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CONVERGING

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DELIVERABLE

D7.2 – Open pilots – Operating status and execution report

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Executive Summary

This deliverable outlines the updates and enhancements implemented across the various Open Pilot Lines between Month 24 (M24) and Month 36 (M36) of the project. These developments involve hardware modifications, software integrations, and other relevant improvements aimed at advancing the technological capabilities of the pilot lines.

The document also reports on the outcomes some of the training provisioning activities done using the CONVERGING Open Pilot Lines. This includes a summary of dissemination and training actions carried out by project partners, such as webinars, workshops, and capacity-building sessions.

Additionally, this deliverable presents the Human Factors and Operator Training Methodology developed by Cranfield University, which offers a structured approach to enhancing operator interaction and performance within the pilot environments.

Also, each Open Pilot section includes a dedicated subsection on the corresponding Industrial Pilot. These sections provide an initial overview of the transition process from Open Pilot to Industrial Pilot, detailing aspects such as final layouts, end-user engagement, assessment structures, implementation timelines, and relevant regulatory considerations.

Section 1 introduces the purpose of this document, highlighting the importance of Open Pilot Lines in fostering innovation and experimentation within manufacturing processes. It details the objectives and structure of the deliverable, offering readers a clear and organized framework.

Section 2 delves into the details of each Open Pilot Line within the CONVERGING network. For each of the Open Pilot Lines, the section showcases its value proposition, a description of the initial setup, including the required hardware and involved modules. Last each OPL presents the next steps to follow and a detailed training plan.

The Automotive Open Pilot Line, managed by TECNALIA, mitigates the risks faced by operators performing repetitive tasks such as polishing draw dies. In this pilot, the robot and operator work together to inspect the dies. The robot then efficiently polishes the damaged areas, extending the dies' lifespan. This collaboration not only enhances production in the automotive industry but also frees operators from hazardous and repetitive tasks.

The White Goods Open Pilot Line, operated by IPK, offers a platform for developing and training assembly tasks for household goods, focusing on the manipulation of small parts, cables, and gaskets. This initiative aims to enhance the automation-readiness of European white-good manufacturers and advance suitable technologies for automating these traditionally manual tasks. By addressing these challenges, it seeks to streamline production processes and position European manufacturers at the forefront of technological innovation in the sector.

The Aeronautics Open Pilot Line is designed and implemented by LMS and hosted at TF-CC premises. This Open Pilot implements smart collaborative robotic solutions for remote inspection and maintenance of aircraft fuel tanks. This would allow to ensure the operator's safety while efficiently executing the complex and dangerous maintenance procedures.

Two complementary Open Pilot Lines (OPLs) have been established for the additive manufacturing use case. The AIMEN OPL focuses on handling, postprocessing, and transporting heavy metal components while ensuring data traceability, simulation, and

ergonomics, and provides training and technical services to support adoption. The LMS OPL, located within TF CC, replicates a realistic industrial environment with a high-payload collaborative robot, safety systems, and an AGV to validate modules involving close human–robot interaction, such as AR/VR-assisted finishing tasks. Together, these OPLs form a scalable and robust testbed where CONVERGING technologies are developed, integrated, and validated, supporting their successful industrial implementation at PRIMA.

Section 3 outlines the forthcoming steps for each Open Pilot Line (OPL) to ensure effective service provisioning. It details the specific actions required to operationalize each OPL, including the development and implementation of comprehensive training plans. These steps are designed to enhance the capabilities of the OPLs, ensuring they are well-equipped to support industry needs and encourage technological advancements.

Section 4 concludes the document by summarizing the pivotal role of Open Pilot Lines (OPLs) in the advancement of manufacturing technologies and reiterates the importance of these facilities in fostering collaboration among industry stakeholders.

This deliverable focuses on the operational status of the Open Pilot Network as reported in D7.1, outlining the key developments, results, and an initial perspective on the forthcoming transition to Industrial Pilots. Further technical enhancements and additional updates will be detailed in Deliverable 7.3, including final enhancements in the OPLs and following the full deployment of the Industrial Pilots at the manufacturing sites.

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Definitions, Acronyms and Abbreviations

Acronym/Abbreviation	Title
AIDT	AI Digital Twin
AISC	AI Station Controller
ARBA	Autonomous Robot Behavior Adjustment
CRC	Collaborative Robot Control
DAR	Data at Rest
DIM	Data in Motion
DWR	Dynamic Work Reorganization
HGC	Hand Guided Control
HPCM	High Payload Collaborative Manipulator
HR	Human Resources
HRI	Human Robot Interaction
MACI	Multi-Actor Contextual Interfaces
PAM	Perception & Autonomy module
PFL	Power and Force Limited
SAM	Safety Assessment and Monitoring
SRP/CS	Safety Related Parts of the Control System
SSM	Speed and Separation Monitoring
TDM	Teaching by Demonstration Module
UML	Universal Modelling Language
WP	Work Package
DWR	Dynamic Work Reorganization

1 Introduction

1.1 Objectives

The CONVERGING initiative has created a network of Open Pilot Lines (OPLs) to demonstrate advanced methodologies and technologies to manufacturing companies. This document offers a comprehensive overview of the design and initial setup of the four OPLs developed under the CONVERGING initiative, highlighting their key features, offerings, and training plans.

1.2 Structure

The deliverable is structured as follows:

1) **Executive Summary:** Provides a concise overview of the main points covered in the document.
2) **Open Pilots:** Presents the updated setup since the last reported status for each Open Pilot Line. This includes all hardware and software required updates and integration with the different modules of the project. Each Open Pilot Line also includes: the Human factors study and operator training methodology, the service provisioning results of the planned activities and future plan of actions and a first draft plan of the transition of the Open Pilots to Industrial Pilots in the end-user's premises. This small draft plan includes the approximate layout of the final demonstrator and the some initial end-user information to successfully carry out the CONVERGING demonstrator at the end user's premises.
    i) <u>Automotive Open Pilot Line - TECNALIA:</u> this OPL is a groundbreaking initiative aimed at revolutionizing the manufacturing sector. This pilot project addresses a significant challenge in car production: the manual and ergonomically risky process of polishing draw dies used in panel creation. By automating this process through inspection, marking, and efficient robotic polishing, the lifespan of these dies is extended, ensuring optimal performance in the future.
    ii) <u>White Goods Open Pilot Line - IPK:</u> this OPL provides a specialized testing environment designed for automating tasks such as grasping, cable placement, cable fastening, and plug insertion. These tasks, traditionally performed manually, have significant potential for automation, particularly in the context of the growing electrification trends in household goods and other sectors like automotive.
    iii) <u>Aeronautics Open Pilot Line – LMS:</u> this OPL introduces the Aeronautic pilot, a specialized environment dedicated to developing smart collaborative solutions for hazardous area inspection and maintenance in the aeronautics sector. This initiative leverages advanced AI-driven robotics within a comprehensive setup that includes an authentic aircraft wing, fuel tank, and a sophisticated robot equipped with cutting-edge sensor systems for remote inspection and maintenance.
    iv) <u>Additive Manufacturing Open Pilot Line – AIMEN / LMS:</u> this setup combines two complementary environments dedicated to advancing post-processing operations in additive manufacturing for medium and large parts. The AIMEN OPL focuses on handling, transporting, and postprocessing heavy metal components while ensuring full data traceability, simulation, and ergonomic assessment. It also acts as an open training and demonstration facility to support adoption of the CONVERGING solutions through technical services and skill development. In parallel, the LMS deployment, located within TF CC premises, provides a realistic industrial environment equipped with a high-payload collaborative robot, safety systems, and an AGV for part transfer. This setup enables the validation of modules requiring close operator–robot interaction, including AR/VR-assisted

finishing tasks, and functions as a pre-final integration step towards deployment at the end-user site~~.~~

3) **Next steps:** This section provides a comprehensive overview of the following activities for each Pilot Line, outlining the next phases of the CONVERGING initiative. This includes the next developments of the pilots, the industrial pilot implementation plan and other planned service provisioning activities.
4) **Conclusions:** This section summarizes the current operational status and progress of the Open Pilots Network. It also presents an overall assessment of the results achieved to date and outlines future expectations concerning both service provisioning and the implementation of the Industrial Pilots.

1.3 Relationship with other CONVERGING work

The relationship to other CONVERGING work is straight forward.

T7.1 focuses on deploying the network designed in T2.3 covering different aspects. The network of Open Pilots will enable us to apply the Open Access policy as indicated by T1.4 to share data and knowledge with the community.

The findings of the validation of the platforms and developments is reported in this document, D7.2, as well as the first preparations for implementation of the real-scale industrial pilot lines. The performance assessment of the CONVERGING solution of the industrial pilots will be reported in D7.3.

2 Automotive Open Pilot Line - TECNALIA

This pilot case focuses on automating the manual process of polishing draw dies in car manufacturing, which is crucial for optimal performance and minimal surface roughness. The current manual process poses ergonomic risks due to difficult positions and repetitive movements for operators. The proposed automation aims to reduce these risks and improve efficiency. The process begins with an operator inspecting the dies for wear or damage, marking any identified issues for repair. A robot then efficiently polishes the damaged areas, restoring functionality, extending the die’s lifespan, and ensuring optimal performance for future production requirements. This innovation in the stamping plant could revolutionize the initial step of producing individual panels in car manufacturing.

2.1 Value Proposition

Companies that actively engage can effortlessly assess the viability of polishing or other operations that might benefit from scanning a working part and planning and executing trajectories over it with a specific tool. This generates precise specifications for an integrator to provide a conclusive resolution faster.

2.2 Description of the current Setup

The automotive OPL is divided into two clearly differentiated setups, fixed and mobile polishing configurations, they have been described in D7.1, and their latest updates and modifications are reported here in D7.2.

The fixed setup’s main asset is a UR20 collaborative robot with 20kg payload. The mobile configuration features a UR10e mounted on top of an AGV for mobile polishing. Both configurations feature a structured light camera and a polishing tool.

This setup simulates the environment of an industrial automotive production line through which the robot will navigate, scan the assigned environment and perform the polishing of the detected part.

2.2.1 Hardware setup

The current hardware setup for the Automotive Pilot is summarized below.

Robotics system:

The configuration of the fixed robotic setup remains unchanged since the last reporting period; however, a brief summary is provided here for completeness. It is important to note that, within the scope of recent developments, the primary focus has shifted toward the enhanced mobile setup, given its strategic role in enabling flexible deployment.

The fixed version of the Open Pilot employs a UR20 robotic arm, with a capacity of 20 kg. The UR20 is mounted on a profiled metal table, providing a stable and modular platform for laboratory testing. A protective cable sleeve has been integrated to safely route the necessary wiring to the end-effector, ensuring reliability and minimizing wear during operation.

In the laboratory setting, the testbed remains relatively simple: the robot is fixed to the workbench, and the part to be processed or scanned is positioned in front of it. This configuration provides a controlled environment for validating core functionalities, prior to full-scale industrial implementation.

The software stack of the fixed setup has been successfully migrated to **ROS 2**, ensuring long-term sustainability, simplified maintenance, and continuous alignment with the latest developments in the robotics ecosystem. Initial operational tests are already being conducted with the new environment to validate both functionality and performance.

This migration marks an important milestone, as it not only confirms the feasibility of the transition but also sets the standard for the evolution of the remaining software modules. Following the same approach, the rest of the components will progressively be adapted to ROS 2, guaranteeing a consistent, future-proof architecture across the entire system.

Figure 1: Fixed setup of the automotive use case.

As previously mentioned, significant updates have been implemented in the mobile robot setup since the last reported state. The earlier version consisted of a UR20 robotic arm mounted on a MiR500 autonomous mobile robot (AMR). While this configuration demonstrated initial feasibility, further analysis and testing revealed key areas for improvement in terms of mobility and operational flexibility.

Figure 2: Previous mobile setup as per of June 2024 at the BIEMH24 fair.

To address these limitations, the current design has transitioned to a more advanced mobile platform equipped with Mecanum wheels, which provide omnidirectional movement and significantly enhance the system's maneuverability in constrained industrial environments. Additionally, an elevating column has been integrated to improve the vertical reach of the robotic arm, enabling effective polishing operations on large-scale stamping dies.

This redesigned mobile solution offers a more robust and versatile platform, better suited to real-world deployment within industrial workcells. Its improved reachability and adaptive mobility contribute directly to increased process efficiency and broader applicability in high-mix, low-volume manufacturing contexts—key aspects aligned with the goals of the project.

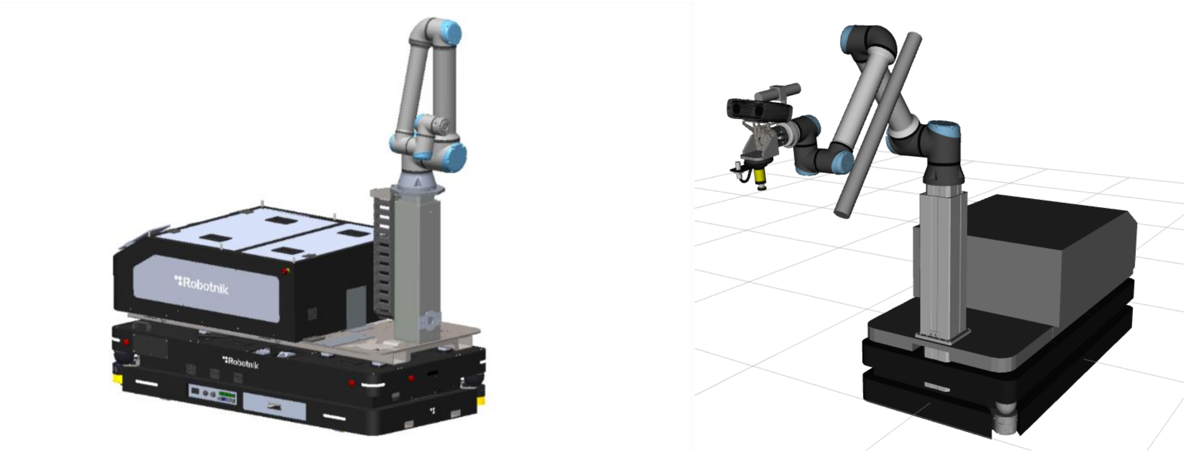


Figure 3: Original CAD model provided by the manufacturer (left) & Digital Twin representation developed and implemented in RVIZ for visualization and simulation (right).

In both the fixed and mobile configurations, the end-effector consists of a ZIVID 2 structured light camera for the PAM module and a MIRKA AIROS 150NV polishing tool. To integrate both the camera and polishing tool into a single end-effector, a custom-designed and 3D-printed extender was required. Additionally, since this extender was originally designed for a previous setup using a UR16, an adapter was needed to accommodate the UR20 robot.

Also, both setups will count with their respective Mixed Reality versions that can be used for the Operator Training (OTM). For this purpose, a VR / XR Meta Quest Pro headset is used. This is currently only available in the fixed setup.

Since the reception of the robotic system in early 2025, development efforts have been primarily focused on preparing the demonstrator based on the new mobile manipulator configuration. This phase has required the implementation of several critical hardware modifications to ensure operational readiness and integration of all necessary components.

Key adaptations include the installation of an external industrial computer, the integration of the polishing tool's control box within the rear compartment of the platform, the extraction and distribution of power supply for both the computer and the tool, as well as the rerouting of the polishing tool's emergency stop button into the main emergency circuit. These interventions were essential to ensure seamless functionality, safety compliance, and compact integration within the mobile base.

During the implementation process, some design issues were identified—most notably, insufficient ventilation within the rear compartment, which caused the onboard computer to overheat and unexpectedly shut down during extended use. This issue was resolved by installing active cooling fans to maintain safe operating temperatures.

A complete overview of all hardware modifications is provided in Deliverable D3.3. Further technical details are also presented in the following subsection, *List of Active Modules: PR*.

Figure 4: Actual current mobile manipulator with Zivid and Mirka end-effector.

Hardware summary

Fixed setup:

- ROBOT: UR20 (fixed)
- CAMERAS: ZIVID 2
- POLISHING TOOL: Mirka AIROS 150NV
- VR / XR HEADSET: Meta Quest Pro
- PC1: Alienware-Aurora-R15
  - OS: UBUNTU 22.04
  - CPU: Intel Core i9-13900K
  - RAM: 64 GB
  - GPU: NVIDIA GeForce RTX 4090
  - HARD-DISK: 2 TB

Current mobile setup:

- ROBOT: UR10e (on AGV)
- AGV: RbRobout + Ewellix900

- CAMERAS: ZIVID 2
- POLISHING TOOL: Mirka AIROS 150NV
- VR / XR HEADSET: Meta Quest Pro
- External PC:
    - OS: Ubuntu 22.04
    - CPU: intel i7
    - RAM: 32 GB
    - GPU: RTX 2080 Super
    - HARD-DISK: 500 GB SSD

2.2.2 List of active modules

Perception and Autonomy module (PAM)

Setup: The Perception and Autonomy Module (PAM) is responsible for perception of the environment and the reconstruction of 3D digital models to support path planning activities. In the context of the Automotive use case, PAM specifically manages the scanning of the robot's workspace and the 3D reconstruction of the part to be polished.

The module operates within an Ubuntu 22 desktop environment. The recommended hardware configuration, based on development and testing setups, includes:

- **RAM**: 32 GB
- **CPU**: Intel Core i9-13900K
- **GPU**: NVIDIA GeForce RTX 4090

Additionally, the use of a **Zivid 2** camera is mandatory for the PAM module in the Automotive OPL setup.

The scan of a stamping die by the PAM module can be seen in the following image.

Figure 5 PAM module performing the scan of a die.

Requirements: Docker, ROS noetic, Python

Customization: In the Automotive use case, the primary function of the Perception and Autonomy Module (PAM) is environment reconstruction utilizing a Zivid 2 camera. This camera has been successfully calibrated remotely in close collaboration between TECNALIA and FORD.

Additionally, the PAM module monitors the force sensor, which is essential to ensure smooth and consistent polishing operations.

Trouble/Solution:

- **Force Detection Stability**:
  Resolved an issue where the application would stop after initiating the polishing and trajectory execution. The root cause was noise interfering with force detection, effectively preventing proper sensor readings. A filtering mechanism has been implemented to mitigate noise and ensure stable force monitoring.
- **Joint Limit Handling**:
  Addressed a bug where the robot would experience an unintended configuration change when operating near joint limits. This has been resolved by introducing safety constraints in both the Cartesian controllers and the physical robot configuration, preventing the system from approaching joint limit boundaries.

Polishing Robot (PR)

Setup: The polishing robot has been tailored specifically for FORD's needs.

