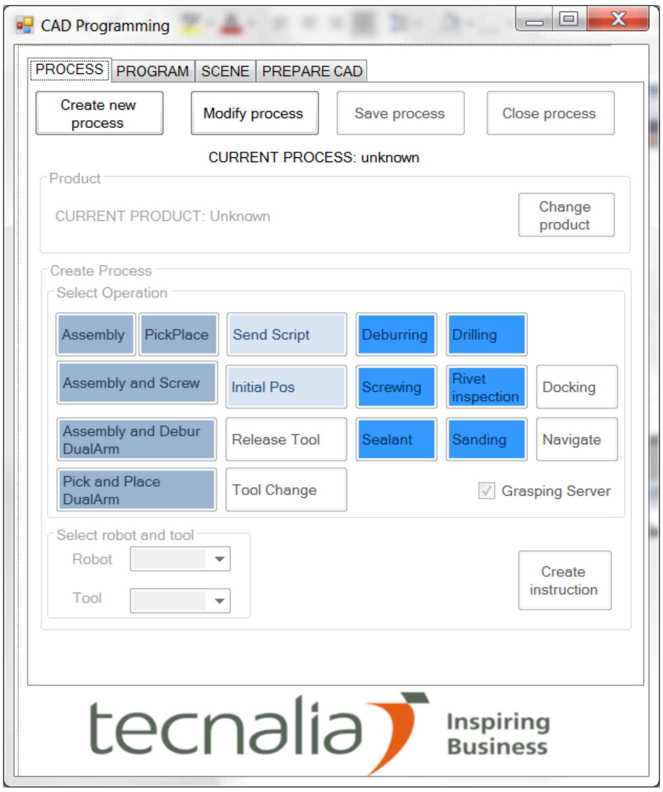


Figure 47: Main GUI of the CAD Programming module

8.3.3.1. Standard 2D based SLAM navigation

The navigation of in the OPS is composed of standard 2D laser-based navigation. Besides the navigation and localization implemented methods, some other actions were necessary for improving the efficiency and safety, namely, the improvement of the wheel low level management and the use of dynamically adaptable robot's footprint to have into account the robot's arm configuration while navigating. As presented in Figure 48, the CAD programming interface can be used for commanding a navigation goal. This action will generate a goal for the navigation stack (Figure 49).

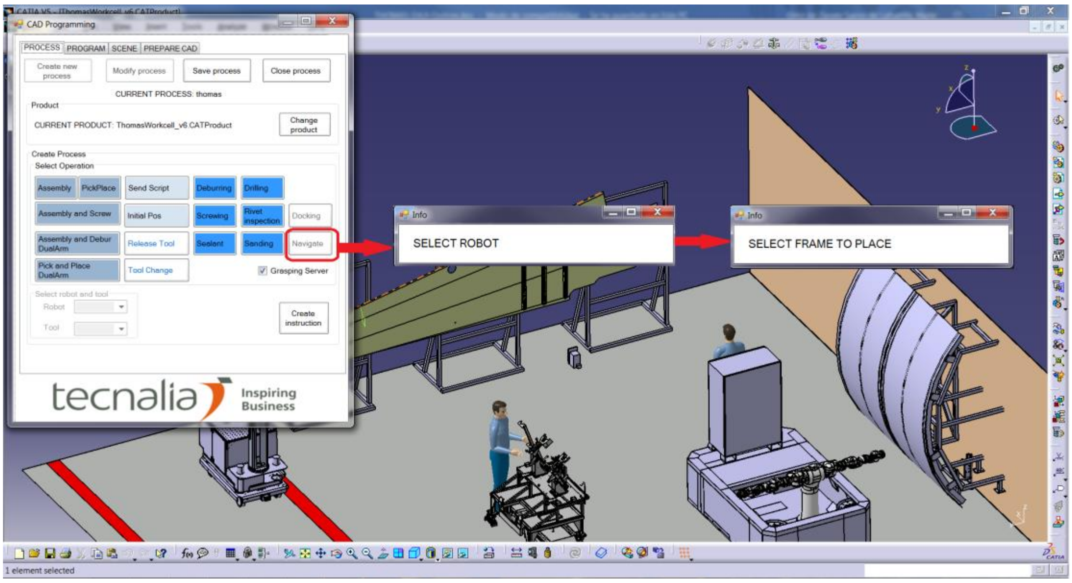


Figure 48: Sending a navigation goal through CAD Programming

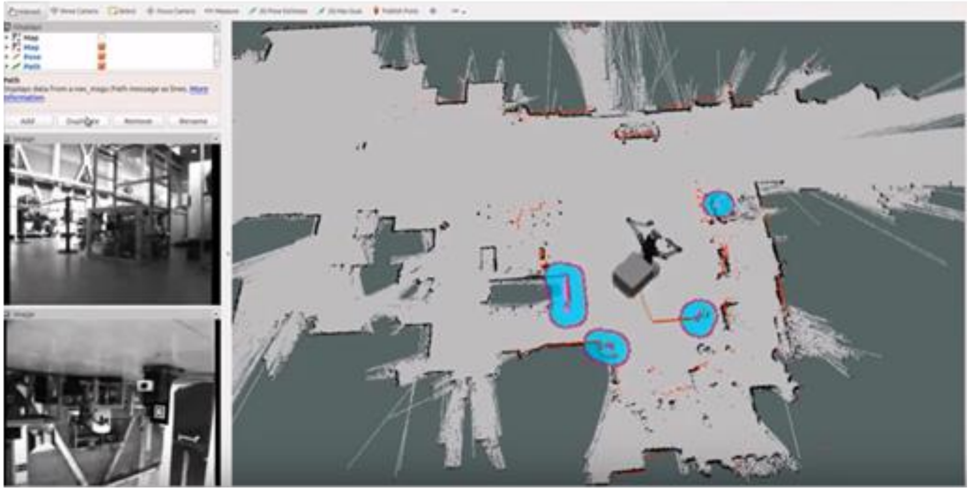


Figure 49: The goal is sent to navigation stack

8.3.3.2. 3D Perception based navigation

Laser-based navigation module consists of several limitations. The main limitations are robot's re-localization problems (robots must start navigation always at a known point in their map) and the limited 2D information about the obstacles comes from MRP's laser scanner sensors. To address these problems 3D perception is integrated inside THOMAS navigation module. In addition, the viability of using 3D semantic maps have been developed, tested and included in OPS n1. On the one hand, the 3D reconstructed map and robot trajectory can be found in Figure 50. On the other hand, in case of

obstacles inside the laser scanner's field of view (Figure 51), the detected elements are projected to the floor and treated as obstacles.