At the core of this development is the TECNALIA Fixed Polishing Robot, an experimental, beta-stage platform designed to test and refine the optimal fixed robot configuration for polishing tasks. This prototype plays a key role in validating new features and ensuring their technical feasibility.

On the other hand, the FORD Fixed PR is the finalized production (industrial) version of this design. It takes a more cautious approach, only integrating new features after they've been rigorously tested and validated in the TECNALIA prototype. This strategy ensures that the Ford workcell adopts only the most reliable and efficient upgrades.

To enhance flexibility and reach, the system also includes the **Mobile Polishing Robot (MR)**. This mobile platform is capable of navigating around the workcell, allowing it to access all areas of the stamping dies and perform polishing operations that would be difficult to achieve with a fixed unit alone.

All robot configurations are operated using dedicated software developed under the CONVERGING project. This software enables users to configure essential polishing parameters such as speed, pressure, and trajectory, ensuring consistent, high-quality results across both fixed and mobile systems.

Requirements: PAM module, Docker, ROS noetic, SAM module

Customization: As part of the ongoing customization efforts for the Operational Process Line (OPL), a new mobile manipulator is currently under development. This updated configuration replaces the existing MiR500 platform with an RB-Robout AGV, a strategic decision aimed at improving performance, adaptability, and long-term reliability.

The RB-Robout AGV offers several advantages that better align with the evolving demands of the OPL. Its design includes a mobile column that adds an additional degree of freedom to the manipulator, enabling it to reach extended areas within the workcell. Furthermore, the platform’s industrial-grade robustness and compact maneuverability—enhanced by its mecanum wheels—allow for smoother movement in constrained environments without requiring turning maneuvers.

Significant customizations have also been implemented to integrate the SAM module and the polishing tool effectively into the new robotic setup, ensuring full compatibility with the updated platform and supporting seamless operation within the OP, reported in D3.3 and summarized here:

- Integration of a high-performance onboard computer equipped with a dedicated GPU to support real-time perception and planning tasks.
- Installation of the Mirka sanding tool controller box for tool actuation and control.
- Addition of dedicated power supplies (48V, 24V, and 5V) to support various system components.
- Integration of the Mirka emergency stop into the main robot safety circuit.
- Deployment of a KVM switch to enable switching between the onboard robot computer and the CONVERGING controller computer.
- Connection of the Zivid 3D camera for inspection and environment scanning.
- Implementation of structured cable routing and holders to ensure robustness and safety during operation.

Trouble/Solution: During operation, the robot’s rear cabinet was experiencing excessive heat accumulation, which led to the control computer overheating and shutting down unexpectedly. To address this issue and ensure stable system performance, three cooling fans were installed across the rear cabinet. This modification significantly improved airflow and temperature regulation within the enclosure, effectively resolving the overheating problem.

The newly installed fans can be seen in the following image.

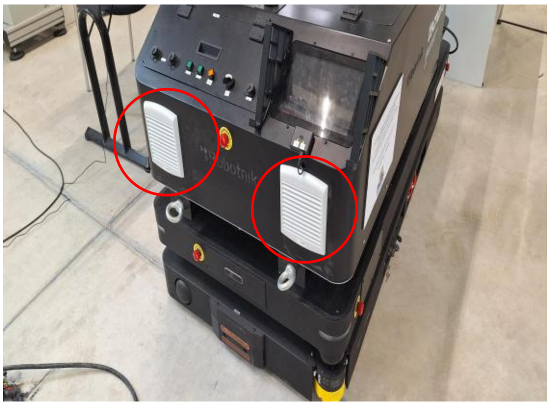


Figure 6: Newly installed fans on the mobile manipulator for cooling.

AI Digital Twin (AIDT)

Setup: The AIDT module is based on Visual Component 4.0 OLP (Offline Robot Programming) simulation software. For this OPL, the UR robot setup with Mirka Tools virtual shop floor representation is created. This allows the operator in FORD to create robot programs in virtual environment and test the programs and parameters in virtual environment without interrupting the ongoing process. The same program is then post processed and used in the robot program. Exploiting the UR Real Time Data Exchange interface provided by Visual Components, the online execution can be replicated in the simulation as well.

In addition to that, MR (Mobile Polishing Robot) shop floor virtual representation was created in Visual Components 4.0 software. This allows users to test different scenarios in virtual representation without using the actual physical resource. The robot systems might be working in one facility, but users can plan scenarios to use the same platform in different facilities without having access to the physical robot setup.

Requirements: Recommended specifications:

- CPU: equivalent to Intel i7-8xxx processor
- RAM: 8GB
- HDD: 3Gb of available space
- Graphics cards: Nvidia GPU at least 4GB
- Graphics display resolution: 1920 x 1080 (FHD)
- Mouse: three buttons
- 64 bit OS: Windows 10 or Windows 11

Customization: Since the last reported status, Visual Components has developed a new Digital Twin of the mobile manipulator setup featuring the RB-Robout platform. This digital model has been fully integrated into the Visual Components software environment, enabling accurate simulation of the polishing operation. The integration supports virtual validation, path planning, and process optimization within a realistic and interactive 3D environment.

The Visual Components model can be seen in the following image.

Figure 7: Digital Twin of the new mobile manipulator in Visual Components.

Operator Training module (OTM)

Setup: The Operator Training Module is an autonomous training and work process management system that focuses on training and capacity building of human resources using the latest technologies in Extended Realities such as Augmented (or Mixed) Reality and Virtual Reality.

This module is connected to the robot's ROS control system for its operation, and in this way it can not only carry out the assigned polishing operation by controlling the robot with the Extended Reality device using Mixed Reality, but it also allows the operator to be guided during the same real operation with the robot, or to train autonomously in carrying out the task using Mixed Reality (seeing the environment around him) or in Virtual Reality (in a virtual immersive environment).

For safety reasons, we use the real ROS system connected to a virtual UR20 robot simulated by the Extended Reality device itself.

Requirements: Docker, PR module, VR/XR goggles

Customization: In the latest iteration, the FORD workcell featuring the UR16e robot has been integrated into the Unity environment for execution in Virtual and Augmented Reality (VR/AR). This allows for immersive visualization and interaction with the system. The differences between the fixed setup and the FORD-specific configuration within the Unity workcell can be observed in the following image.

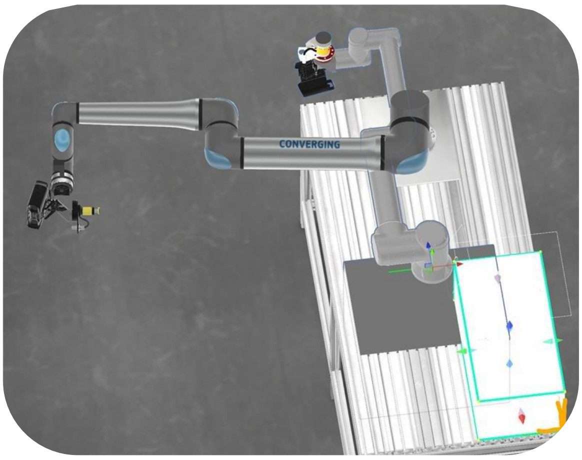


Figure 8: Unity workcell capture where both fixed and Ford robots can be observed simultaneously.

Multi Actor Contextual Interface (MACI)

Setup: The MACI module serves as a link between human operators and the polishing robot, enabling operators to interact with the robot. Using the AR-Smart Pen system and AR glasses, operators can mark scratches on the dies, highlighting specific areas that need attention. The application lets them draw scratch areas, customize the scratch characteristics, and direct the robot in a 3D space to perform the necessary polishing. It also offers pop-up confirmations and user-friendly, customizable themes to enhance the interaction between humans and the robot.

Requirements: PR module, ROS, Microsoft HoloLens 2, Stylus XR

Customization: No further changes since the last reported status.

AI Station Controller (AISC)

Setup: The setup involves the robotic cell connected to the PC1 (Ubuntu) via an Ethernet switch. The AISC runs over a Docker environment in conjunction with ROS Noetic package.

Requirements: ROS Noetic, Docker

Customization: In order to have a centralized execution manager, it is planned to introduce the AISC in the final demonstrator for the automotive use case and the corresponding work has already started.

Data at Rest (DAR)

Setup: In order to be able to visualize critical polishing data, our custom Grafana communication protocol is implemented with the DAR.

The purpose of the Data at Rest module is to enable users to access the data produced by the open pilot line and choosing particular contexts (1).

Through an interactive table interface (3), users can refresh (2) and click on individual entries (4) to explore the data associated with each product planning. Current developments include asset modeling in Asset Administration Shells (AAS) and the implementation of data analytics functionalities using real process variables such as torque and speed setpoints. This will allow deeper insights into machine behavior and production performance.

The Data at Rest module is a module deployed in an internal server at AIMEN. Furthermore, online access is allowed only to authorized users through an authorization service.

Requirements: Docker, AISC, DIM

Customization: None

Safety Assessment and Monitoring Module (SAM)

Setup: The main purpose of this module is to collect the status of the safety elements and controllers of the shop floor, including diagnostic and Fail-Safe data from the controllers and from the different safety functions of the system, such as those of the safety PLC, scanners and robots.

For the Automotive OPL this safety measures only include a protective cover for the polishing tool to avoid any operator to get their finger inside the polishing tool range while the cobot is in operation.

Requirements: PR module

Customization: In the following picture the designed protective covers for the Mirka AIROS 350CV at the Ford setup and for the Mirka AIROS 550NV at Tecnalia’s mobile setup can be observed.

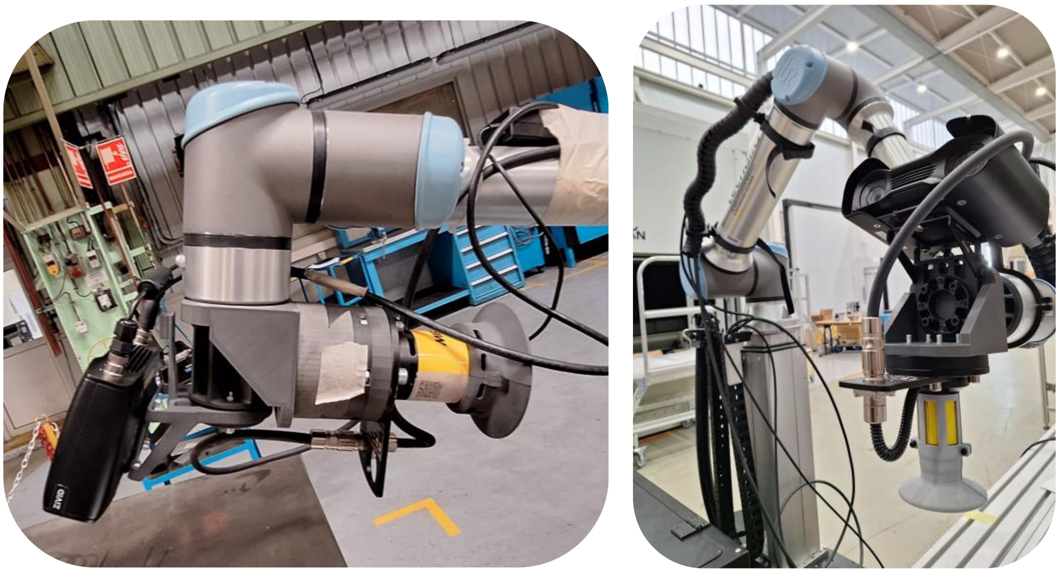


Figure 9: The different polishing tools with their corresponding safety cover.

Trouble/Solution: The current protective cover of the Mirka Airos 350NV is slightly oversized, causing it to make contact with the surface before the polishing tool itself. A redesign of the cover is necessary.

Additionally, both existing protective cover designs provide minimal clearance, significantly limiting the robot's path planning capabilities. This issue becomes problematic when polishing curved surfaces, where collisions between the cover and the part can lead to planning failures. There remains considerable room for improvement in the design to increase clearance and develop a more robust and reliable safety solution.

2.3 OPL System Level Functionalities (SLFs)

2.3.1 High Level Functionalities

Following the layout of D2.1, details for modules features in D2.2 and D7.1 initial setups, the following are the System Level Functionalities for the Aeronautics OPL.

Table 1: High level system functionalities.

#	High Level Functionality	Short description
1	Operator teaches the polishing process for die through VR/AR	This module enables operators to remotely teach the polishing process for dies using VR/AR. It allows defining polishing patterns, target areas, and key parameters (force, velocity, length), while providing a virtual review of the process.
2	Operator oversees the polishing process of dies.	This module supports operators in supervising the die polishing process. They can identify dies and repair areas through various interfaces, report issues at any stage, and propose improved polishing parameters.

#	High Level Functionality	Short description
3	System autonomously performs and optimizes the polishing process.	This module autonomously executes and optimizes die polishing. It scans and measures parts, generates and performs optimal polishing trajectories, and continuously improves by learning from operator feedback, detected errors, and past executions.
4	Collaborative quality checks	This module enables collaborative quality assurance. The system conducts automated checks, prompts operators to review and flag issues, reworks defective areas, and collects statistics on patterns and parameters to identify recurring problems and enhance learning.
5	System assesses and enforces safety.	This module ensures safety by detecting and responding to potential incidents. It informs the operator of risks, manages recovery procedures, and provides alerts in high-risk situations to maintain secure operations
6	System coordinates and supports Operator.	This module coordinates and supports the operator during the process. It provides timely instructions for required actions, enables verification reporting, and records operator feedback to ensure accurate task execution.
7	System optimizes and executes multiple polishing operations.	This module optimizes and carries out multiple polishing operations. It plans efficient trajectories, executes them across different dies, and adapts parameters to ensure consistent quality and productivity.
8	System is digitally simulated.	This module provides digital simulation through a virtual twin. It supports operator training with VR/AR and enables operation testing in AR to validate processes before execution.

2.3.2 Low Level Functionalities

2.3.2.1 Operator teaches the polishing process for die through VR/AR

Offsite/VR

A – Operator teaches the polishing patterns and the areas that need polishing for a die

Table 2: Operator teaches the polishing patterns and the areas that need polishing for a die.

Step #	Operation	From	To	Status
1	Start VR teaching mode	Operator	OTM	Functionally validated
2	Start in VR Teaching mode	OTM	TDM	Functionally validated

Step #	Operation	From	To	Status
3	Select dies	Operator	OTM	Functionally validated
4	Get dies	OTM	CRC	Functionally validated
5	Select/define polishing area	Operator	OTM	Functionally validated
6	Get die polishing areas	OTM	CRC	Functionally validated
7	Define die polishing areas pattern	Operator	OTM	Functionally validated
8	Get pattern	OTM	CRC	Functionally validated
9	Edit pattern	Operator	OTM	Functionally validated
10	Pattern teaching process	OTM	TDM	Functionally validated
11	Teaching complete	Operator	OTM	Functionally validated
12	Stop VR training mode	OTM	TDM	Functionally validated
13	Update	TDM	CRC	Functionally validated

B - Operator defines parameters such as contact force, orthogonal velocity, and length of polishing for specific dies.

Table 3: Operator defines parameters such as contact force, orthogonal velocity, and

Step #	Operation	From	To	Status
14	Start VR teaching mode	Operator	OTM	Functionally validated
15	Get dies	OTM	CRC	Functionally validated
16	Show dies list	OTM	Operator	Functionally validated
17	Select dies	Operator	OTM	Functionally validated
18	Select/define polishing area	Operator	OTM	Functionally validated
19	Get die polishing areas	OTM	CRC	Functionally validated
20	Define die polishing areas pattern	Operator	OTM	Functionally validated
21	Get pattern	OTM	CRC	Functionally validated
22	Select pattern polishing parameters	Operator	OTM	Functionally validated
23	Get polishing parameters	OTM	ARBA	Functionally validated
24	Edit polishing parameters	Operator	OTM	Functionally validated
25	Parameter definition complete	Operator	OTM	Functionally validated
26	Update	TDM	ARBA	Functionally validated

C - Operator reviews virtual polishing process (VR)

Table 4: Operator reviews virtual polishing process (VR)

Step #	Operation	From	To	Status
27	3D Virtual Robot Execution	OTM	Operator	Functionally validated

Onsite – VR / AR

A – Operator teaches the polishing patterns and the areas that need polishing for a die

Table 5: Operator teaches the polishing patterns and the areas that need polishing for a die.

Step #	Operation	From	To	Status
28	Start AR teaching mode	Operator	MACI	Functionally validated
29	Request Teaching Mode	AISC	MACI	Pending
30	Select die	Operator	MACI	Functionally validated
31	Select / define polishing area	Operator	MACI	Functionally validated
32	Get areas	MACI	CRC	Functionally validated
33	Select / define patterns	Operator	MACI	Functionally validated
34	Get patterns	MACI	CRC	Functionally validated
35	View patter execution for (Die, Area) in AR	MACI	Operator	Functionally validated
36	Start Teaching Selected Pattern	Operator	MACI	Functionally validated
37	Start teaching for (Die, Pattern)	MACI	AISC	Functionally validated
38	Start Editing (Die, Area, Pattern)	AISC	TDM	Functionally validated
39	Teaching Mode Control	TDM	MR	Functionally validated
40	Teach Cobot patterns	Operator	MR	Functionally validated
41	Teaching Completed	Operator	MACI	Functionally validated
42	Stop Teaching Mode	MACI	AISC	Functionally validated
43	Save Edited (Die, Area, Pattern)	AISC	TDM	Functionally validated
44	Update (Die, Area, Pattern)	TDM	CRC	Functionally validated
45	Optional Review Patterns in VR	MACI	Operator	Functionally validated
46	Start Pattern Dry Execution	Operator	MACI	Functionally validated
47	Request (Die, Area, Pattern) Dry Execution	MACI	AISC	Functionally validated
48	Execute (Die, Area, Pattern)	AISC	CRC	Functionally validated
49	Teaching Parameters autonomous behaviour	CRC	adjustment	Functionally validated
50	Control Robot	CRC	MR	Functionally validated

B – Operator defines parameter such as contact force, orthogonal velocity, and length of polishing for specific dies

Table 6: Operator teaches the polishing patterns and the areas that need polishing for a die.