Figure 50: Final 3D map of the environment and robot trajectory

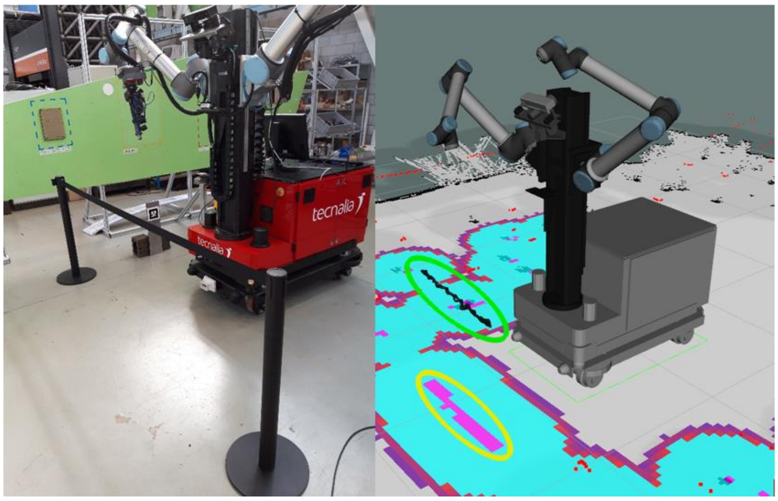


Figure 51: Obstacle above the laser's plane detected and projected to the obstacle map

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

The static docking is achieved using visual servoing with respect of a reference marker. This 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 and electrical power (Figure 52). The docking process is configured by simply selecting the camera of the OPS which is required and establishing the accepted tolerance (see Figure 53).

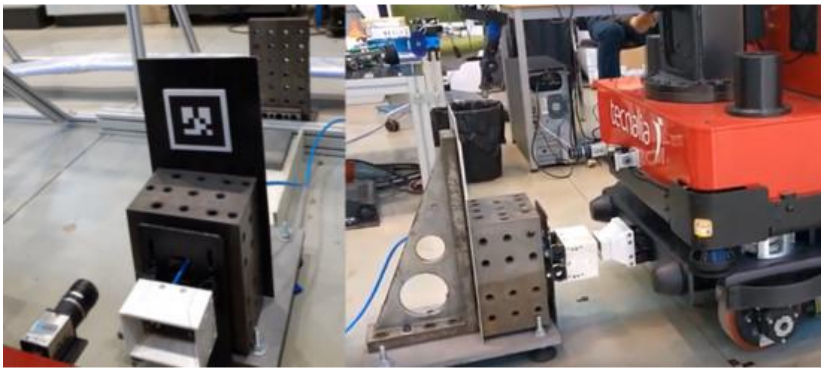


Figure 52: Docking system with charge station and marker installed

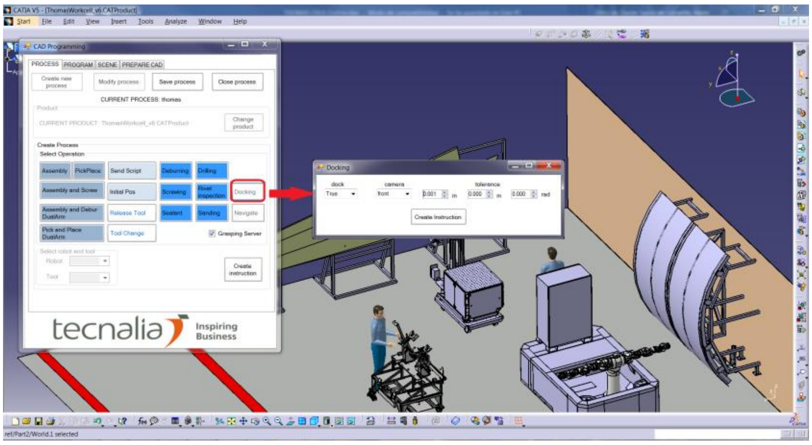


Figure 53: Configuring the dock skill through CAD Programming

8.3.3.4. Tool exchanging system

In order to face different industrial processes, the THOMAS aeronautic OPS has been prepared for using various tools. Since all the tools cannot be used at the same time, a tool exchanging system has been designed and implemented to enable the OPS a flexible behaviour from a hardware and tooling point of view. Each workstation contains an exchanging station with the required tools, and the OPS can automatically exchange the end-effectors through the easy-to-use interface and skill engine as presented in Figure 54. Figure 55 shows the mechanical design of the tool exchanging stations.

Figure 54: Tool exchanging configuration through CAD Programming

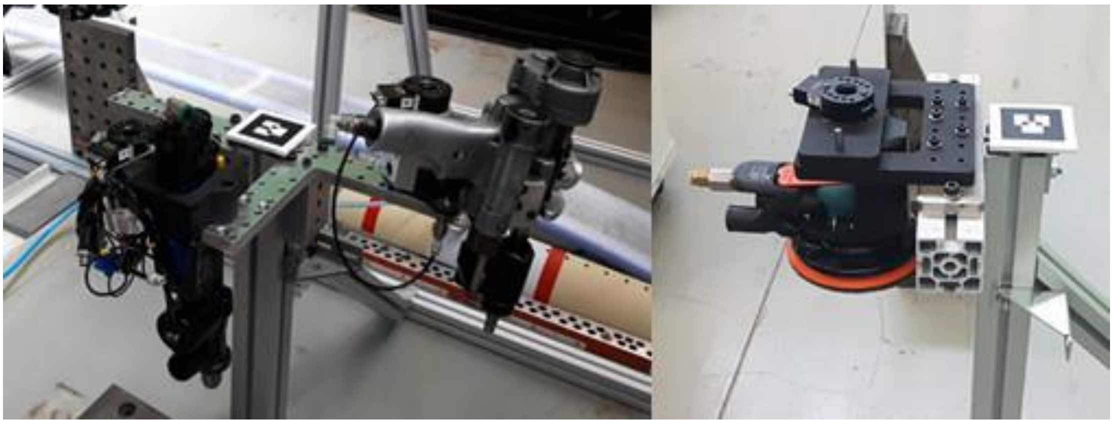


Figure 55: Mechanical design of the tool exchanging stations

8.3.3.5. Drilling on templates

THOMAS aeronautic OPS provides drilling capabilities through the CAD Programming interface and developed drilling skills (Figure 56). Drilling operation involves a ROBOCEPTION rc_visard 160 stereo camera and a texture projector for the template's detection, a ROBOCEPTION rc_visard 65 stereo camera and texture projector for the hole pose estimation, and a Setitec pneumatic ADU for drilling operations' execution (Figure 57).