Step #	Operation	From	To	Status
51	Start VR teaching mode	Operator	MACI	Functionally validated
52	Get dies	MACI	CRC	Functionally validated
53	Show dies List	MACI	Operator	Functionally validated
54	Select die	Operator	MACI	Functionally validated
55	Select/define polishing area	Operator	MACI	Functionally validated
56	Get die polishing areas	MACI	CRC	Functionally validated
57	Define die polishing areas pattern	Operator	MACI	Functionally validated
58	Get pattern	MACI	CRC	Functionally validated

59	Select pattern polishing parameters	Operator	MACI	Functionally validated
60	Get polishing parameters for (Pattern, Die, Area)	MACI	ARBA	Functionally validated
61	Edit Polishing parameter for (Pattern, Die, Area)	Operator	MACI	Functionally validated
62	Parameter Definition completed	Operator	MACI	Functionally validated
63	Update / Provide (Pattern, Die, Area, Parameters)	TDM	ARBA	Functionally validated

2.3.2.2 Operator oversees the polishing process of dies

A - Operator indicates the die and the die repair area using multiple interfaces.

Table 7: Operator indicates the die and the die repair area using multiple interfaces.

Step #	Operation	From	To	Status
1	Notices issue and requests to intervene	Operator	MACI	Functionally validated
2	Reports issue with die	MACI	AISC	Functionally validated
3	Pause	AISC	CRC	Functionally validated
4	Notify operator to start indicating	AISC	MACI	Functionally validated
5	Notification	MACI	Operator	Functionally validated
6	Mark the area of dies that need polishing	Operator	MACI	Functionally validated
7	Indicate marking complete	Operator	MACI	Functionally validated
8	Marking completed	MACI	AISC	Functionally validated
9	Indicate updated params	Operator	MACI	Functionally validated
10	Send polishing pattern indications	MACI	AISC	Functionally validated
11	Start polishing	AISC	CRC	Functionally validated
12	Polishing parameters control	CRC	ARBA	Functionally validated
13	Control	CRC	MR	Functionally validated
14	Control	CRC	End effector	Functionally validated
15	Status, trajectory	MR	CRC	Functionally validated

B - Operators suggests improved polishing parameters for polishing operation.

Table 8: Operators suggests improved polishing parameters for polishing operation.

Step #	Operation	From	To	Status
16	Notices issue and requests to intervene	Operator	MACI	Functionally validated
17	Reports issue with die	MACI	AISC	Functionally validated
18	Pause	AISC	CRC	Functionally validated
19	Notify operator to start indicating	AISC	MACI	Functionally validated
20	Notification	MACI	Operator	Functionally validated
21	Specify Polishing parameters for a Die, area, pattern	Operator	MACI	Functionally validated
22	Indicate polishing parameter complete	Operator	MACI	Functionally validated

Step #	Operation	From	To	Status
23	Updated parameter	MACI	AISC	Functionally validated
24	Update parameters for Die, Area, Pattern	AISC	ARBA	Functionally validated
25	Start polishing	AISC	CRC	Functionally validated
26	Polishing parameters control	CRC	ARBA	Functionally validated
27	Control	CRC	MR	Functionally validated
28	Control	CRC	End effector	Functionally validated
29	Status, trajectory	MR	CRC	Functionally validated

2.3.2.3 System autonomously performs and optimizes the polishing process

A - Scan, identify and measure real die parts accurately

Table 9: Scan, identify and measure real die parts accurately.

Step #	Operation	From	To	Status
1	Start 3D scanning	AISC	CRC	Functionally validated
2	Create initial robot scanning path	CRC	CRC	Functionally validated
3	3D scan	CRC	PAM	Functionally validated
4	Update path planning	CRC	CRC	Functionally validated
5	Update 3D Model	CRC	CRC	Functionally validated
6	3D model, Path	CRC	DIM	Functionally validated
7	Get Context	DIM	DIM	Functionally validated
8	Dies, 3D model, Scanning Path	DIM	DAR	Functionally validated

B - Generate optimal pattern trajectory based on 3D scan.

Table 10: Generate optimal pattern trajectory based on 3D scan.

Step #	Operation	From	To	Status
9	Generate Pattern trajectory	AISC	CRC	Functionally validated
10	Get 3D model	CRC	DAR	Functionally validated
11	Generate optimal pattern trajectory	CRC	CRC	Functionally validated
12	Optimal pattern, trajectory, Die, Pattern	CRC	DAR	Functionally validated

C - Execute the optimized polishing trajectory.

Table 11: Execute the optimized polishing trajectory.

Step #	Operation	From	To	Status
13	Start Polishing	AISC	CRC	Functionally validated
14	Get optimal Trajectory	CRC	DAR	Functionally validated
15	Polishing Parameters Control	CRC	ARBA	Functionally validated
16	Control	CRC	MR	Functionally validated
17	Status trajectory	MR	CRC	Functionally validated

D - Learn from past executions, such as human operator suggestions, identified errors, past real die part scans, past generated trajectories.

Table 12: Learn from past executions.

Step #	Operation	From	To	Status
18	Updated parameters	Operator	MACI	Functionally validated
19	Updated parameters	MACI	AISC	In progress
20	Get context	DIM	DIM	In progress
21	Updated parameters	DIM	DAR	In progress
22	Areas with quality issues	MACI	AISC	In progress
23	Areas with quality issues	AISC	DIM	Not tested
24	Get context	DIM	DIM	Not tested
25	Areas with quality issues	DIM	DAR	Not tested
26	3D model, path	CRC	DIM	Not tested
27	Get context	DIM	DIM	Not tested
28	Die, 3D model, Scanning Path	DIM	DAR	Not tested
29	Calculate statistics	DAR	DAR	In progress
30	Access Past Data	CRC	DAR	Not tested
31	Create trajectory	CRC	CRC	Not tested
32	Get areas with High probability of quality issue	MACI	DAR	Not tested

2.3.2.4 System autonomously performs and optimizes the polishing process

A - Collaborative quality checks

Table 13: Collaborative quality checks.

Step #	Operation	From	To	Status
1	Measurements task	AISC	CRC	Functionally validated
2	Generate Path	CRC	CRC	Not tested
3	Quality issues statistics	CRC	DAR	In progress
4	Control motion	CRC	MR	Functionally validated
5	Perform measurements	CRC	PAM	Functionally validated
6	Report measurements	PAM	DIM	Functionally validated
7	Get context	DIM	DIM	Not tested
8	Push results	DIM	DAR	Not tested

B - System informs operator to perform quality check.

- Operator performs quality check

- Operator indicates areas with quality issues

Table 14: Quality check performance.

Step #	Operation	From	To	Status
9	Perform quality checks	AISC	MACI	Not tested

Step #	Operation	From	To	Status
10	Perform quality checks	MACI	Operator	Not tested
11	Visualize high probability areas	AISC	MACI	Not tested
12	Visualize Areas with high probability of quality issues	MACI	DAR	Not tested
13	Perform quality checks	Operator	Operator	Not tested
14	Indicate areas with quality issues	MACI	Operator	Not tested
15	Areas with quality issues	MACI	AISC	Not tested
16	Areas with quality issues	AISC	DIM	Not tested
17	Get context	DIM	DIM	Not tested
18	Areas with quality issues, Part, Process	DIM	DAR	Not tested

C - System reworks areas with quality issues

Table 15: System reworks areas with quality issues.

Step #	Operation	From	To	Status
19	Start Polishing	AISC	CRC	Functionally validated
20	Polishing Parameters Control	CRC	ARBA	Functionally validated
21	Control	CRC	MR	Functionally validated
22	Control	CRC	End effector	Functionally validated
23	Status, Trajectory	End effector	CRC	Functionally validated

D - System captures statistics about patterns and polishing parameters/Learning process, System can identify where we have issues more frequently.

Table 16: Statistics capture.

Step #	Operation	From	To	Status
1	Calculate statistics	DAR	DAR	In progress
2	Visualize quality issues	DAR	AIDT	In progress

2.3.2.5 System assesses and enforces safety

A - Detect potential safety incidents

B - The system reacts to safety incidents

Table 17: Safety incidents detection/ reaction.

Step #	Operation	From	To	Status
1	Safety connection - Sensing	safety	Safety sensors	Functionally validated
2	Safety Connection - Stop	safety	MR	Functionally validated
3	Send Safety Data	safety	Safety cloud	Functionally validated
4	Safety Status	safety	AISC	Functionally validated

Step #	Operation	From	To	Status
5	Safety Event	safety	AISC	Functionally validated

C - The system informs the Human Operator

D - The system notifies operator in high risk events

Table 18: High risk events information.

Step #	Operation	From	To	Status
9	The system informs the human operator	AISC	MACI	Functionally validated
10	Show Safety information	MACI	Operator	Functionally validated

E - System reworks areas with quality issues

Table 19: Areas reworking.

Step #	Operation	From	To	Status
19	Verify safety	Operator	Operator	Functionally validated
20	Ensure safety	Operator	MACI	Functionally validated
21	Ensure safety	MACI	AISC	Functionally validated
22	Recover operation	AISC	Safety	Functionally validated

2.3.2.6 System coordinates and supports Operator

A - The system informs the operator when verification actions are needed

B – The operator views instructions about required polishing actions

C - The Operator notifies the system when a verification action is completed

D - The operator reports the results of the verification

Table 20: Verification actions.

Step #	Operation	From	To	Status
1	Request Verification task	AISC	MACI	Functionally validated
2	Show verification Task	MACI	Operator	Functionally validated
3	See instructions	Operator	MACI	Functionally validated
4	Perform Verifications Task	Operator	Operator	Functionally validated
5	Input Verification Result	Operator	MACI	Functionally validated
6	Verification Result	MACI	AISC	Functionally validated

2.3.2.7 System optimizes and executes multiple polishing operations

Table 21: Polishing operations optimization/ execution.

Step #	Operation	From	To	Status
1	Execute Task	AISC	CRC	Functionally validated
2	Execute Task	CRC	MR	Functionally validated

Step #	Operation	From	To	Status
3	Execute Task	AISC	CRC	Functionally validated
4	Execute Task	CRC	Operator	Functionally validated
5	Execute Task	CRC	MR	Functionally validated
6	Execute Task	CRC	Operator	Functionally validated
7	Execute Task	AISC	CRC	Functionally validated
8	Execute Task	CRC	MR	Functionally validated
9	Execute Task	AISC	CRC	Functionally validated
10	Execute Task	CRC	Operator	Functionally validated
11	Execute Task	CRC	MR	Functionally validated
12	Execute Task	CRC	Operator	Functionally validated

2.3.2.8 System is digitally simulated

A - Use the digital twin combined with VR and AR for training

Table 22: System's simulation.

Step #	Operation	From	To	Status
1	Start in training mode	AISC	CRC	Functionally validated
2	Execute polishing task	AISC	CRC	Functionally validated
3	Execute polishing task	CRC	AIDT	Functionally validated
4	Enable trajectory visualization	AISC	MACI	Functionally validated
5	Visualize training information	AISC	MACI	Functionally validated
6	Planned trajectory	CRC	MACI	Functionally validated
7	Joint values	AIDT	MACI	Functionally validated
8	Robot Trajectory	MACI	Operator	Functionally validated
9	Execution Status	AIDT	MACI	Functionally validated

B - Use the digital twin combined with AR for operation testing before execution

Table 23: Operation testing before execution.

Step #	Operation	From	To	Status
10	Execute polishing task	CRC	AIDT	Functionally validated
11	Enable Trajectory Visualization	AISC	MACI	Functionally validated
12	Planned trajectory	CRC	MACI	Functionally validated
13	Joint values	AIDT	MACI	Functionally validated
14	Robot trajectory	MACI	Operator	Functionally validated
15	Execution Status	AIDT	MACI	Functionally validated
16	Execute polishing task	CRC	MR	Functionally validated
17	Enable Trajectory Visualization	AISC	MACI	Functionally validated
18	Planned trajectory	CRC	MACI	Functionally validated
19	Joint values	AIDT	MACI	Functionally validated
20	Robot trajectory	MACI	Operator	Functionally validated
21	Execution Status	AIDT	MACI	Functionally validated

2.4 Service provisioning

2.4.1 Automotive use case webinar

2.4.1.1 Attendance overview

As part of the service provisioning strategy for the Open Pilot Line (OPL), a dedicated webinar was organized by TECNALIA on April 3rd, 2025.

The webinar, hosted by TECNALIA, focused on introducing the innovative robotic polishing solution developed within the CONVERGING project. The session highlighted how the system leverages high-precision sensors and collaborative robotics to automate the polishing of industrial parts—especially those that deviate from their original CAD models due to wear, deformation, or manufacturing variations.

Key features presented included automated path generation through part scanning, an intuitive user interface for non-expert operators, consistent surface quality ensured by force-controlled polishing, and enhanced safety using collaborative robots. The solution’s adaptability to large components—particularly when integrated into a mobile platform—was also emphasized.

The webinar addressed the potential for reduced manual labor, lower occupational risks, and improved production consistency. Finally, the speakers discussed implementation challenges and shared strategies for facilitating adoption and maximizing return on investment in robotic automation.

The objective of this session was to showcase the capabilities of the automotive use case demonstrator, raise awareness among potential industrial adopters, and generate qualified leads for further collaboration, in this direction, the selected language for the webinar was **Spanish**. The event attracted a total of 67 registrants, of whom 44 attended live. From this pool, 19 qualified leads were generated, resulting in a conversion rate of 28% from total registrants to leads.

Participant engagement was notably high, with an average interest level of 91% sustained throughout the session. The webinar prompted 8 audience questions, indicating active involvement. Post-event feedback was overwhelmingly positive: attendees rated the usefulness of the webinar at an average of 4.4 out of 5, while the presenters’ expertise received a score of 4.7 out of 5.

The most engaging topics, based on participant feedback and question frequency, were related to the system’s ability to handle large parts, achieve shiny surface finishes, ensure high precision, and support iterative polishing processes. A breakdown of the registration sources is illustrated in the pie chart included below, providing insights into the most effective outreach channels.

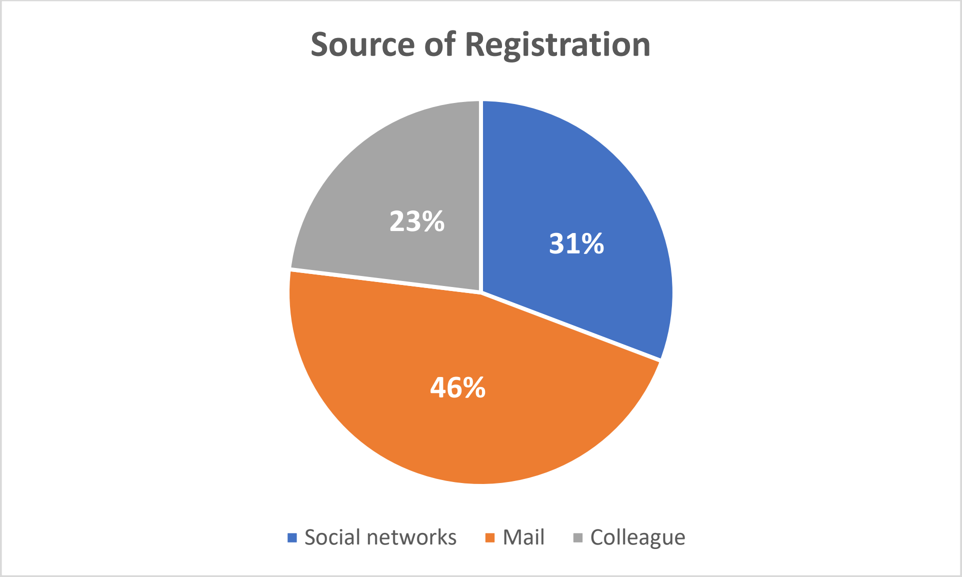


Figure 10: Pie chart representing the percentages of the source of the registered participants.

2.4.1.2 Qualitative Feedback

What subjects would the participants like to see in a future webinar?

- *“Underwater applications.”*
- *“Treatment of big objects where the arm is out of reach. Tool change.”*
- *“Other robotized tools and accessories compatible with the showcased technologies.”*

Participants found the webinar valuable and are interested in exploring more advanced and specialized applications in future sessions. Suggested topics include topics that would be interesting to develop for the technology such as tool changing.

How could the event be improved?

- *“Really liked the real-time demonstration, it looks more professional and attractive than a pwpt. Well done.”*
- *“Related demonstration to deburring. We observe high demand in the market related to this.”*
- *“3D homogenization with 3D abrasive Scotch & Brite style.”*

Participants clearly value practical, real-world demonstrations, especially when they go beyond static presentations. Moreover, there is a strong interest in industry-relevant processes, such as deburring, which participants identify as having high market demand. Lastly, the mention of 3D homogenization with advanced abrasives implies an appetite for more sophisticated and niche use cases.

2.4.1.3 Related questions

- *“Did you have any problems with shiny parts?”*
- *“What happens with parts so big that they don’t fit into the scan? Or parts that require polishing on all their sides..”*
- *“Do you have experience with very small parts that require really high accuracy?.”*

- *“Can the dust generated from the polishing become a problem?”*

The questions raised by participants reveal a strong interest in the real-world limitations and edge cases of the showcased solution.

2.4.1.4 Post-Event Reach

The recorded session uploaded to YouTube has accumulated 121 views (as of now).
Video link: Watch on Youtube

2.4.2 Operator training workshop

As outlined in the previous section on Human Factors, operator training is a key component of the CONVERGING project. It is designed to ensure that end users involved in the industrial pilot deployments are fully equipped to interact with advanced automation technologies. This approach supports both the adoption and sustainability of innovative robotic systems in real-world manufacturing environments.

In this context, a dedicated extended reality (XR) operator training workshop was conducted in early June 2025 at FORD’s facilities. The training was targeted at shop-floor personnel who would directly operate or interact with the deployed robotic systems.

The workshop was structured in two phases:

1. **Virtual Reality (VR) Training:** Operators were first immersed in a fully simulated environment replicating the open pilot scenario. This phase took place in a controlled training room, allowing trainees to familiarize themselves with the workflow, robotic movements, safety protocols, and human-machine interface without exposure to real-world risks. The VR simulation provided an effective and low-pressure environment for initial learning and procedural training.
2. **Augmented Reality (AR) Training:** After completing the VR component, operators transitioned to hands-on training using AR devices, interacting with the actual robotic system on the shop floor. The AR system overlaid real-time digital information and guidance onto the physical environment, assisting users in executing tasks and reinforcing the procedures learned during the VR session. This mixed-reality step served to bridge the gap between simulation and real-world operation, improving confidence and situational awareness.

Usability Evaluation

To assess the effectiveness and user acceptance of the XR training, participants completed a System Usability Scale (SUS) questionnaire following each training module. Results were as follows:

- **VR Training:** Achieved a SUS score of 79.16, indicating a high level of usability and user satisfaction. This score falls within the “Good to Excellent” range, reflecting the clarity, intuitiveness, and effectiveness of the VR module.
- **AR Training:** Received a SUS score of 76.00, which also indicates “Good” usability. While slightly lower than the VR module, this score still confirms the utility and user-friendliness of the AR experience in a real operational setting.

These results validate the XR-based training approach as a highly effective method for preparing operators to work with advanced robotic systems in industrial environments. The combination of immersive learning and real-time augmented guidance contributes to increased safety, efficiency, and operator confidence—critical factors for the successful deployment of the CONVERGING industrial pilots.

2.4.3 Future work timeline

To ensure the adoption and dissemination of the technologies developed under CONVERGING, a set of services are available for professionals such as open days, workshops, events and other webinars. These include diverse technologies related to the automotive use case such as VR/XR operator training, basic training in robot programming or robotized polishing for industrial parts with collaborative robots. The list of services can be seen in the table below.

Table 24: Planned future service provisioning actions for the automotive use case.

Topic Title	Description	Duration	Tentative Dates	Format	Type
Robotized polishing for industrial parts with collaborative robots for non-experts	Second Automotive OPL webinar. This webinar introduces the fundamentals of automated polishing using collaborative robots (cobots). From 3D reconstruction to automated robot path planning.	1h	Q1 2026	Remote	Webinar
Extended reality operator training	This service leverages Extended Reality (XR) technologies—including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—to provide immersive, hands-on training for operators in complex and high-risk environments.	2h (multiple sessions)		In person	On demand
Basic concepts of robot safety in collaborative spaces	This webinar provides an introduction to fundamental safety principles for working with collaborative robots (cobots) in shared workspaces	4h		Remote	On demand
Basic training in robot programming	Provides a foundational understanding of robot programming, equipping participants with the essential skills to operate and program industrial and collaborative robots	2h		Remote	On demand
Basic principles of	This webinar introduces the fundamental concepts	1h		Remote	On demand

Topic Title	Description	Duration	Tentative Dates	Format	Type
environment reconstruction with vision sensors	of environment reconstruction using vision sensors, focusing on how robots perceive and interpret their surroundings for precise navigation, object detection, and manipulation				
Basic principles of automatic trajectory generation	Introduces the fundamental concepts of automatic trajectory generation, focusing on how robots plan and execute smooth, efficient movements for various industrial applications	1h		Remote	On demand
Force control in collaborative robots for steady pressure application	Principles of force control in collaborative robots (cobots), focusing on how precise force regulation enables consistent and reliable pressure application in automated task	1h		Remote	On demand

Other dissemination and industry events are planned, such as the attendance to the BIEMH-26 fair in Bilbao or the inauguration of a new building in TECNALIA San Sebastián where the automotive use case technologies will be showcased, however dates are not yet confirmed.

2.5 Industrial deployment planning

2.5.1 M48 plan and timeline

This section provides some basic information about the end user of the pilot, outlining needs and operational context. It also details the challenges and plans to transition from the open pilots to an operating industrial pilot under T7.2 towards M48.

2.5.2 End user information

The end user involved in this pilot is the **FORD Valencia Plant**, a key automotive manufacturing site located in Almussafes, Valencia, Spain. The site is one of FORD’s major production facilities in Europe and plays a strategic role in the production of vehicle components and final assembly. The pilot activities for the CONVERGING project are carried out in collaboration with personnel from the Fabricación y Montaje (Manufacturing and Assembly) division, specifically within the Estampación (Stamping) department.

Department

- **Team / Department Name:**
  Fabricación y Montaje / Estampación (Manufacturing and Assembly / Stamping)
  This department is responsible for the transformation of raw metal sheets into

stamped parts that form the structural components of the vehicles. The stamping process includes high-speed forming machines and requires precision and coordination between human operators and automated equipment.

Points of Contact

- José B. Ramírez Cortés
- Ceferino Torres Chapa

User Competency Level

- **Target User Profile:** Technical Operators
  The primary users engaged in the pilot activities were experienced technical operators, typically responsible for the operation and supervision of high-tonnage stamping machines, quality checks, and line maintenance. These users possess a strong understanding of industrial machinery, safety protocols, and production workflows, but have limited prior experience with extended reality (XR) systems or collaborative robotics.
- **Training Needs:**
  As XR technologies and human-robot interaction paradigms were introduced, tailored training was necessary to ensure smooth adoption. The training focused on usability, intuitive interaction design, and safety in XR-assisted workflows.

Operational Environment

- **Environment Conditions:** Workshop (Industrial Shop Floor)
  The pilot was executed in a fully operational workshop environment within the stamping department. Conditions included:
  - High ambient noise due to mechanical presses
  - Dynamic movement of materials and forklifts
  - Presence of heavy-duty equipment and automated systems
  - Standard industrial lighting and ventilation
  - Requirement for adherence to strict occupational safety standards

2.5.3 Industrial pilot setup

TECNALIA has been collaborating closely with FORD since the beginning of the CONVERGING project, jointly developing an industrial pilot located at FORD's production facilities in Valencia.

To facilitate seamless integration and reduce the need for integration visits, an automated deployment and update system was implemented using Ansible. This infrastructure has significantly streamlined the collaboration between both organizations, enabling faster development cycles and remote integration capabilities.

As a result of this joint effort, an operational industrial pilot is now in place. The system is centered around a UR16e collaborative robotic arm, which features a 16 kg payload capacity and is equipped with a force control sensor to ensure precision and adaptability in polishing tasks. The robot is mounted on a robust, heavy-duty metallic support structure, ensuring stability during operation. This structure is positioned directly in front of an authentic automotive stamping die, fulfilling the technical requirements and physical alignment of the designated use case. The stamping die itself is secured on a separate metallic frame, approximately one meter in height.

The robotic end-effector integrates a Zivid 2 3D camera, the same model used in TECNALIA's fixed laboratory setup. At the FORD facility, several Mirka polishing tools are available to support the pilot's objectives. The primary safety housing has been developed around the Mirka AIROS 350CV, although the robot is capable of interfacing with multiple tool types.

A dedicated PC workstation, running Ubuntu Linux OS and equipped with a GPU, is installed alongside the robot controller. This system manages the computational load required for real-time 3D environment reconstruction based on the camera input.

The simulated robotic workcell, representing the deployed configuration, is illustrated in the following image.

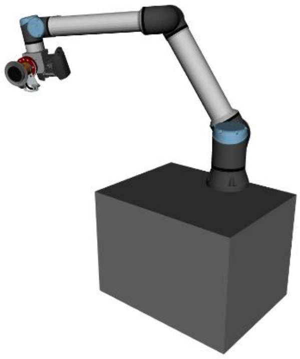


Figure 11: Designed workcell for simulation in RVIZ of the actual FORD automotive setup.

Also, by means of the GaussianSplatting technique, a realistic reconstruction of the automotive plant has been represented. This has been reconstructed from several pictures and a video.

This reconstruction allows to better plan the layout and implementation of a final demonstrator. Also, this will be useful to be added to the Unity workcell.

Figure 12: Reconstruction of the automotive working environment through Gaussian Splatting.

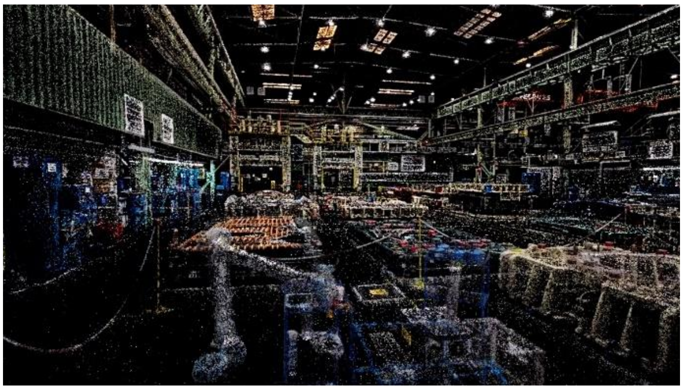


Figure 13: Reconstruction through Gaussian Splatting. Point cloud image to show that it is a 3D image.

The actual collaborative workcell at FORD's premises, described above, is illustrated in the following image.

Figure 14: Actual FORD automotive industrial pilot cell during the integration and training journey (June 2025).

The final version of the industrial pilot will integrate both the fixed setup at FORD's production facilities—as previously described—and the mobile setup currently located at TECNALIA's premises.

A joint demonstrator combining both configurations is currently under planning and coordination.

A critical factor in finalizing the joint demonstrator is the definition of the warehouse layout at FORD's site. This will significantly impact the navigation capabilities and overall feasibility of the mobile robotic platform. Once the layout is confirmed, detailed preparations will begin for the shipment and deployment of the mobile pilot setup to FORD's facilities.

Upon arrival of the mobile system, a dedicated integration period will be required to configure, adapt, and validate the joint demonstrator. This phase will ensure seamless interoperability between the fixed and mobile components, enabling a fully operational and representative industrial scenario.

3 White Goods Open Pilot Line - IPK

A flexible robotic cell for the assembly of small household appliances has been developed. As the degree of automation for white-goods assembly today is limited, especially in areas of cabling or the installation of sensitive / flexible materials, it is likely that changes to the product design as well as new automation technologies are needed. This open pilot aims to increase the degree of automation for the European manufacture of White Goods by lowering barriers to feasibility studies and providing trainings which can educate automation engineers at end-users. At the same time, the open-pilot allows the easier test and validation of new automation technologies, which can improve the speed or generality for the challenging tasks.

3.1 Value Proposition

The White Goods open pilot line provides a platform for development and training around assembly tasks for household white goods. This includes the manipulation of small parts, cables, gaskets and other tasks which have classically been difficult for robotic manipulation. As these tasks are today often not automated, the main value propositions are:

- To improve the automation-readiness of European white-good manufacturers by:
    - Lowering barriers to feasibility studies with existing products, allowing identification of challenging design aspects as well as suitable technologies for automation
    - Improving background knowledge of what design aspects present automation challenges, such that automation engineers can readily identify tasks that can be automated today and which industrial partners they should contact for this.
- Improve suitable technologies for the automation of these tasks by:
    - Providing a test environment with challenging automation problems
    - Providing an open ROS-compatible environment where new modules can be readily integrated.

3.2 Description of the current Setup

Since D7.1, several changes have been made to this OPL, introducing new modules, upgrading existing modules, and simplifying the setup to allow stable experimentation and deployment. These changes are split into the Hardware and Active Modules sections below, with references to the individual sections as necessary.

3.2.1 Hardware setup

The hardware setup has been changed as:

(1) adapted to integrate safety measures,
(2) change material supply to increase efficiency,
(3) simplified to make experimentation simpler

For the safety measures, changes have been made to the end-effectors and a force/torque sensor has been integrated at the end-effector. These changes can be seen in the following images. For further details regarding design and validation, please refer to D6.3.

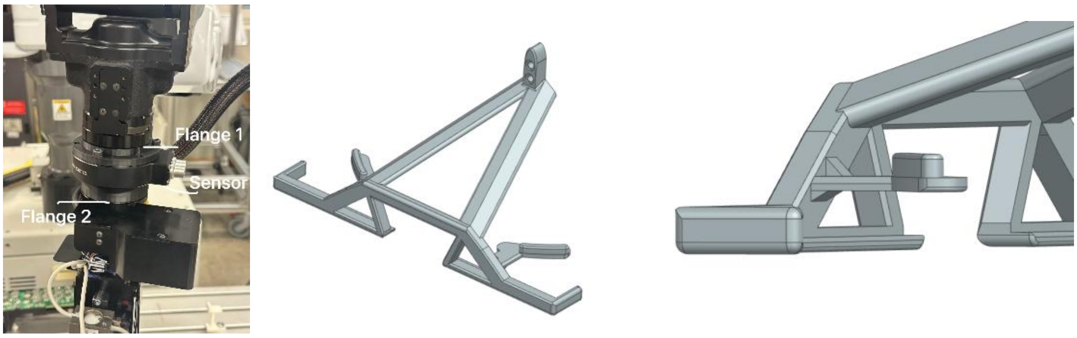


Figure 15: (left) Integration of the AIDIN force/torque sensor to the wrist of the Kawada robot. (right) Adaptation of the coil gripper to add the safety features and a second shelf for carrying the smaller rounded hobs.

An end-effector for the screwdriving task has also been developed by LMS. The electrical integration is performed over the Kawada DIOs and a tool-changer system is integrated to allow the end-effector to be changed.

Additionally, a safety PLC has been integrated to the pedestal of the Kawada robot, and a speed-monitoring device provided by Kawada integrated. Please see D6.3 and D3.3 for further details on the design and integration of these.

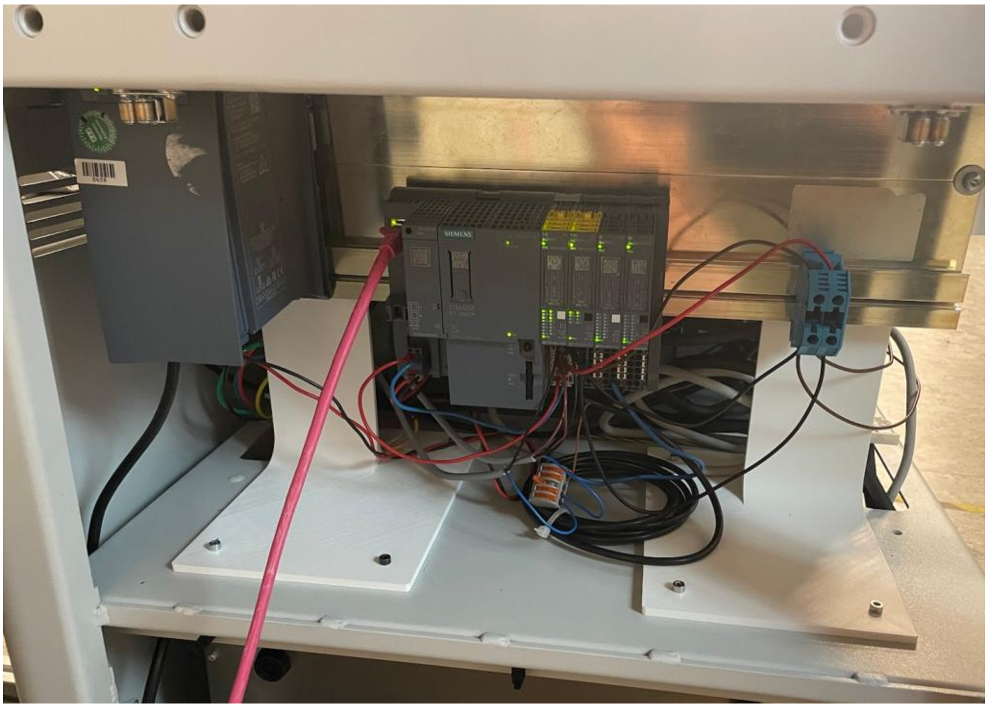


Figure 16: Safety PLC integrated to the pedastal of the Kawada Robot.

To improve the efficiency of handling, a magazine concept which supplies the coils in a vertical stack is developed and tested. This setup is compatible with the material supply that ELUX currently uses, and should improve the transferability of the manipulation strategies.

Figure 17: Alternative magazine for the coils to allow a stack while also not colliding with the gripper geometry.

In simplifying the experimental setup, the Kawada-ROS driver was dockerized and deployed on the main PC, allowing the removal of the Intel NUC which was shown in D7.1.

3.2.2 List of active modules

Since D7.**1**, several modules have been upgraded and added, while others have been maintained.

AI Station Controller (AISC):

Setup: The setup of the AISC has not changed from D7.1, it is a pure software-based solution running on the main development PC.

Requirements: Docker, local CRC services available, standard web browser for the user interface.

Customization: Since D7.1, the tasks used in the AISC have been updated to reflect the new demonstrator process. The AISC has also been updated to allow it to check the expected time for remaining for multiple tasks in parallel, which is adjusted to match the names from the CRC.

Collaborative Robot Control (CRC)

Setup: The setup of CRC has not changed from D7.1

Requirements: The system has been Dockerized, thus the requirements are now Docker as well as the HRC services and topics.

Customization: The module has been adapted with parameters on the timeouts for re-planning, the distances and velocity limits, as well as the calibration between camera system and robot. The CRC has also been adapted to launch several planners in parallel, which has been reflected in the launch files.

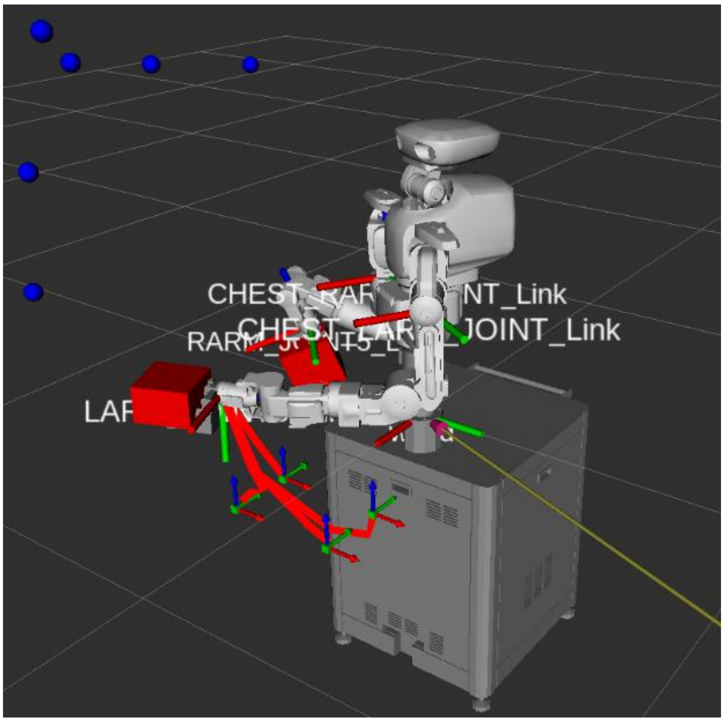


Figure 18: CRC with visualized trajectories to multiple target locations. The human pose can be seen as the blue points to the far left.

Perception and Autonomy module (PAM):

Setup: The setup has remained unchanged from D7.1

Requirements: The requirements are unchanged from D7.1.

Customization: The camera system has been re-calibrated relative to the robot after the robot setup has been moved within the IPK facilities.