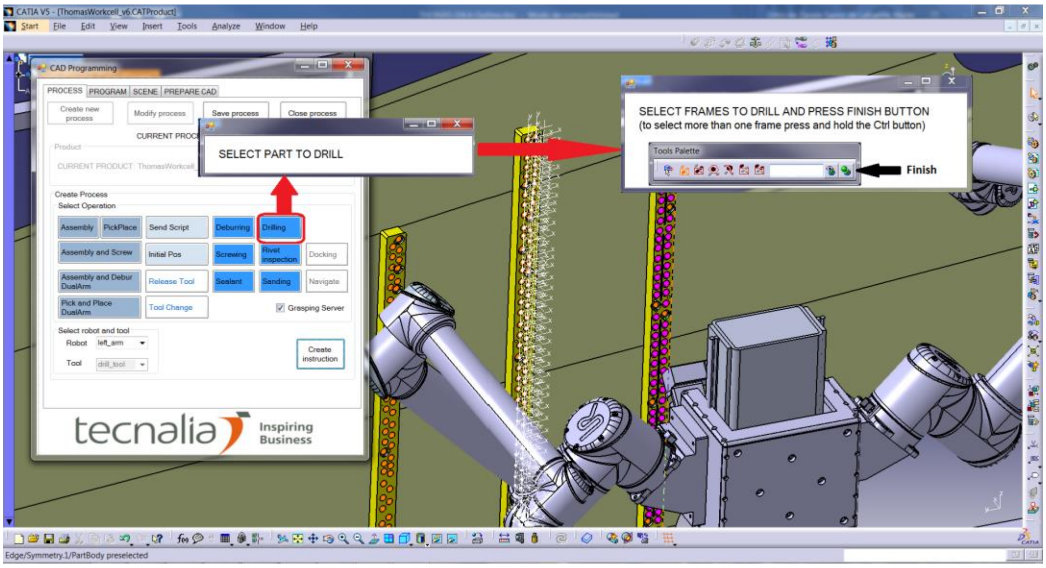


Figure 56: Drilling capability through CAD Programming

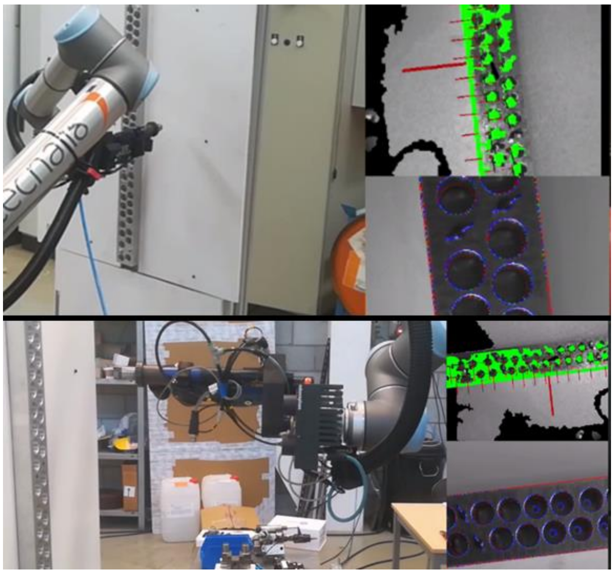


Figure 57: Involved hardware for drilling

8.3.3.6. Sanding Process

THOMAS aeronautic OPS allows the execution of paint sanding trying to replicate the corresponding human process (see Figure 58). Based on an On-Robot/Optoforce Force and Torque control device, it is feasible to maintain a controlled motion along the skin of an aircraft. Using the force control module, the sandpaper of the machine can constantly in contact with the surface, allowing a uniform sanding process.

As shown before, the CAD Programming interface provides an easy way for configuring a sanding process, simply selecting the arm with the appropriate tool and the target part to be sanded (see Figure 59).

Figure 58: Sanding capability developed in THOMAS

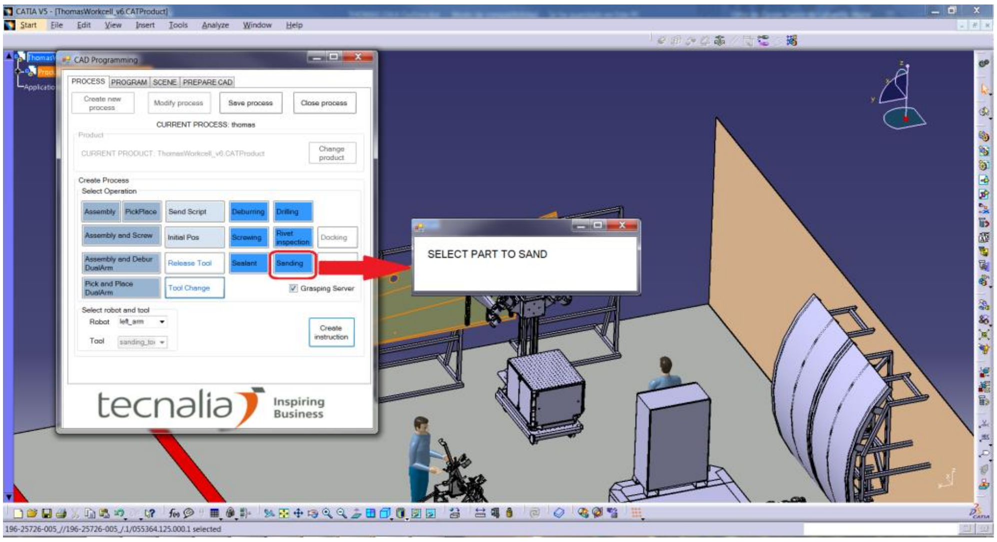


Figure 59: Sanding capability through CAD Programming

8.3.3.7. Rivet inspection

The aeronautic OPS developed in THOMAS project provides rivet installation quality inspection capabilities. Based on different sensors that have been tested in various conditions, the deviation of the rivet head with respect to the surface of the wing can be measured. In this way it can be determined if it is a valid installation or not. The rivet inspection skills can be triggered via the CAD Programming interface, in the same way with the other features. On the one hand, the Figure 60 shows how can be selected the rivet inspection operation. On the other hand, Figure 63 shows the results of the rivet inspection software and how this process can be executed using different vision sensors (Figure 61, Figure 62).

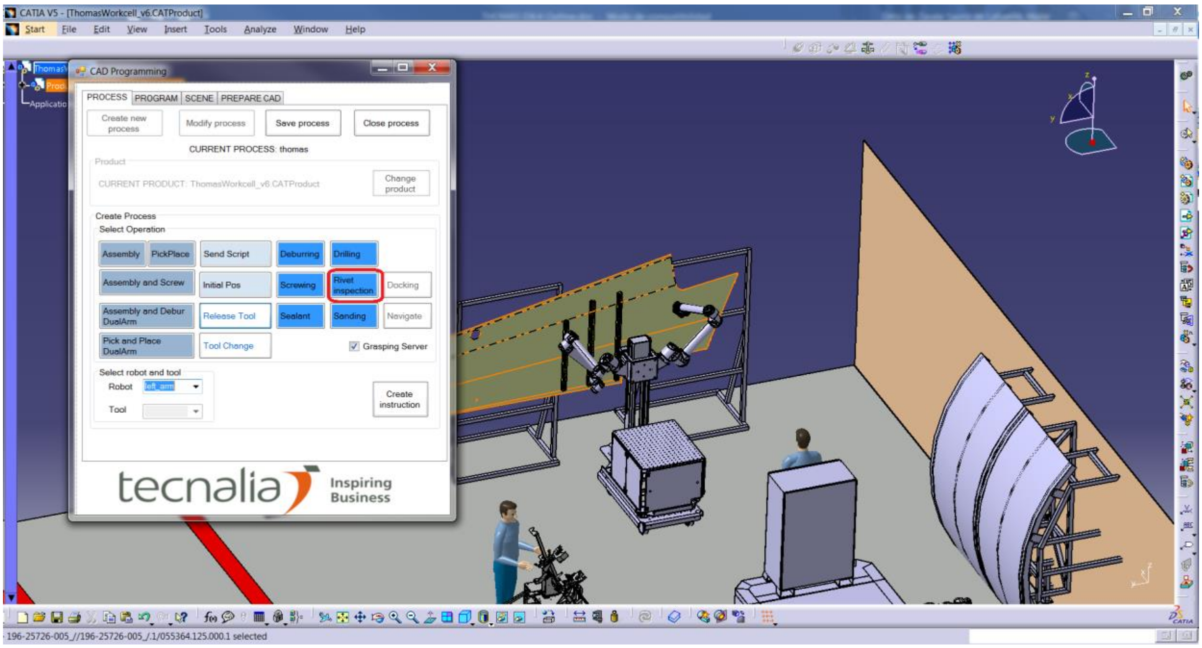


Figure 60: Rivet inspection capability through CAD Programming

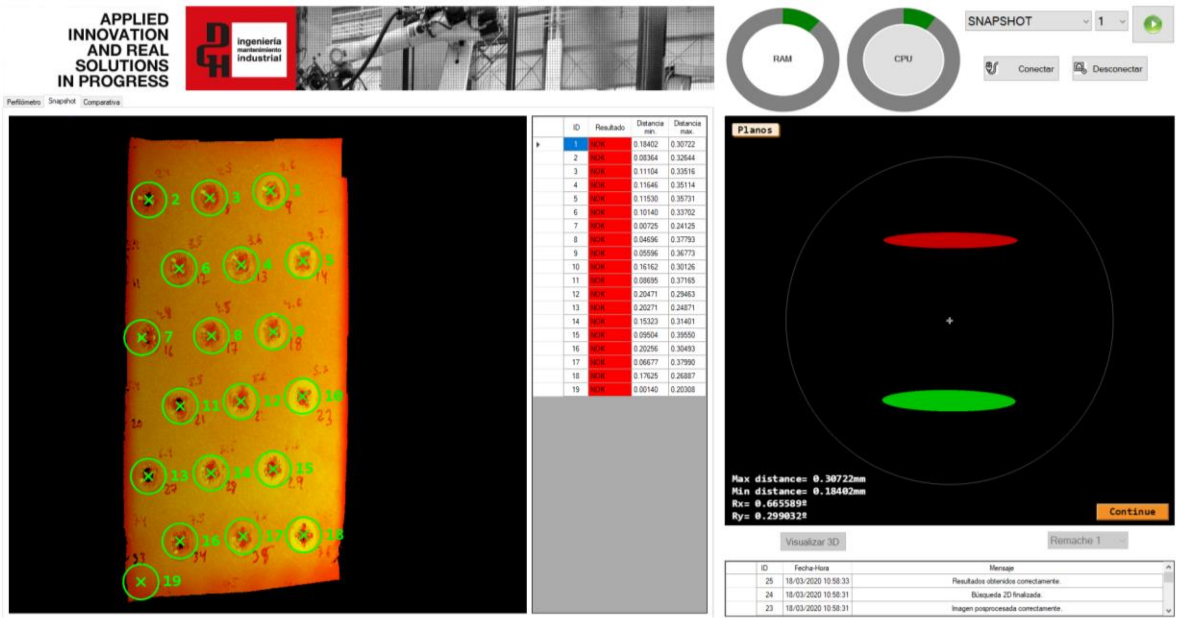


Figure 61: Snapshot Camera

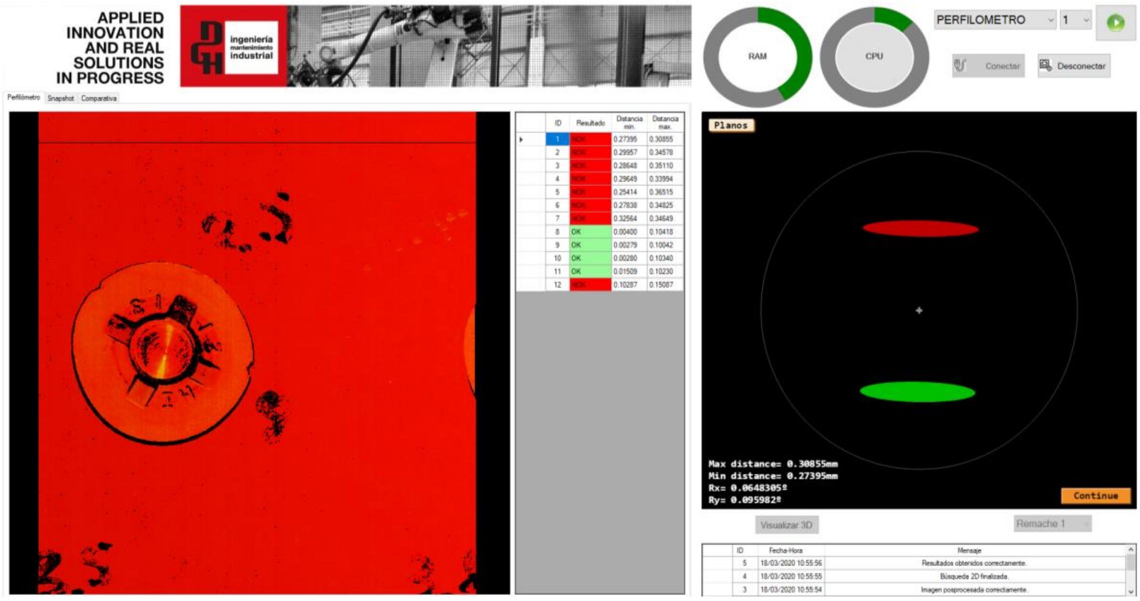


Figure 62: Profilometer camera

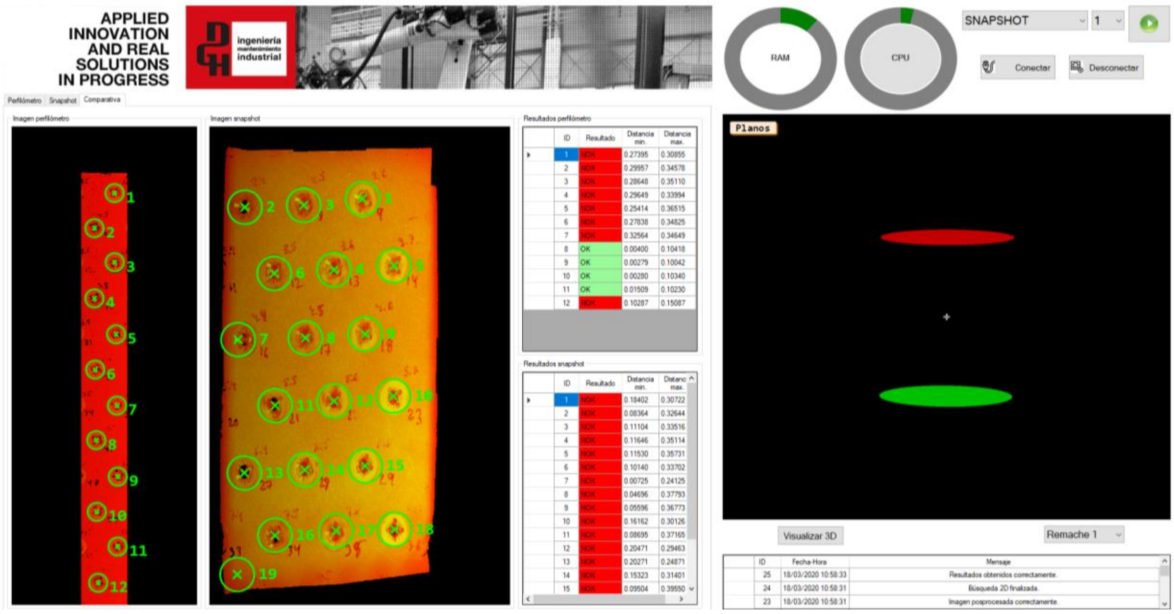


Figure 63: Rivet inspection software results: Snapshot-Profilometer-Comparison of Both

8.3.4. Safety concept

The safety concept of THOMAS project is partially demonstrated in the aeronautic OPS due to the installed modules on the MRP_n1. Based on the fact that a newer version of the MRP in included in the automotive OPS and the safety concept based on this MRP, the full safety concept is demonstrated in the automotive use case. Trying to maintain the consistency of the whole system, THOMAS safety system has been partially integrated inside the aeronautic OPS.

To guarantee the safety, two different safety modes have been implemented, the safety during operation and the safety during navigation. Due to the limited integration of the safety modules, this zone switching action must be triggered when the robot docks to a docking station.

8.3.4.1. Safety during operation

The OPS n1 is equipped with two safety laser scanners (SICK S300 laser scanners) placed at the two corners of the MRP. These devices provide a field of view of 360 degrees in total. They are connected

with a general safety relay capable to switch the robot down in case that any obstacle enters in their field of view. The initial target was to replace the SICK S300 with the Microscan 3 laser scanners but trying to assure the consistency of the whole MRP this migration has been done partially. Until M42 of the project, the laser scanner sensors and the Flexisoft modules have been installed on aeronautic OPS MRP, but the ECU for human detection process has not been integrated.

To guarantee the human safety inside THOMAS, no humans will be able to work near the robot during operations' execution. If an operator is detected very close to the MRP, closer than the security limit of safety fields (1.5 meters near UR robots and 0.5 meters behind the MRP) the robot system will enter in an emergency stop.

8.3.4.2. Safety during navigation

Using the same safety hardware in the operation mode, the aeronautic OPS must guarantee that in case of MRP's autonomous navigation, operators are able to execute their processes in a safety way either if they are detected inside the cell (when OPS is executing in-cell navigation), or in the general area of the shopfloor (when is executing cell-to-cell navigation).