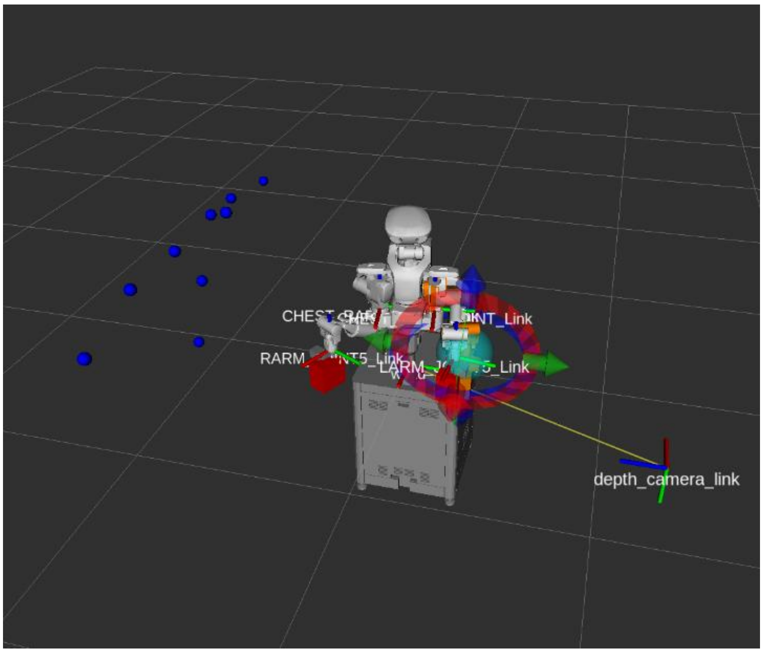
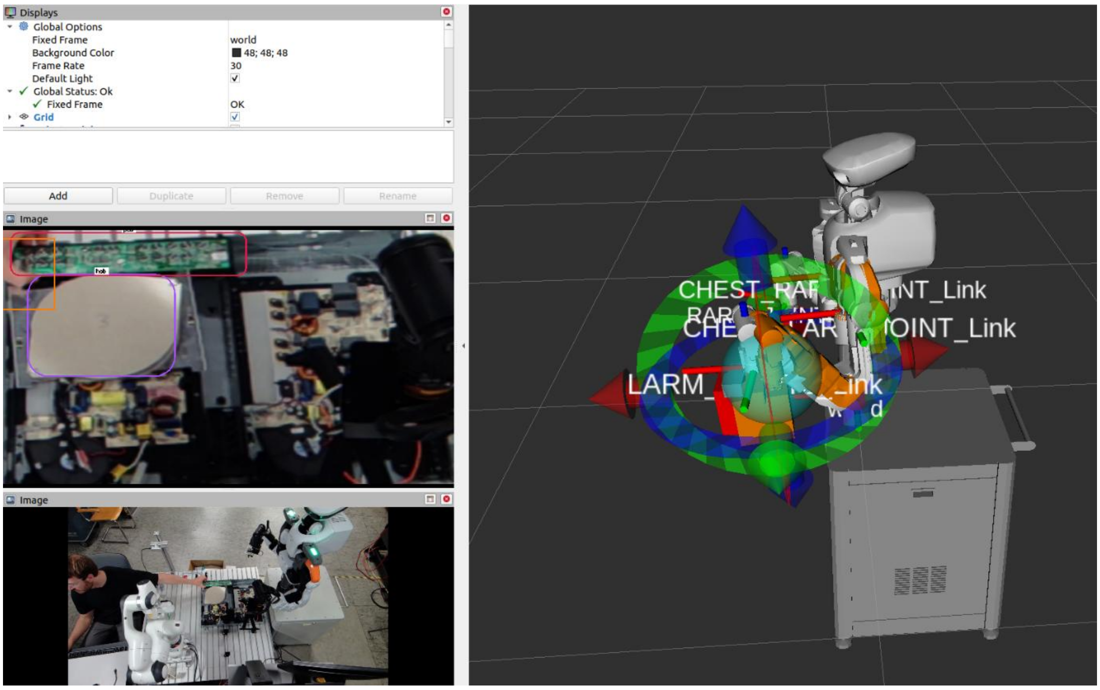


Figure 19: RVIZ environment with the calibrated camera pose, estimated human pose, and MoveIt interface for Kawada.



Displays
Global Options
Fixed Frame world
Background Color 48; 48; 48
Frame Rate 30
Default Light ✓
✓ Global Status: Ok
✓ Fixed Frame OK
Grid ✓

Figure 20: Integrated visualization of the PAM parts detection module with the RVIZ environment.

Humanoid Collaborative Robot (HCR)

Setup: The setup has remained unchanged. Internal changes on the Kawada (mounting of a safety PLC) as well as the end-effectors as detailed in D3.3 has occurred.

Requirements: The Intel NUC is no longer required

Customization: The ROS driver is now dockerized and can be run on the development PC, allowing the removal of the Intel NUC. The ROS motion streaming interface has been tuned for smoother teleoperation and control via CRC. The control of the torso joint has been added, as well as the publishing of motor torques.

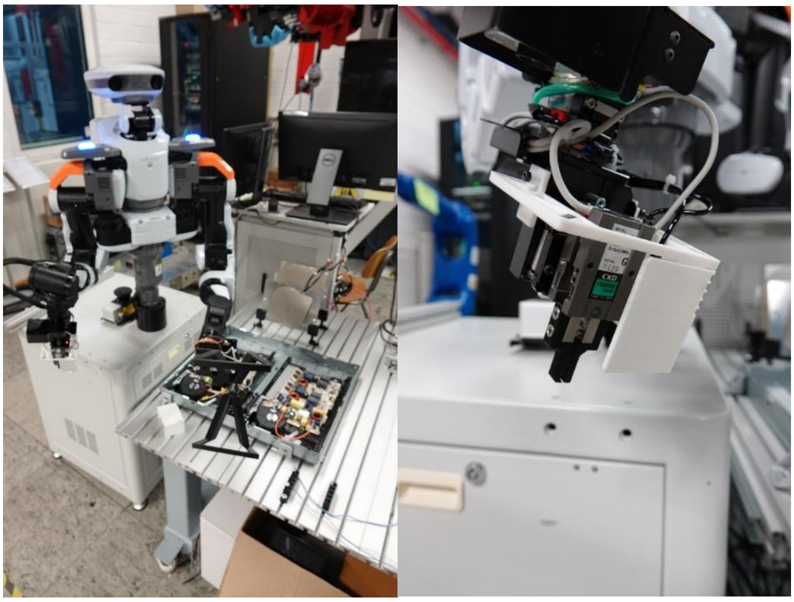


Figure 21: Overview of Kawada Nextage robot at IPK (left) and cabling gripper with covering (right).

Figure 22: Detailed view of coil grasping fingers.

Multi Actor Contextual Interfaces (MACI)

Setup: No changes in the setup from D7.1.

Requirements: No changes in requirements from D7.1.

Figure 23: Detailed view of projector and cameras on the mounting system.

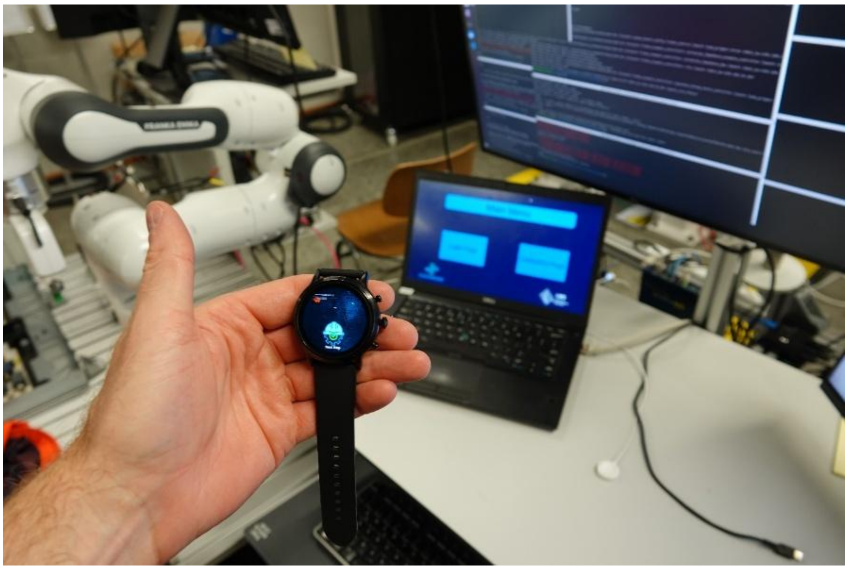


Figure 24: Smartwatch with operator interface displayed.

3.3 OPL System Level Functionalities (SLFs)

3.3.1 High level System Functionalities

The open pilot line has several different system-level functionalities that show the integrated performance of the software and hardware module to address specific scenarios relevant to the use case. They can be seen in Table 25: High level functionalities.

Table 25: High level functionalities in the White Goods open pilot line

#	High Level Functionality	Short description
1	Flexible operator assistance from the HCR	The robot can execute actions autonomously (by the AISC schedule) as well as when requested for the human operator (via the MACI module). This provides operator control over the execution flow and timing, e.g. operator requests the robot to bring the small hob.
2	Online assembly monitoring and task instructions	The operator interfaces allow the display of the current assembly step (via the projector system), the validation of the correct assembly (via the PAM module), which is synchronized with the task-planning information (AISC), e.g. online update to the assembly state, the visualization of the instructions on the table, and the live updates in the AISC.
3	Collision-aware task selection	The system is capable of dynamically replanning according to the current human pose to maintain distance and velocity limits with respect to the human, and these results are incorporated the selection of the task from the AISC, e.g. AISC selects which hob location to place, which changes based on with or without the human presence.
4	Online ergonomic information	The operator’s posture is evaluated based on the pose estimate provided by the PAM. This ergonomic information is provided as feedback to the operator.
5	Error detection to operator assistance	An error during the assembly process (failed insertion of plug, missing plug) is detected, and a notification is given to the

#	High Level Functionality	Short description
		operator to allow them to correct the error then resume operation of the cell.

3.3.2 Lower-level System Functionalities

A – Flexible operator interaction with assistance from the HCR

Table 26: Low-level system functionalities involved in this higher-level functionality.

Step #	Operation	From	To	Status
1	Task and actions plan in generated	DWR	AISC	Not integrated yet
2	Operator starts the task	MACI	AISC	Functionally validated
3	Robot's first task is started	AISC	CRC	Functionally validated
4	Robot grasps the hob and places it	CRC	HCR	Functionally validated
5	Robot moves back to a neutral position	CRC	HCR	Functionally validated
6	Operator makes verbal request for new hob	MACI	AISC	Functionally validated
7	Request sent to move robot to pick new hob and brings it to the location	AISC	CRC	Functionally validated
8	Robot moves to pick the hob	CRC	HCR	Functionally validated
9	Robot undertakes the screwing task	AISC	HCR	Not integrated yet
10	Robot switches end effectors	HCR	-	Not integrated yet

B – Online assembly monitoring and task instructions

Table 27:Online assembly monitoring and task instructions.

Step #	Operation	From	To	Status
1	Operator starts the task	MACI	AISC	Functionally validated
2	Robot's first task is started	AISC	CRC	Functionally validated
3	Robot grasps the hob and places it	CRC	HCR	Functionally validated
4	The operator continues in their assembly of the cable	-	-	Functionally validated
5	The operator indicates they have finished	MACI	AISC	Functionally validated
6	The request for validation is sent	AISC	PAM	Functionally validated
7	The PAM module checks module visually and reports the result	PAM	MACI	Functionally validated
8	The MACI displays the result	MACI	-	Functionally validated
9	SAM check safety events online	SAM	HCR	Not integrated yet
10	Process metrics are uploaded to DAR	AISC	DAR	Not integrated yet

C – Collision aware task selection

Table 28: Collision aware task selection.

Step #	Operation	From	To	Status
1	The CRC planer is started for each goal option	-	CRC	Functionally validated
2	Operator starts the task	MACI	AISC	Functionally validated
3	The time to take each task is checked	AISC	CRC	Functionally validated
4	The CRC reports the time considering the operators current position	CRC	AISC	Functionally validated
5	The AISC decides which is best and starts execution	AISC	CRC	Functionally validated
6	The motion to that goal location is started	CRC	HCR	Functionally validated

D – Online operator ergonomics evaluation

Table 29: Online operator ergonomics evaluation.

Step #	Operation	From	To	Status
1	The UXE evaluator is started	-	UXE	Functionally validated
2	Operator starts the task	MACI	AISC	Functionally validated
3	The operator’s pose is measured	PAM	UXE	Functionally validated
4	The operator’s ergonomic score is estimated and displayed	UXE	MACI	Functionally validated

E – Error detection for operator assistance

Table 30: Error detection for operator assistance.

Step #	Operation	From	To	Status
1	Operator starts the task	MACI	AISC	Functionally validated
2	Robot’s first task is started	AISC	CRC	Functionally validated
3	Robot grasps the cable and places it	CRC	HCR	Functionally validated
4	The forces during the assembly are checked and an error is detected	PAM	MACI/HCR	Functionally validated
5	A robot stop is executed	HCR	-	Functionally validated
6	A display that an error has occurred is shown	MACI	-	Functionally validated

3.4 Service provisioning

3.4.1 Assessment of the planned events

The planned services in the context of this open pilot are presented in following table.

Table 31: Planned events assessments for the white goods open pilot line.

	Training Services	Technical Services	Consulting Services
Objective/Outcome	Courses, webinars, workshops	Test and validate technologies	Improve product automation potential
Target audience	Professionals, workers, universities	Technology providers	Factory engineers
Equipment	Open Pilot Line	HCR, CRC, MACI, DAR	HCR, CRC, MACI, UXE, DAR
Customizable	no	yes	yes
Fee	500 Euro/participant	1000 Euro / estimated engineer-day	1000 Euro / estimated engineer-day
Location	Anywhere	IPK Facilities	IPK Facilities
Delivery Timeline	Available Immediately	Available from November 2024	Available immediately

A first training on the use of AI-enabled manipulation for white goods and electronics has been delivered on 20.08.2025 at a large Industrial Electronics manufacturer in Berlin as a directly-contracted industrial project. The title of the training is *"AI methods for robot-supported electronics assembly"*, and was presented in German. The translated agenda for the training portions that presented CONVERGING results is as follows:

1) Challenges in fine manipulation for final assembly of electronics goods
2) End-effector solutions for cable handling, plug insertion, and PCB handling
3) Material supply solutions for cable supply
4) AI manipulation strategies for cable routing and PCB handling
5) PCB handling and cable routing

With this, the results of the HCR, ARBA, and PAM for the white-goods OPL are presented in both image and video form. The video of the task setup was used to show competence to acquire the training contract. This training was provided as an on-site service and was followed by brainstorming of the challenges on-site as well as possible solution approaches.

The seminar was attended by 13 production engineers and management staff, and this training module for "*AI methods for robot-supported electronics assembly*" was one of four modules covering various aspects of AI-supported methods for production.

From the participant feedback, the qualitative feedback specific to the CONVERGING module were as follows:

- "To get operator support in an error case would need new concepts for integrating the pilot line."
- "The robot is slow during the assembly."
- "This was an interesting overview to state of the art"

The quantitative feedback to the CONVERGING module were as follows:

Question	Responses
I now have an overview of state of the art in electronics assembly.	10 Fully agree 2 Mostly agree
I understand the main challenges in electronics assembly and how the production can be changed to address them.	6 Fully agree 5 Mostly agree

Question	Responses
Addressing these challenges in electronics assembly will have a large impact.	13 Fully agree
I believe that one final assembly electronics station in our factory will be automated in the next 3 years	3 Mostly agree 9 Neither agree or disagree

3.4.2 Future work timeline

At least one additional public webinar training will be offered in November 2025, before the assembly line is delivered to ELUX. The title of the planned training is *"Human-involved error handling for robustness in industrial tasks."* The planned agenda is as follows:

1) Human-supported error handling today
2) Integration of error handling in robotic manipulation tasks
    a. Fully autonomous cells
    b. Collaborative methods for error handling
3) Methods for error detection and task monitoring in robotic manipulation
    a. Error detection methods: visual, time-series based
    b. Error correction methods
4) Demonstration in white-goods assembly

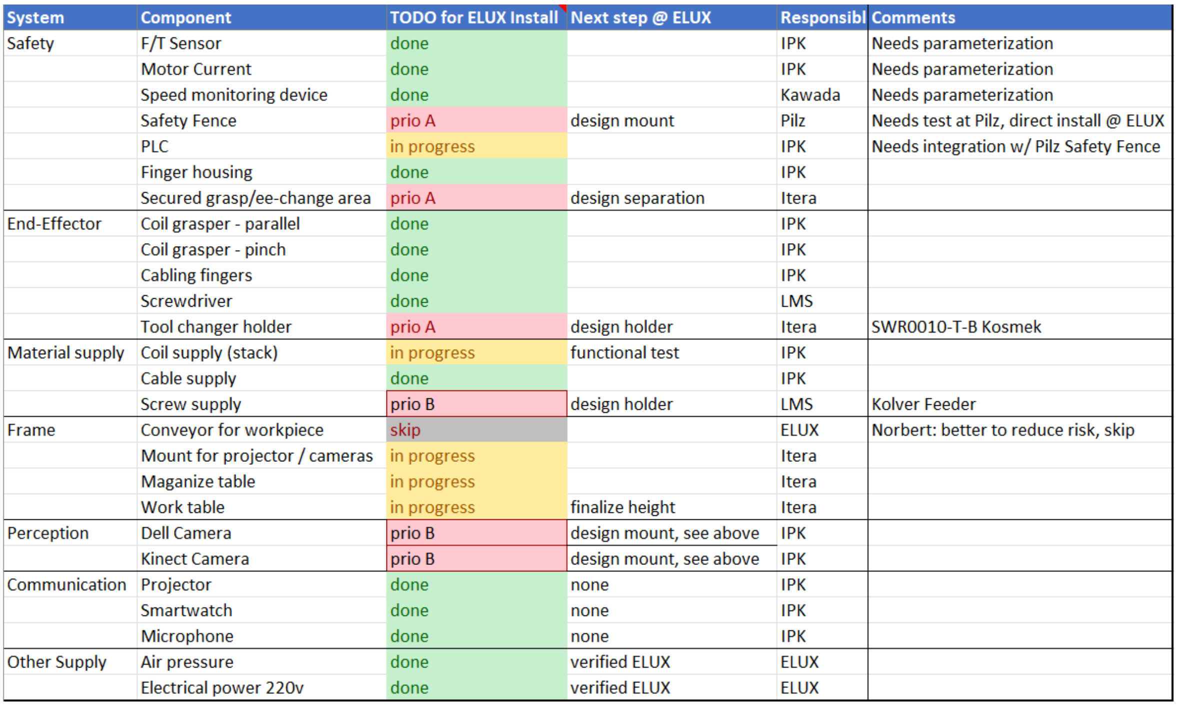
The workshop will be held on-site at IPK with industrial engineers. The CONVERGING results from PAM will be presented for both task monitoring and error detection, and the integrated assembly process will be shown for the final demonstrator.

3.5 Industrial deployment planning

3.5.1 M48 plan and timeline

An overview of the individual sub-systems required for the final integration at ELUX, as well as the current status, responsible partner, and next step, can be seen in Table 32.

Table 32: Overview of integration atctivities for ELUX install.



System	Component	TODO for ELUX Install	Next step @ ELUX	Responsibl	Comments
Safety	F/T Sensor	done		IPK	Needs parameterization
	Motor Current	done		IPK	Needs parameterization
	Speed monitoring device	done		Kawada	Needs parameterization
	Safety Fence	prio A	design mount	Pilz	Needs test at Pilz, direct install @ ELUX
	PLC	in progress		IPK	Needs integration w/ Pilz Safety Fence
	Finger housing	done		IPK	
	Secured grasp/ee-change area	prio A	design separation	Itera	
End-Effector	Coil grasper - parallel	done		IPK	
	Coil grasper - pinch	done		IPK	
	Cabling fingers	done		IPK	
	Screwdriver	done		LMS	
	Tool changer holder	prio A	design holder	Itera	SWR0010-T-B Kosmek
Material supply	Coil supply (stack)	in progress	functional test	IPK	
	Cable supply	done		IPK	
	Screw supply	prio B	design holder	LMS	Kolver Feeder
Frame	Conveyor for workpiece	skip		ELUX	Norbert: better to reduce risk, skip
	Mount for projector / cameras	in progress		Itera	
	Maganize table	in progress		Itera	
	Work table	in progress	finalize height	Itera	
Perception	Dell Camera	prio B	design mount, see above	IPK	
	Kinect Camera	prio B	design mount, see above	IPK	
Communication	Projector	done	none	IPK	
	Smartwatch	done	none	IPK	
	Microphone	done	none	IPK	
Other Supply	Air pressure	done	verified ELUX	ELUX	
	Electrical power 220v	done	verified ELUX	ELUX	

A CAD model of the integrated cell has been prepared by ITERA which can be seen in the following section. For the integration planning, at least two integration visits from IPK are planned

- Initial integration trip Feb 2026
    - Installation of mechanical hardware, including: robot, safety fences, magazines, cameras, projector, tool-change holder and computer
    - Electrical integration of: safety fence, robot, cameras, projector, computer
    - Initial tests of software integration
    - Reprogramming of taught positions for the new cell layout and initial tests of motion
- Second integration trip in Apr 2026
    - Adjustment of any hardware changes, task changes, or layout changes identified from the first integration trip
    - Finalization of the process flow for the complete demonstrator
    - Tests with operators to evaluate acceptance, KPIs, etc.

3.5.2 End user information and final pilot draft layout

For the integration at ELUX, a test room has been identified separated from the production line with the following features:

- 4x4m of floor space
- A standard door, closeable to prevent unauthorized access
- Pressure air at 6bar
- Standard 220v electrical supply

A variety of existing equipment at ELUX is available, including the coil material supply and centering mechanisms, seen in Figure 25 and Figure 26. The room itself can be seen in Figure 27, which includes a locked door to secure access to the demonstrator during the pilot validation phase.

Figure 25: Current production line and coil material supply.

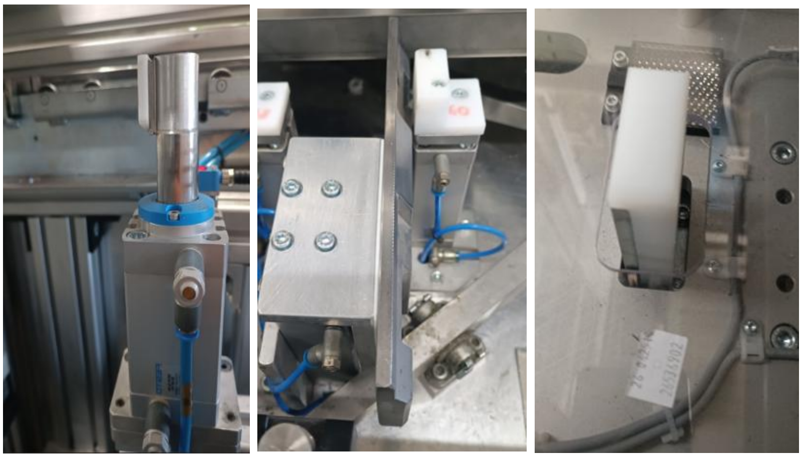


Figure 26: Hob centering mechanisms available at ELUX.

Figure 27: Planned Pilot Line Location in the Factory at Rothenburg.

The planned industrial pilot line has been laid out through a series of meetings involving ELUX, IPK, ITERA, PILZ and KAWADA. The initial sketch provided by ELUX after the first meeting can be seen in Figure 28. In following meetings, the need for safety isolation on certain pinch-hazards (tool changing, grasping of hobs) was identified and an adjusted schematic has been prepared as seen in Figure 29. This schematic is being used to produce a design of the demonstrator on a detail level that can allow additional components (e.g. aluminum profile) to be ordered, as seen in Figure 30.

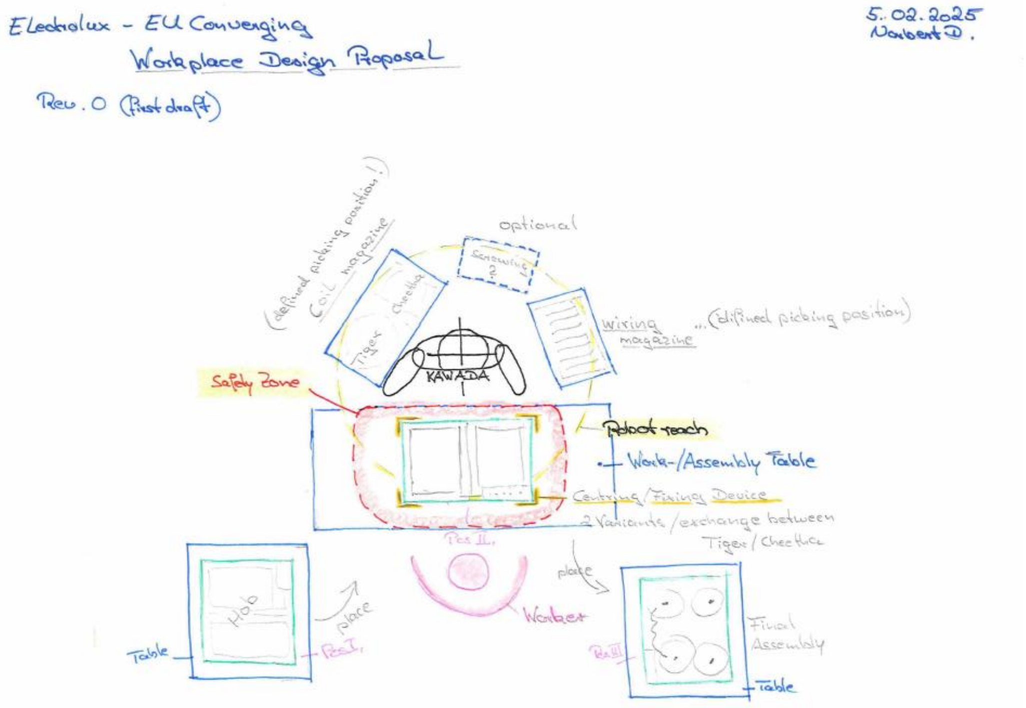


Figure 28: Initial draft of layout provided by ELUX after the initial planning meeting.

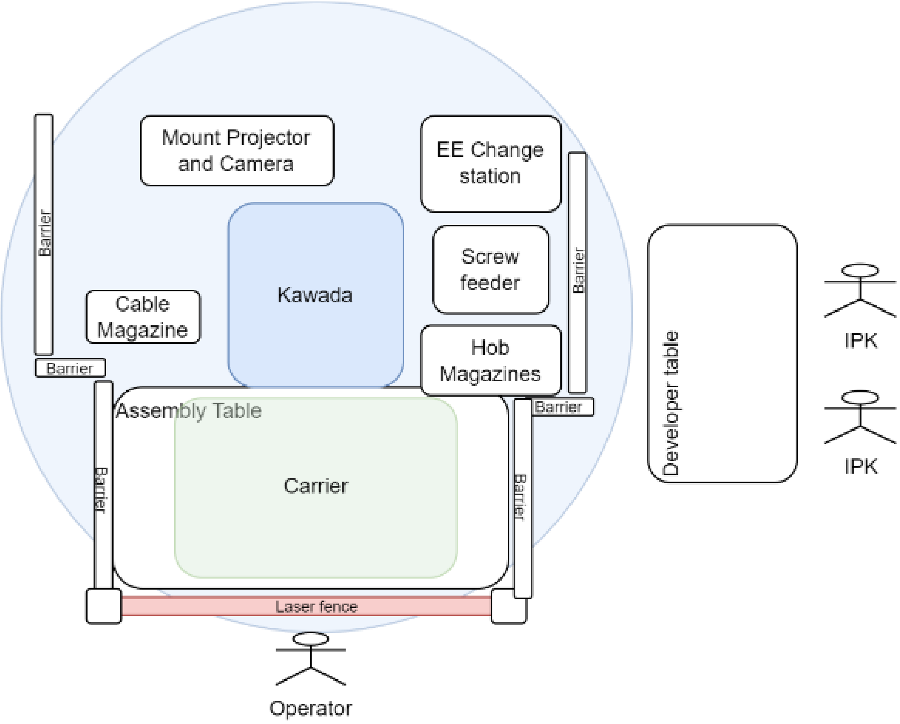


Figure 29: Revised layout including additional safety and separation hardware in discussion with PILZ.

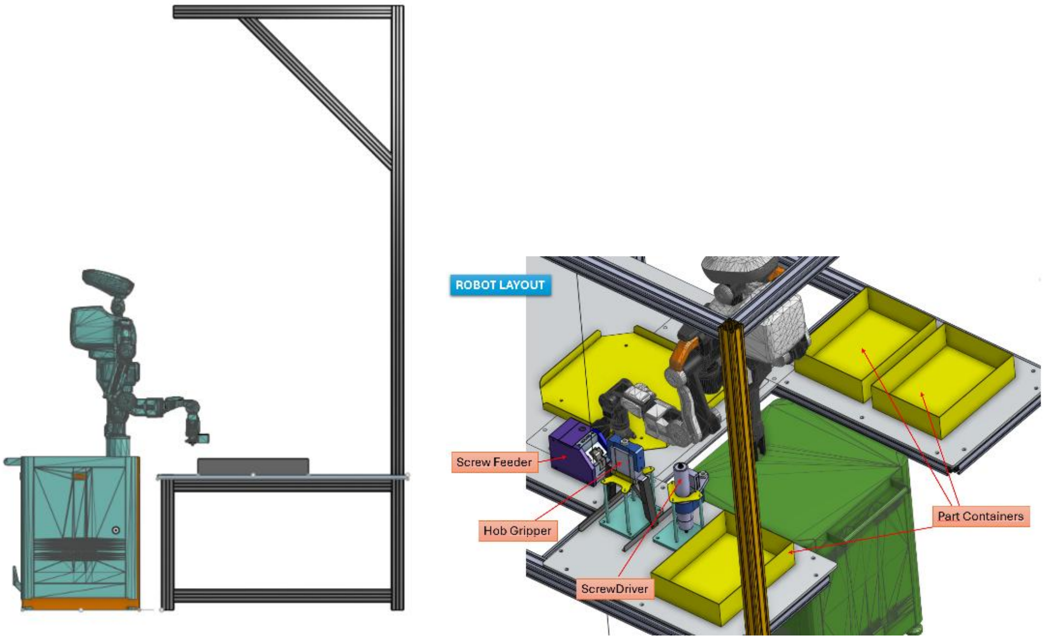


Figure 30: Planned robot cell showing the worktable and overhead mount for cameras and projector.

4 Aeronautics Open Pilot Line – TF-CC

In the context of CONVERING, a custom multi-robot system has been developed, that aspires to support aircraft fuel tank maintenance involving advanced technologies and equipment to improve inspection and repair processes. The key component is the implementation of a smart, collaborative robot system augmented with smart mechatronics to perform Non-Destructive Testing (NDT) and Foreign Object Debris (FOD) detection. The robot will use "vision" sensors and AI-based decision-making to detect damages, identifies their characteristics (like type, location, and size), and prevents FOD incidents through anomaly detection, reviewed by an operator. The primary role of the system is to reduce risks for human operators by minimizing their exposure to hazardous environments and speeding up the overall maintenance process.

4.1 Value Proposition

The Aircraft Fuel Tank Maintenance Pilot Line offers a platform for the development and training around inspection and maintenance tasks for aircraft fuel tanks. This includes challenging tasks like navigation in confined spaces, detecting damage, and performing repairs—areas that have traditionally been difficult to automate. Since many of these tasks are still performed manually, the key value propositions of this pilot line are:

- Enhancing automation readiness for fuel tank maintenance by:
    - Increasing awareness of which maintenance tasks present automation challenges, so maintenance engineers can better determine which tasks can be automated and which industry partners to engage with.
    - Deciding practices for the integration of beyond state-of-the-art technologies.
    - Concluding to technology applicability potential to support automation in the fuel tank maintenance and inspection.
- Advancing suitable technologies for automating fuel tank maintenance by:
    - Providing a test environment with complex automation challenges such as damage detection and confined space manoeuvrability.
    - Offering a realistic testing environment where new modules, sensors, and AI algorithms can be seamlessly integrated for testing and optimization.

4.2 Description of the current Setup

The Aeronautics Open Pilot line has been deployed by LMS in TF-CC premises as described also in D7.1. A few changes to the current setup have been performed in order to enhance the stability and area clearance of the installed aluminium profile structure and mounted fuel tank on top of it. New steel anchor mounts have been placed between the floor and the four aluminium anchor points that hold tightly the hole mounting structure. The new placed mounts are stronger and more robust utilizing larger area and more mounting points of the profiles and bigger anchoring screws. The intermediate connections of the profiles structure have also been enhanced with thicker steel than the previous setup for more robust mounting points.

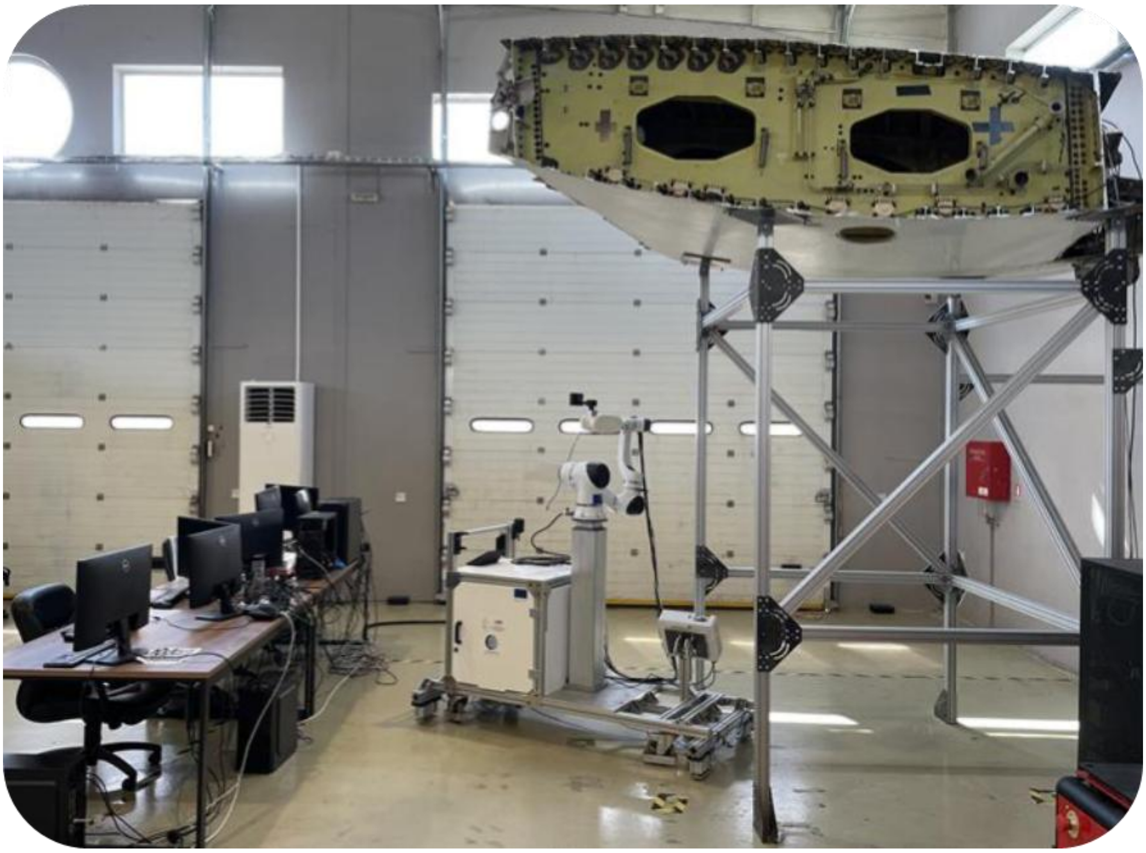


Figure 31: Current setup of Aeronautics use case.

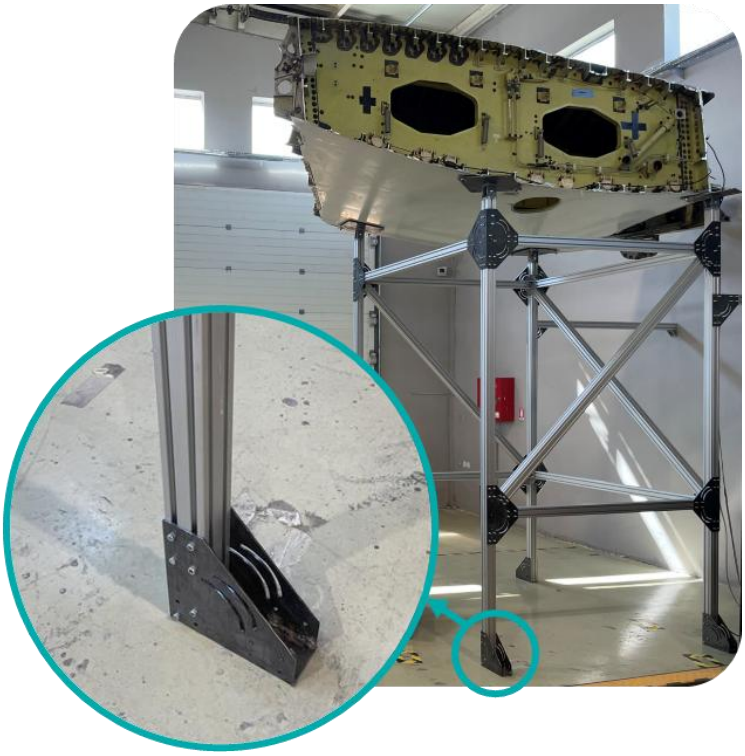


Figure 32: New anchoring mounts.