With the hardware installed in the OPS n2, the safety zones can be dynamically modified depending of the speed and direction of the MRP and combined with human detection modules. Since the aeronautic OPS does not have completely integrated all safety modules the safety zone must be static (0.5 meters around the whole OPS), reducing the efficiency of the path planner and the navigation stack.

9. PILOT CASE MITIGATION PLAN & ECONOMICAL / TECHNICAL GAINS

T Upon the completion of the first period of the project (M18), THOMAS consortium supported by the Expert reviewer have identified the need to incorporate a strategy to address the following issues:

9.1. Aeronautics Pilot Case – End User: AERNNOVA

The following sub-sections are focusing on the mitigation plan and the cost – benefit analysis performed for the aeronautics pilot case of the project.

9.1.1. Aeronautics pilot case mitigation plan

The aeronautics sector, focusing on the production paradigm adopted, has great different compared to the automotive sector. In contrast with the automotive assembly lines, the aeronautics shopfloors are organized in job shops. Given the personalized nature of their products, the process requirements are changing rapidly as well as the configuration of the job shops. To this extend, AERNNOVA is really interested on the deployment of robots that can autonomously navigate in different workshops undertaking multiple tasks. Assessing the application of THOMAS OPS on the tree selected workstations (drilling, riveting and paint sanding) by AERNNOVA, it was resulted that this is still up – to – date and in accordance with their agenda. However, the applicability in additional use cases has been investigated so to have them as a back up solution. Two use cases have been selected and are described in the following sub-sections.

9.1.1.1. Application of sealants on the product structure

The process can be altered by the specific requirements of the parts of the structure to be manufactured, but basically consists of:

Table 14: Sealant application on the product structure

STEP	TASK	PERFORM BY
1	Carry out deep cleaning of the surface where the sealant will be applied, and also on the surface of the other joint face, if applicable.	HUMAN
2	verify correct cleaning	HUMAN
3	Apply the sealant. Depending on the type of application, the sealant must be "worked" in different ways: - Extend it by the surface. - Form "button" in rivets. - Form "fillet" on the edges of pieces.	THOMAS MRP
4	Verify correct application	HUMAN

The following figure presents some technical specifications on the process that needs to be execution in this workstation.