4.2.1 Hardware setup

Robotic System:

To cover properly all the electrical components and controllers of the robot, an enclosure casing has been designed and installed on the cart. The enclosure is a custom design for the specific use case to properly fit and mount all the sub-components, while providing easy accessibility. In Figure 33, the initial and final implemented design is presented.

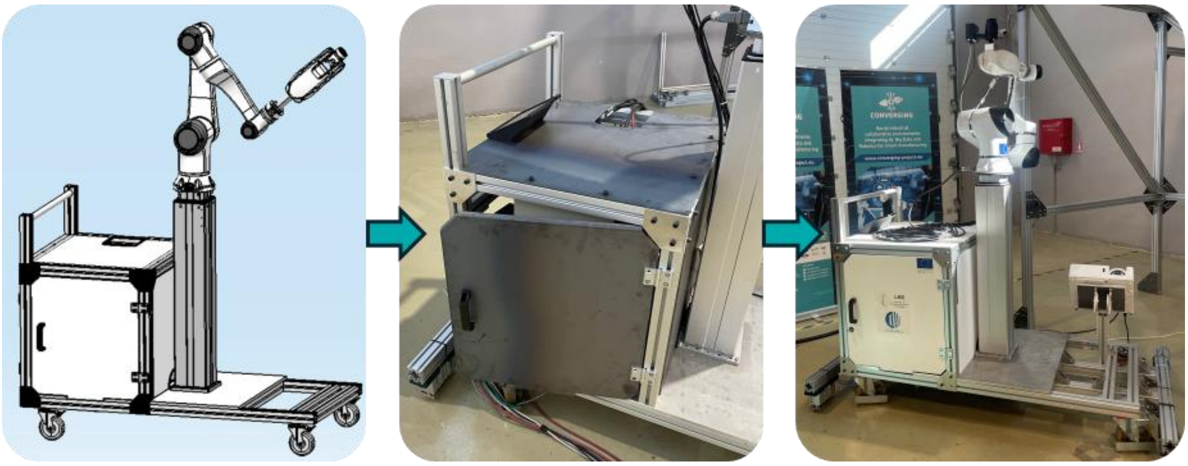


Figure 33: Design of electrical enclosure design and implementation.

Electrical setup:

Due to multiple electrical components that are used for the robot's operability, an electrical cabinet has been installed on the cart, consisted of electrical plugs, fuses, circuit breaker and relays. The design and final installation of the electrical cabinet inside the robot's enclosure casing is presented in Figure 34.

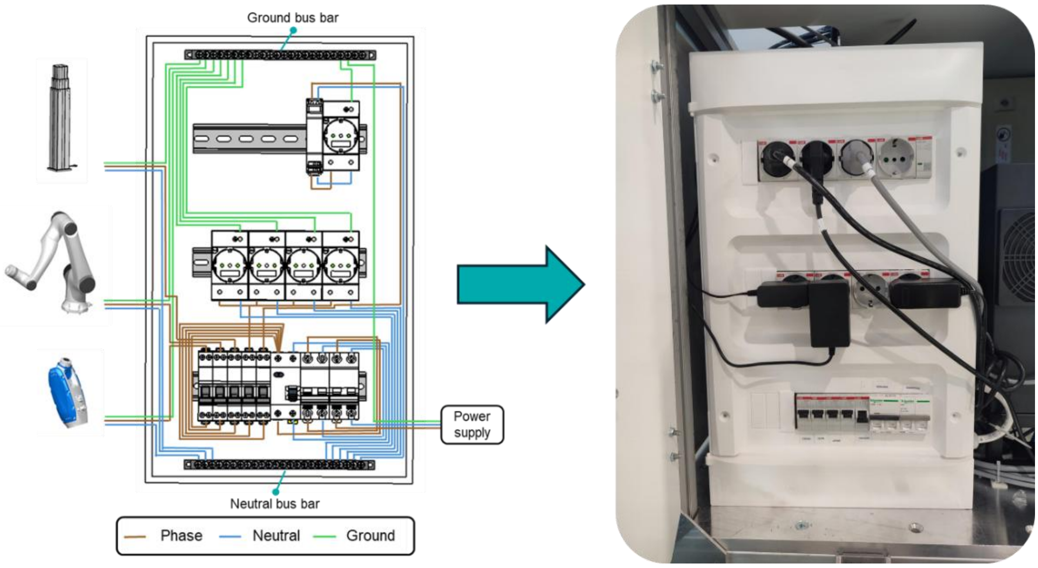


Figure 34: Design of electrical cabinet and final installation inside the robot.

Also, due to the mobility feature of the cart, all the cables that are used for the operability of the robot are wrapped to a cable organizer tube in order to avoid cables lying under the cart's wheel and actuators system (Figure 35).

Figure 35: Cable management tube for all cables of cart.

Sensors:

For the needs of the use case a new 3D sensor has been equipped to the robot. The new sensor, Orbbec Femto Bolt (Figure 36), shares identical features with the previously used Azure Kinect. It has a ToF technology to acquire depth data and produces very accurate depth image without the presence of incorrect depth values as stereo vision and structured light cameras. Also, the new camera is 50% smaller in length that the previous sensor.

Figure 36: Orbbec Femto Bolt 3D sensor.

To properly mount and protect the camera from collision and scratches, a protective mount casing has been designed, printed and installed on the robot. In Figure 37, the design of the protective mount casing and final installation on the robot is presented.

Figure 37: Protective mount design and final installation on robot.

4.2.2 List of active modules

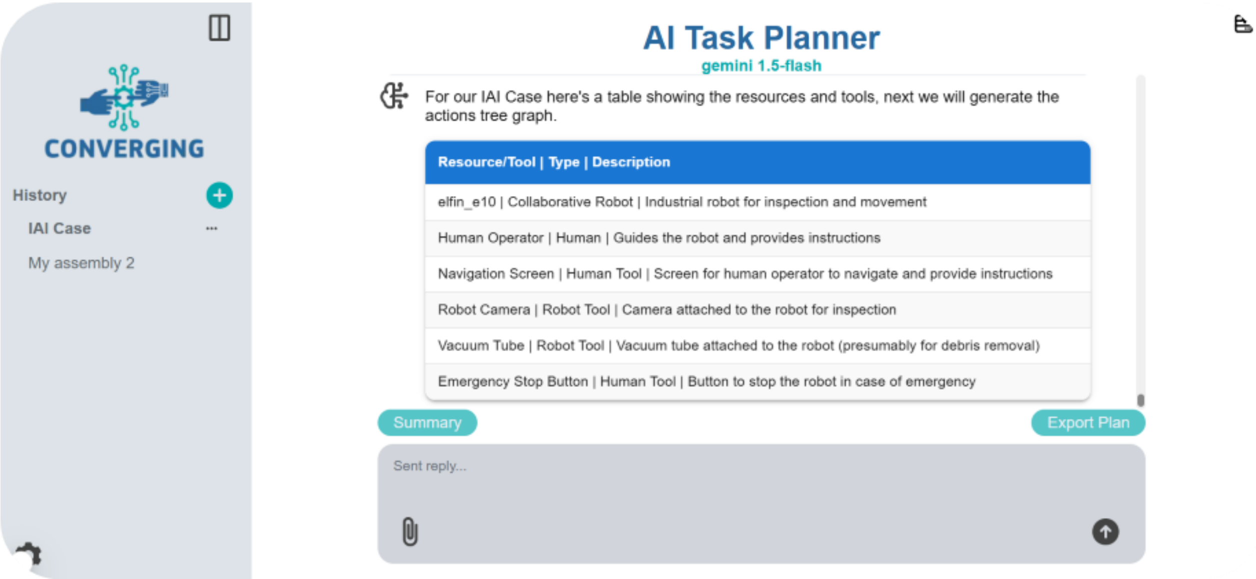
Dynamic Work Reorganization (DWR)

Setup: DWR module is responsible for generating schedules of actions/tasks based on the Aeronautics use case and the available resources. A LMM model is used where video sample along with sound instructions is provided. The LMM analyses the video frames and the instructions and generated a JSON file that contains high-level tasks ready for distribution for each available resource, robot or operator. In order to match the needed structure for the AISC integration a script parsing the tasks JSON utilizing simulation classes for available agents with context of their skills, it generates the lower level actions that are transformed into formatting that the AISC can handle. The generated schedule of actions is distributed to the AISC, and it further used in the execution process.

Requirements: For the DWR module an internet connection is needed, in order to upload the video with the instruction and then receive the generated schedule. Due to web API calls, the hardware needs for that module are very low, and a PC with low hardware requirements is needed. For the transformation of the tasks to AISC compatibility we need to define the simulation agents with the corresponding skills of the real resources.

Customization: No customization is needed for the Aeronautics case. The provided video with the instructions is the only thing that is needed for the generation of a plan/schedule.

Trouble/Solution: -



For our IAI Case here's a table showing the resources and tools, next we will generate the actions tree graph.

Resource/Tool	Type	Description
elfin_e10	Collaborative Robot	Industrial robot for inspection and movement
Human Operator	Human	Guides the robot and provides instructions
Navigation Screen	Human Tool	Screen for human operator to navigate and provide instructions
Robot Camera	Robot Tool	Camera attached to the robot for inspection
Vacuum Tube	Robot Tool	Vacuum tube attached to the robot (presumably for debris removal)
Emergency Stop Button	Human Tool	Button to stop the robot in case of emergency

Figure 38: DWR module interface for Aeronautics pilot.

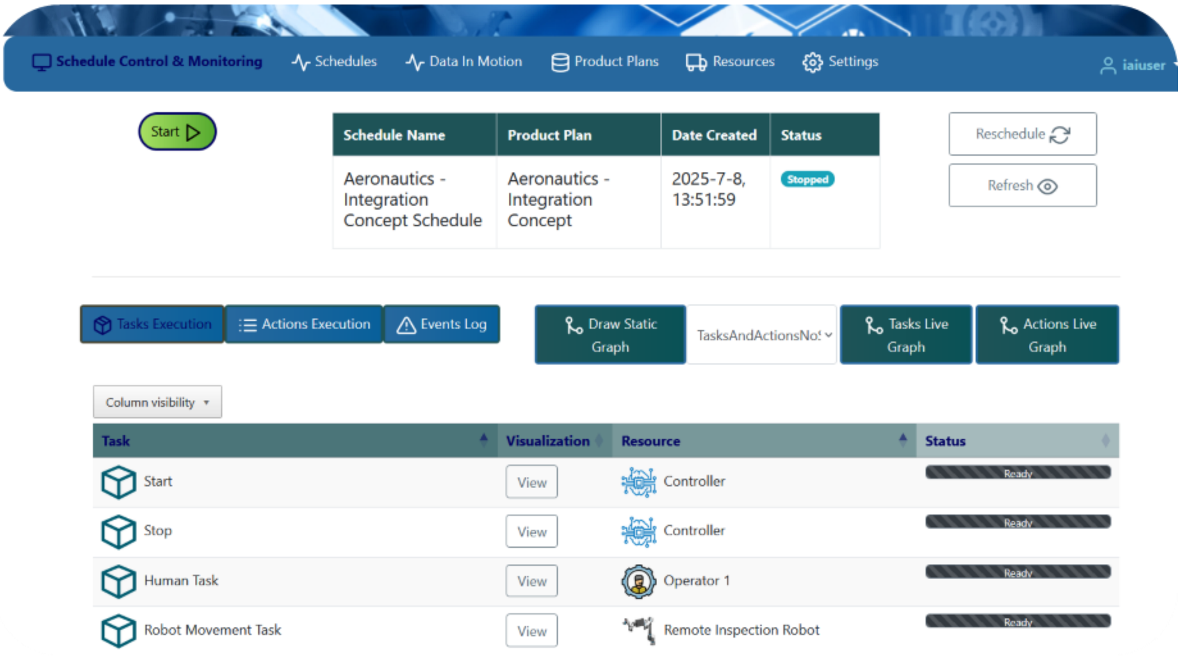
AI station controller (AISC)

Setup: The AISC module is the orchestrator which requests the execution of functionalities from other modules following a higher level scenario. It requests and monitors command execution, waits and reacts on the results from each process call. In this way, it controls the whole process flow and based on the results decides the next action call that will complete the inspection process of the airplane tank. The execution is observable and controllable by an information rich user interface that includes real time monitoring and control, allowing the user to pause, resume and cancel different workflows.

Requirements: The AISC requires a PC which runs Ubuntu 20.04 for ROS1 or Ubuntu 22.04 for ROS2. AISC is efficient and scalable, and most cases would run perfectly well in a medium performance PC. It is distributed as a docker image and requires docker and docker compose. The integrated version for each pilot case is customized by docker compose yaml files that defines the connections with other modules such as the MongoDB and Knowledge Repository submodules. Docker images already contain required dependencies such the appropriate java libraries and compatible JDK version.

Customization: The existing interfaces messages of ROS and respective topics have been assigned to AISC in order to make the appropriate calls to each module. A customized dynamic workflow, execution schedule has also been created and can be easily adjusted to accommodate the needs of the Pilot Case.

Trouble/Solution: -



Schedule Name	Product Plan	Date Created	Status
Aeronautics - Integration Concept Schedule	Aeronautics - Integration Concept	2025-7-8, 13:51:59	Stopped

Task	Visualization	Resource	Status
Start	View	Controller	Ready
Stop	View	Controller	Ready
Human Task	View	Operator 1	Ready
Robot Movement Task	View	Remote Inspection Robot	Ready

Figure 39: AISC user interface for Aeronautics pilot.

Perception and Autonomy module (PAM)

Setup: PAM module is in charge of understanding and analysing the data from the robot's surroundings and environment of the tank in order to calculate coordinates for navigation goals, detect rivets that are mounted inside the tank surface and FOD that may exist inside the tank space. Furthermore, the 3D reconstruction of RGB point cloud and collision map are generated while the robot scans the area after the first successful entrance process.

Requirements: PAM module uses a medium-high performance PC with Ubuntu 20.04 for ROS1 and Ubuntu 22.04 for ROS2. Also, a 3D sensor which in this case in the Orbbec Femto Bolt ToF sensor. Along with these, CUDA drivers 11.8 or higher are tested and required, SDK and drivers for Orbbec sensor, and PyTorch, 2.1.0 or higher, deep learning framework for running deep learning models. For the 3D reconstruction of the environment, RTAB-Map 0.22.1 library is required.

Customization: Using images from the physical airplane tank and images from tools and components that are frequently used for the maintenance process, the deep learning models have been trained for specific objects/classes/rivets that need to detect throughout the maintenance. Also, the hyperparameters of 3D reconstruction module are tuned to fit the needs for the collision and RGB map.

Trouble/Solution: In 3D reconstruction process the fuse of point cloud requires heavy calculations that slow down the process and a less dense point cloud parameter had to be used that can still capture the area of the tank but not utilizing fully the provided camera point cloud.

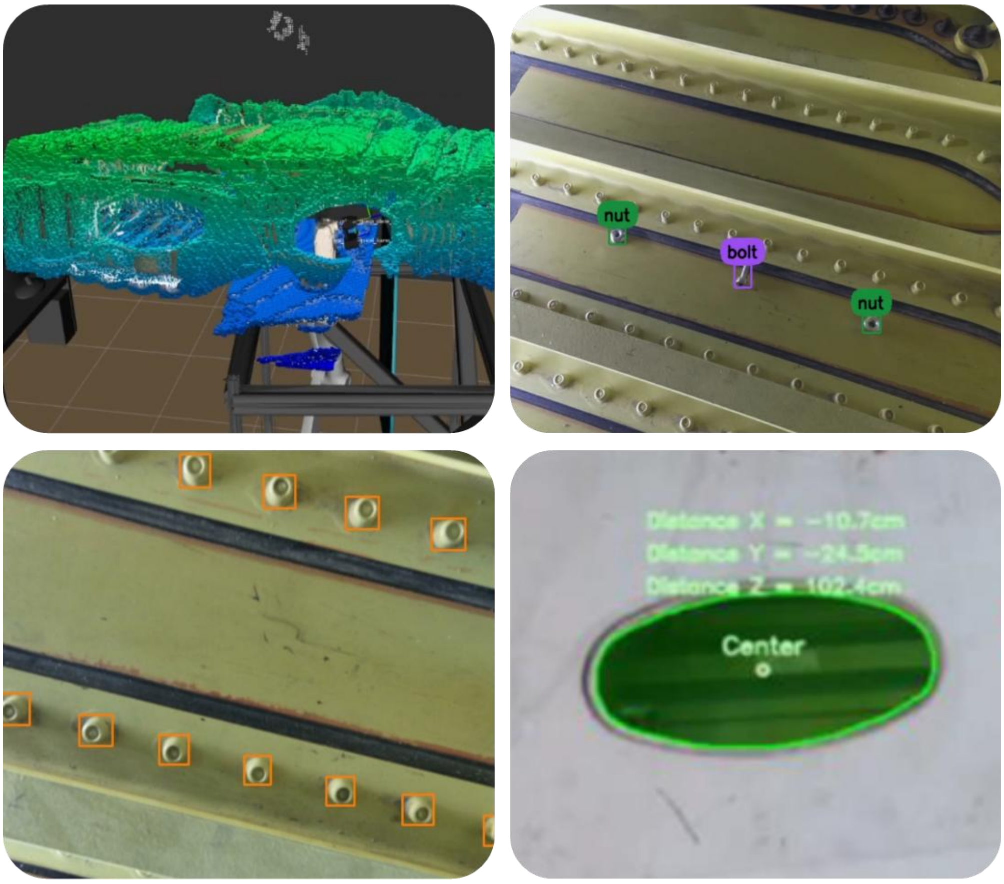


Figure 40: PAM module processes.