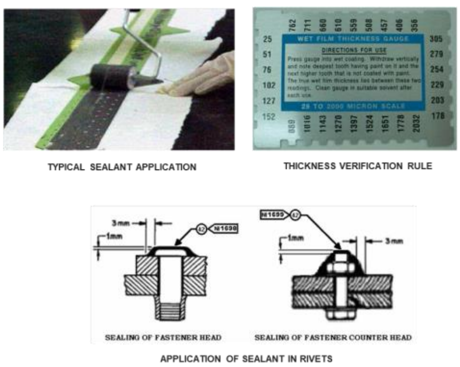
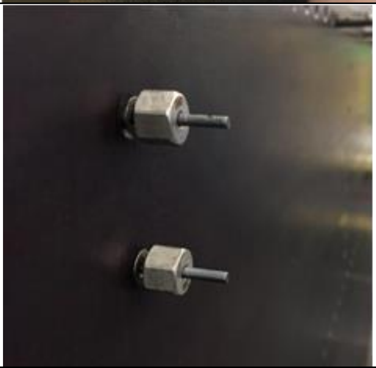


Figure 64: Sealant application to product structure

9.1.1.2. Structure riveting by means of a blind rivet (MBF type)

The process can be altered by the specific requirements of the parts of the structure to be manufactured, but basically consists of:

Table 15: Structure riveting workflow

STEP	TASK	PERFORM BY	Process figure
1	Sealant wetting of rivets and drills	HUMAN	
2	Insert the rivets into the drills	HUMAN	
3	Attach the rivet-gun to the rivet	THOMAS MRP / COLLABORATIVE	
4	Operate the rivet-gun until the rivet rod breaks	THOMAS MRP / COLLABORATIVE	
5	Discard rivet rod	THOMAS MRP / COLLABORATIVE	
6	Repeat steps 3 to 6 until complete riveting of the union	THOMAS MRP / COLLABORATIVE	N/A
7	Clean the excess sealant	HUMAN	

9.1.2. Aeronautics pilot case cost Technical / Economical gains

9.1.2.1. **Technical gains – Key Performance Indicators (KPIs)**

To quantify the technical benefits from the THOMAS OPS deployment in the AERNNOVA pilot case specific KPIs have been defined and are kept – up – to date since the first months of the project during the industrial pilot case scenarios definition phase.

The KPIs being presented in the following tables are to be understood in this context. Thus, the KPIs for drilling are quite accurate numbers measured from a TRL 6 automation process of various sample drilling templates. In the sanding and rivet inspection cases, the KPIs are measured over proof of concept developments.

The KPIs status M42 will be presented in the following tables. In Aeronautics use case the KPIs updates of M36 status is not significant because we have pendant the installation of demonstrator in real layout for to have real measurement of KPIs of the different processes.

Aeronautic use case's KPIs have not change in last 6 months of the project because all integration tasks are pendant that the demonstrator is on the real Aeronautic use case layout (AERNNOVA Factory Berantevilla (Spain)). This open issue has been delayed for several medical reasons (Covid19 virus Pandemic) at least M46.

In this way we are presented in order of the processes: Drilling, Sanding and Riveting inspection KPIs tables:

Table 16: Drilling use case KPIs

KPI	Baseline	M42	Target
Cycle time per 7 holes **	0,31*7 = 2,17min 2,7 hrs (520 drills)	2 min 2,47 hrs (520 drills)	0,16*7 = 1,12 min 1,42 hrs (520 drills)
Incorrect diameter drills (%)	0,015 % (6000 drills)	To be tested ***	0,01 %
Drills not made (%)	0,015 % (6000 drills)	To be tested ***	0,01 %
Amount of rework (CP, CPK)	CP 1,5 (Sigma of the process 4,5) *	To be tested ***	CP 2 (Sigma of the process 6)*
Time to deploy for new product ****	N/A	6h	3h
Task sharing level with human	0 %	To be tested ***	80 % robot - 20% human
Level of automation	5 %	To be tested ***	80 %

***** EN 9103: This Aerospace Standard is designed to drive the improvement of manufacturing processes through adequate planning and effective management of Key Characteristic variation. The Key Characteristic focus is intended to improve confidence for part features whose variation has a significant influence on end product form, fit, performance, service life and manufacturability.

CP 1,5 (process capability) indicates that for every 10000 holes in 13.5 we will have some type of defect, such as forgetting to perform it.

six sigma table.xls

*** Drilling tests in real part planned to be done from M40. DELAYED at least until M46
**** Time to re-program and re-configure with the OPS already running in AERNNOVA

Table 17: Paint sanding process use case KPIs

KPI	Baseline	M42	Target
Cycle time	0,2 h/m2	0,18 h/m2	0,16 h/m2

Time of exposure of person to cromates or dust	2h/person and day *	To be tested in AERNNOVA	0,5h /person per shift **
Sanding of all required surfaces (%) ****	98 %	To be tested with a real wing model	95%
Time to deploy for new product***	N/A	6h	3h
Task sharing level with human	0 %	To be tested in AERNNOVA	30%
Level of automation	5 %	To be tested in AERNNOVA	70%

* Needed 4 people by shift (8h) three shifts per day

** Robot maintenance tasks etc.

*** Time to re-program and re-configure with the MRP already running in AERNNOVA
With the MRP already running in AERNNOVA. DELAYED at least until M46

**** Sanding of all required surfaces is expected to be slightly smaller in the automated case because the robot might not be able to sand in some of the parts of the wing for reachability or configuration problems. The final volumes of the surfaces that can be sand will be calculated from a CAD simulation.

Table 18: Riveting use case KPIs

KPI	Baseline	Target
Assure all rivets are inspected	0 %	100 %
Optimization in reliability of the process against the manual scanning (% should be at least the same)	N/A (Manual process, not scanned)	10 %
Cycle time / manual scanning with sensor / manual scanning with measurement comparison clock (time)	5 Seg./Rivet (manual inspection with measurement comparison clock)	5 Seg./Rivet
Successfully marking of the incorrect rivets (%)	N/A	100%
Rivet detection (*) (%)	95 %	100 %
Time to deploy	N/A	3h
Task sharing level with human	N/A	5 %
Level of automation	0 %	95 %

In Riveting inspection use case, the KPIs status in M42 are very close to the final version because this process is implemented in Aeronautic OPS and running well.

9.1.2.2. **Economic gains – Cost benefit analysis**

Following the cost – benefit analysis performed for the PSA case, the same strategy has been implemented for investigating the economic gains for the AERNNOVA pilot. In this first version of the business case the focus has been given in the drilling use case of the aeronautics scenario.

The same two groups of costs, the investment and the annual operating cost have been used for quantifying the comparison of the current manual drilling set up to the THOMAS OPS deployment (optimistic and pessimistic case).

Table 19 analyses the investment cost that was required for the current set up at AERNNOVA as well as the for the two cases of THOMAS OPS implementation. This exercise has been done for the case of drilling which, has been the most interesting case to be automated for AERNNOVA from the beginning of the project. In addition, following the increase of interest of the paint sanding operation

automation, the same exercise has been done for it. The cost – benefit analysis was not done for rivet quality inspection operation because it has been selected as the less interesting process which is not envisioned to be included in any automation plans inside AERNNOVA in the near future.

Table 19: Drilling – Investment cost of Current AERNNOVA state vs THOMAS OPS (2 cases)

	Manual Drilling	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Equipment Cost	65.200€ (60.000€ for drilling templates, 5.200 €/Unit for drilling machine)	204.500€ (140.000€ for MRP, 60.000€ for drilling templates, 5.200 €/Unit for drilling machine, 2.000€ for fixtures)	271.200€ (200.000€ for MRP, 60.000€ for drilling templates, 5.200 €/Unit for drilling machine, 6.000€ for fixtures)
Consumables / sensors cost	-	5.000€	7.000€
Commissioning labour cost	2.300€ (tooling set-up)	4.000€	23.000€
Energy lines (Electric, Pressurised air etc.)	752€ (start-up)	9.000€	20.000€
Total investment Cost (€)	**68.252€**	**222.500 €**	**321.200 €**

In the following table, the operating costs of the above cases has been estimated by the consortium based on current values from the end user and experience of the technology providers and the system integrators.

Table 20: Drilling – Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Manual Drilling	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Engineering cost (per year)	218€	2.000€	2.000€
Maintenance cost (per year)	1.152€ (Drill spare parts)	4.000€	4.000€
Operation cost – Electricity, pressurized air (per year)	60.000€ (Drills)	62.000€	62.000€
Labor cost (1 person, 2 shifts, 220 days) (per year)	124.500€	30.000€ (1 operator)	30.000€ (1 operator)
Cost for quality defects (per year)	180€	100€	100€
Cost due to MSD[2] (per year)	1.000€	400€	400€
Total Running Cost (€)	**187.050€**	**98.500€**	**98.500€**

Following the same procedure with the drilling use case of the aeronautics scenario, the investment and the operating cost for the sanding use case are presented in Table 21 and Table 22 accordingly.

Table 21: Investment cost of Current AERNNOVA state vs THOMAS OPS – Sanding use case (2 cases)

[2] MSD: Musculoskeletal Disorders. These are caused due to the non-ergonomic nature of human operators' tasks. This leads in injuries of humans and thus their unavailability for specific period.

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Equipment Cost	90.300€ (90.000€ Sanding booth, 300€/Unit for ro- torbital sander)	231.300€ (140.000€ for MRP, 90.000€ Sanding booth, 300€/Unit for ro-torbital sander, 1.000€ for fixtures)	291.300€ (200.000€ for MRP, 90.000€ Sanding booth, 300€/Unit for ro-torbital sander, 1.000€ for fixtures)
Consumables / sensors cost	-	5.000€	7.000€
Commissioning labour cost	100€ (tooling set-up)	4.000€	23.000€
Energy lines (Electric, Pressurised air etc.)	100€ (start-up)	9.000€	20.000€
Total investment Cost (€)	**90.500 €**	**249.300 €**	**341.300 €**

Based on the above analysis, the payback Head To Head Point (HTHP) has been calculated for both the optimistic and pessimistic case of cell deployment. As illustrated in Figure 65, in the optimistic case the HTHP is in 21 months, while for the pessimistic case is in 34 months.

Table 22: Operating cost of Current AERNNOVA state vs THOMAS OPS – Sanding use case (2 scenarios)

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Engineering cost (per year)	218€	2.000€	2.000 €
Maintenance cost (per year)	2.000 €	4.000€	4.000 €
Operation cost – Electricity, pressurized air (per year)	6.000€	62.000€	62.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	124.500€	30.000€ (1 operator)	30.000 € (1 operator)
Cost for quality defects (per year)	180€	100€	100 €
Cost due to MSD* (per year)	1.000€	400€	400 €
Total Running Cost (€)	**133.898€**	**98.500€**	**98.500 €**

Based on the above analysis, the payback Head To Head Point (HTHP) has been calculated for both the optimistic and pessimistic case of cell deployment for the drilling and the sanding use cases of the aeronautic scenario. Regarding the drilling use case, as illustrated in Figure 65, in the optimistic case the HTHP is in 21 months, while for the pessimistic case is in 34 months.

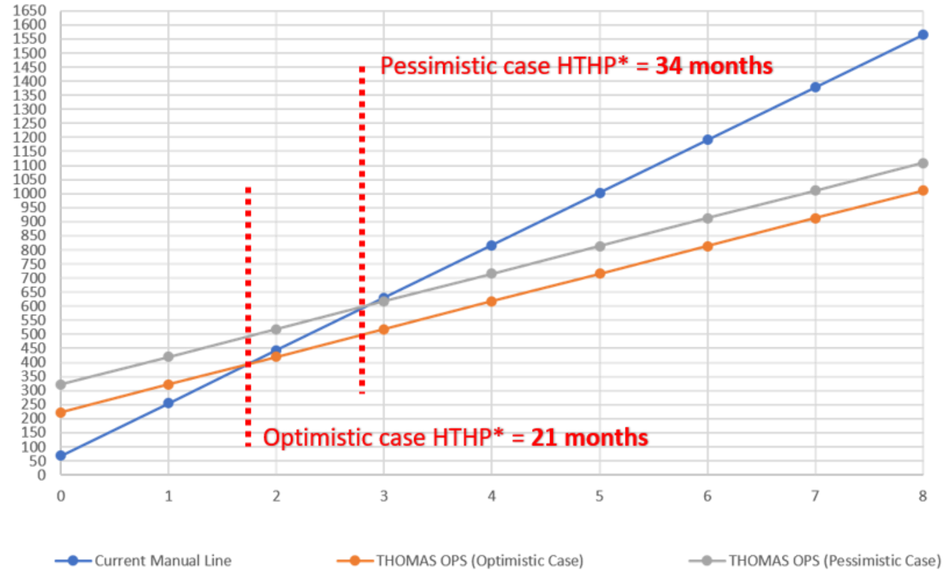


Figure 65: HTHP[3] after THOMAS OPS deployment in drilling use case

As for the sanding use case, as presented in Figure 66, in the optimistic case the HTHP is in 54 months, while for the pessimistic case is in 88 months.

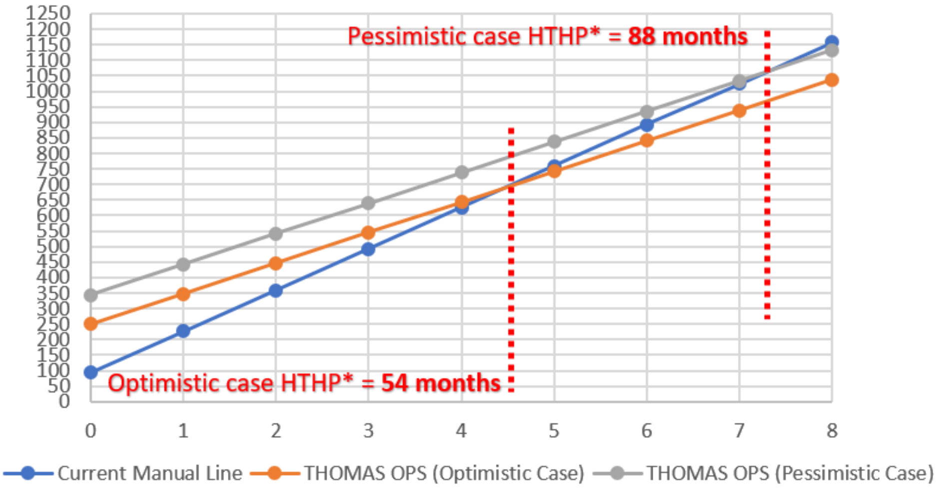


Figure 66: HTHP[4] after THOMAS OPS deployment in sanding use case

COMBINED ANALYSIS DRILLING AND SANDING

Even if independent analysis per operation is interesting. A combined analysis gives a good indication of the strength of a flexible solution such as this of THOMAS. It has been considered that one MRP can perform the drilling and sanding operations required in AERNNOVA in one year. This is not 100% accurate as it might happen that in peak work times the would be required an additional robot to drill and sand in parallel, but it gives an idea of the strength of the flexibility of the solution. In a future workshop it is expected that robot work shifts would be organized in order to optimize the amount of MRPs required to perform all the operations.

[3] HTHP: payback Head To Head Point

[4] HTHP: payback Head To Head Point

Table 23: Drilling and Sanding – Investment cost of Current AERNNOVA state vs THOMAS OPS (2 cases)

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Equipment Cost	90.300€ (90.000€ Sanding booth,300€/Unit for ro-torbital sander) 65.200€ (60.000€ for drilling templates, 5.200 €/Unit for drilling machine)	298.500€ (MRP: 140.000€, drilling:65.200€, sanding:90.300€, fixtures:3000€)	356.500€ (200.000€ for MRP, 65.200€ drilling, 90.000€ Sanding booth,300€/Unit for ro-torbital sander,1.000€ 1for fixtures)
Consumables / sensors cost	-	10.000€	7.000€
Commissioning labour cost	100€ (tooling set-up)	8.000€	23.000€
Energy lines (Electric, Pressurised air etc.)	100€ (start-up)	18.000€	20.000€
Total investment Cost (€)	**155.700 €**	**334.500 €**	**406.500 €**

Table 24: Drilling and Sanding – Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Engineering cost (per year)	436 €	2.000 €	2.000 €
Maintenance cost (per year)	3152	5.000 €	5.000 €
Operation cost – Electricity, pressurized air (per year)	14.000 €	124.000 €	124.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	249.000 €	30.000 €	30.000 €
Cost for quality defects (per year)	360 €	100 €	100 €
Cost due to MSD* (per year)	2.000 €	400 €	400 €
Total Running Cost (€)	**268.948 €**	**161.500 €**	**161.500 €**

In case for a combination between the sanding and the drilling use cases, as presented in Figure 67, in the optimistic case the HTHP is in 20 months, while for the pessimistic case is in 28 months.

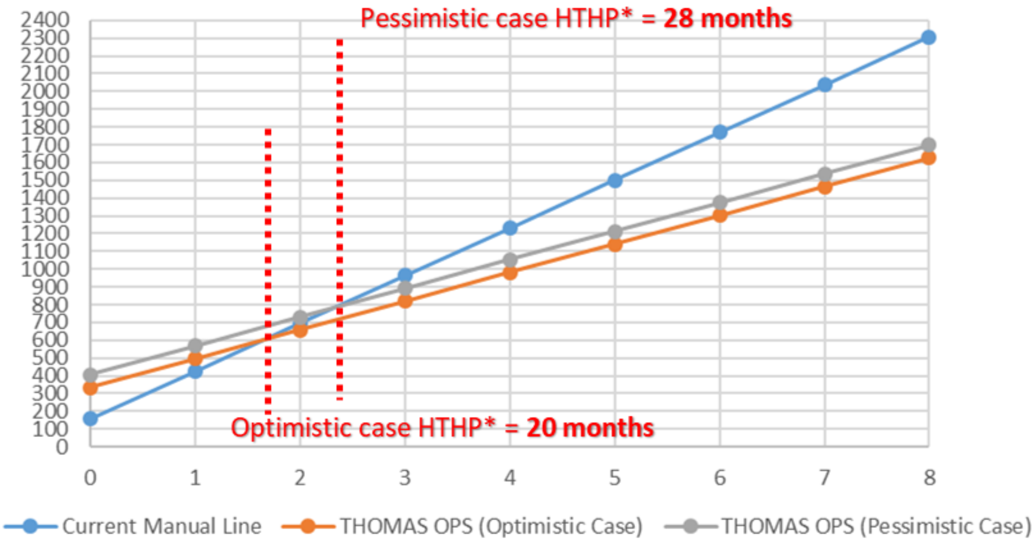


Figure 67: HTHP[5] after THOMAS OPS deployment in combined drilling and sanding use cases

[5] HTHP: payback Head To Head Point

10. CONCLUSIONS

The final version of THOMAS Open Production Station (OPS) as a Product is presented in the above sections. Through the running period of the WP6, all partners' activities have been oriented around: a) Start running all processes of the THOMAS Mobile Resources and b) Integrating and implementing the final prototype of the individual resources under the final testbeds set up at LMS and TECNALIA premises.

On M42 of the project, both THOMAS OPS n1 and n2 are prepared for the execution of all THOMAS activities in real demonstrators' areas in both end users' premises that will take place by the end of the project (M48).

The fine tuning and final integration activities for THOMAS OPS is running with the target on transferred to the real layout of the final demonstrators that will take place on the last 6 months of the project until M48.

Finally, each use case's mitigation plan and economical gains as presented in deliverables D7.3 and D7.4 are documented in the above sections and no further updates have been reported since M36 of the project.

11. GLOSSARY

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

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