Remote inspection Robot (RIR)

Setup: The RIR module consists of a custom designed robot utilizing three robotic systems mounted on top of each other. Specifically, a liftkit column which has the ability to extend linearly up to 1.4 meters, a 6DoF Han's Elfin 10 robot, and a 2DoF Comau Racer 3 wrist utilizing the 5th and 6th joints. In total, RIR robot consists of 9 joints where one of them is the linear extension from the liftkit column. Also, a gripper mounted at the end effector of the robot is used for the 3D sensor, NDT & FOD grippers.

Requirements: For the communication of RIR robot, an ethernet switch is needed where two of the robots (Ewellix Liftkit, Comau wrist) are connected through TCP/IP protocol. For the connection of the Elfin robot a dedicated ethernet cable is needed to be connected directly to an ethernet port or USB port using a USB to ethernet adapter, communicating through Ethercat protocol. Also, a medium performance PC is need with Ubuntu 20.04 or Ubuntu 22.04 that will run ROS and ROS2 respectively.

Customization: For the communication with the Comau wrist robot, modifications to the Comau ROS driver were performed for correct data communication needed due to the custom number of robot's joints. Furthermore, the development of Comau Open Controller driver was performed in order to synchronize the motion of Elfin and Comau robots. This new developed driver provides the ability for external real-time control of the position of Comau's joints, resulting in synchronized trajectory execution.

Trouble/Solution: The Ewellix liftkit column which extends linearly, doesn't provide the ability for real-time position and velocity control. Due to this limitation, the synchronized trajectory execution when the liftkit joint is included is not feasible with this setup. For that reason, trajectories are segmented exclusively for Liftkit and Elfin-Comau groups, resulting in multiple intermediate trajectories execution.

Elfin and Comau wrist robots did not have the ability to control a perfectly synchronized trajectory, because the Comau robot was not controlled using real-time position control. For that reason, the Comau Open Controller was installed to the software of the robot, and the Comau Open Controller driver was developed for the communication and external control of the robot's joint positions, resulting in complete synchronization of the robot's motion.

Due to the height and extension of the liftkit column, while the robot is in motion, there are vibrations that are created due to non-stiff mounting point of the robot's base. As first step, the mounting aluminum profiles were extended out of the cart's center of mass to reduce the trembling-vibration of a trajectory.

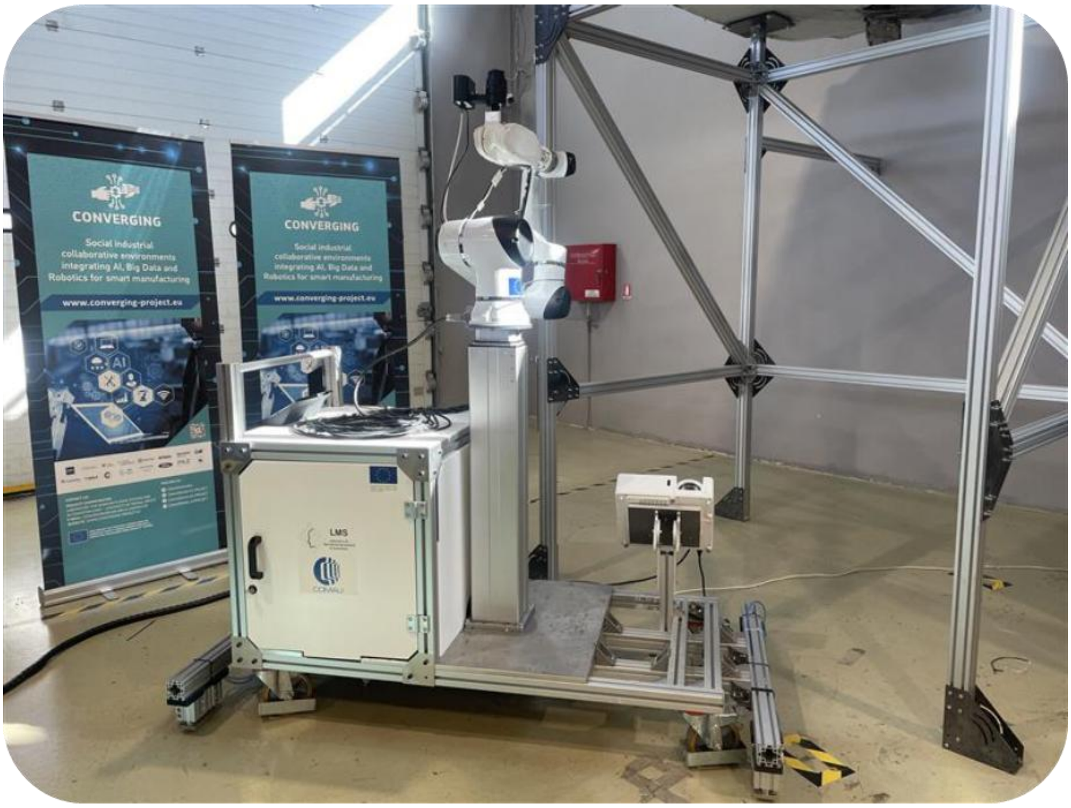


Figure 41: RIR robot.

AI Digital Twin (AIDT)

Setup: The AIDT module is responsible for creating a virtual replica of the IAI system in the digital environment to perform all necessary calculations for the robot's motion trajectory and to recreate all parts of the real-world scenario in the virtual space.

Requirements: A medium-high performance PC is required for the AIDT module to run properly. Also, the installation of the Visual Components' software along with a valid license of the application.

Customization: The RIR robot has been virtually modelled in the digital environment(Figure 42), using the developed behaviours. Similarly, the other components, including the aeronautics cell area with its aluminium structure, have been created. Point cloud data is imported into the digital twin. A voxel-like approach is applied to the point cloud data to enhance collision detection, as detailed in D4.3.

Trouble/Solution: - The AIDT, developed on top of Visual Components' software (VC), deploys a UI that provides users with access to system configuration and robotics capabilities. For the integration within the CONVERGING framework, a communication system has been deployed to communicate through ROS 2(Figure 43). Additionally, VC interfaces have been extended to access robotic solver capabilities (more details in D4.3). The current deployed solution, VC software, receives Cartesian poses through ROS2 to solve the robot´s motion trajectory and posts the solved joint values to the ROS2 system. A MQTT-based solution was developed for this purpose, and the development was shifted from VC4.0 to the VC5.0 simulation platform, which offers enhanced robot controllers, solvers, and MQTT connectivity features. Due to the effectiveness/speed of the VC solution in collision free robot path planning, as outlined in D4.3, LMS developed an ML based robot path planning, to increase the performance. Robot path planning is still an issue that has not fully been resolved and additional testing/enhancement is needed.

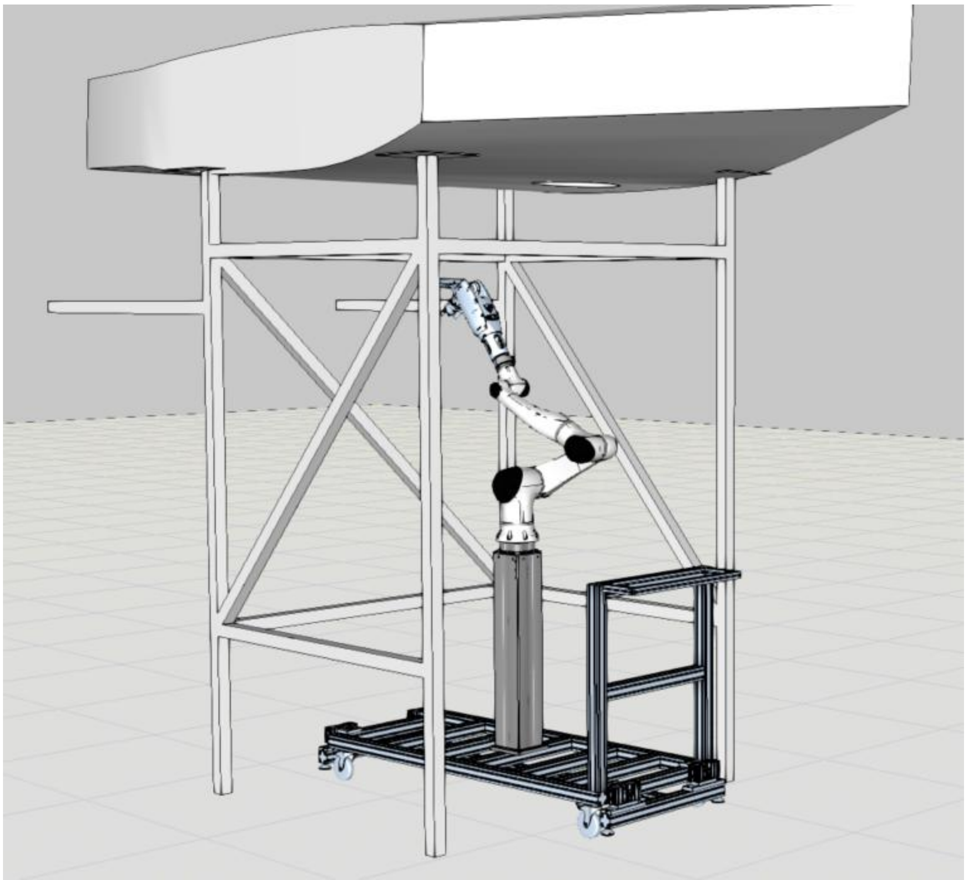
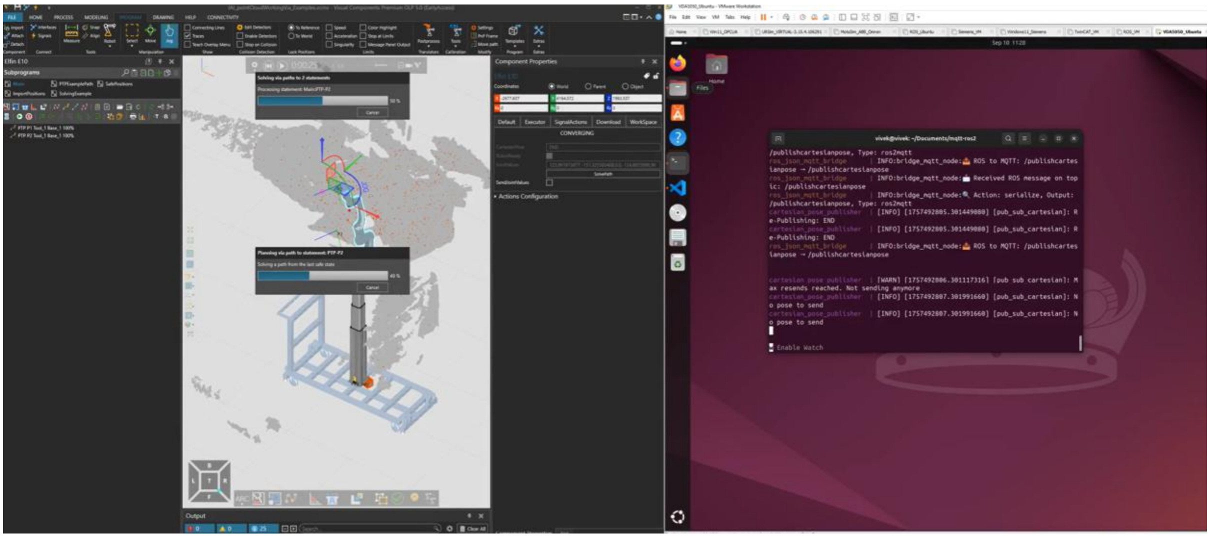


Figure 42: RIR robot in Visual Components software.



```
vivek@vivek: ~/Documents/mqtt-ros2
/publishcartesianpose, Type: ros2mqtt
ros_json_mqtt_bridge      | INFO:bridge_mqtt_node:📤 ROS to MQTT: /publishcartes
ianpose → /publishcartesianpose
ros_json_mqtt_bridge      | INFO:bridge_mqtt_node:📩 Received ROS message on top
ic: /publishcartesianpose
ros_json_mqtt_bridge      | INFO:bridge_mqtt_node:🔍 Action: serialize, Output:
/publishcartesianpose, Type: ros2mqtt
cartesian_pose_publisher  | [INFO] [1757492805.301449080] [pub_sub_cartesian]: R
e-Publishing: END
cartesian_pose_publisher  | [INFO] [1757492805.301449080] [pub_sub_cartesian]: R
e-Publishing: END
ros_json_mqtt_bridge      | INFO:bridge_mqtt_node:📤 ROS to MQTT: /publishcartes
ianpose → /publishcartesianpose


cartesian_pose_publisher  | [WARN] [1757492806.301117316] [pub_sub_cartesian]: M
ax resends reached. Not sending anymore
cartesian_pose_publisher  | [INFO] [1757492807.301991660] [pub_sub_cartesian]: N
o pose to send
cartesian_pose_publisher  | [INFO] [1757492807.301991660] [pub_sub_cartesian]: N
o pose to send
█

Enable Watch
```

Figure 43: RIR AIDT communication through ROS2 system.

Multi Actor Contextual Interfaces (MACI)

Setup: MACI module utilizes multiple devices that provide visual instructions to the operator and developed application which can visualize the camera feed, the detection results from vision models, send commands to the robot, and control the process remotely.

Requirements: For the communication between PAM, RIR and MACI modules the ROS bridge web socket server is utilized to send the data in proper format. Also, the ros-sharp (ROS#) package, developed by Siemens, is required for the Unity-ROS interfaces in C#. Also, a low-medium performance PC running windows is needed with installed Spacedesk to allow for local screen connection. An Android or Windows tablet is needed to control the MACI app through the UI project on screen.

Customization: The user interface, buttons and back-end button actions are customized for the Aeronautics pilot case, along with the required interfaces for the ROS-Unity data communication, along with the ROS topics and servers that have been customized for the needs of the case.

Trouble/Solution: The build of the MACI app in Unity for Android devices did not support multiple features needed and lacked in rendering capabilities in compare with a PC build. For that reason, a local network screen casting is utilized offering real-time projection and touch input feedback to the application.

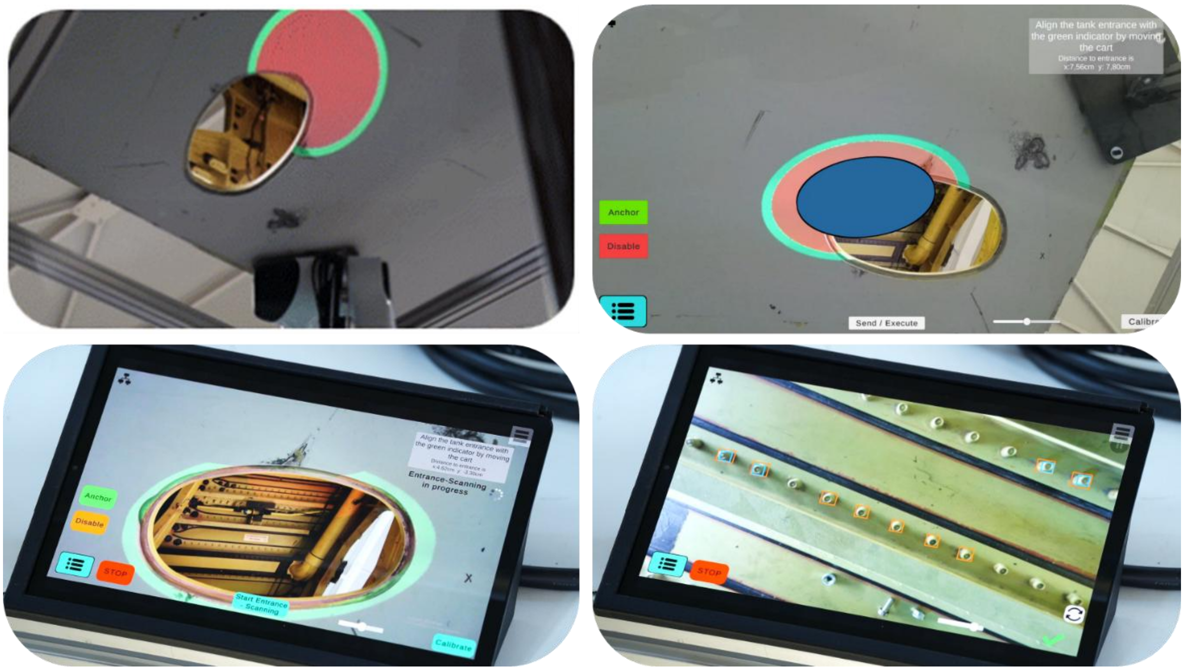


Figure 44: MACI module features.

Data at Rest (DAR)

Setup: The DAR module is responsible for handling and storing data for each respective use case. Various data are stored for further processing and data analytics tasks. Furthermore, contains data that are not changing through the time and execution of manufacturing process. DAR is the data storage of the CONVERGING Big Data Pipeline, acting as a sink or destination of the real time streams of DIM.

Requirements: DAR module utilized MongoDB for data storage and Kafka with custom designed topics for the data communication. Also, the application is built in a Docker container for easy deployment, thus it can run in any OS pc with installed Docker.

Customization: ROS interfaces, topics and Kafka topics have been customized for proper data communication. Also, network parameters have been configured for proper connection and send/receive data packet. At the moment, integration has been performed for some part of the data communication of Aeronautics pilot system. Such data are FOD detection data, NDT detection data, obstacle detection data, NDT results.

Current efforts are focused on:

- Asset modelling in Asset Administration Shells (AAS): Ongoing modelling of the PAM module in AAS to enable seamless integration with other modules, such as AIDT.
- Data analytics development: Implementation of analytics tools to evaluate task performance metrics, supporting improved decision-making and monitoring of inspection activities.

Data in Motion Module (DIM)

Setup: The Data in Motion (DIM) module manages real-time data exchange between HRC shopfloor agents while respecting communication latency requirements tied to robot and operator actions. DIM leverages the OpenFlow knowledge repository semantic models and a direct link to the AI Station Controller to integrate information, combining metrics such as speeds, trajectories, positions, and spatial locations with production-related details like products, dies, parts, and quality results. This enables advanced data analytics. Through a high-throughput stream processing system, DIM efficiently handles large-scale data for continuous operations. DIM can capture, process, fuse and sink real time data for the CONVERGING Big Data Pipeline, sinking captured and processed data streams to the DAR.

Requirements: DIM needs an Ubuntu OS pc. DIM is highly configurable, efficient and scalable so the hardware requirements largely depend on the volume and frequency of data that need to be processed, in most cases a relatively not so high performance PC would be sufficient It is distributed as a docker image and requires docker and docker compose. The integrated version for each pilot case is customized by docker compose yaml files that defines the connections with other modules and submodules such as ROS Monitoring and Change Data Capture (CDS) submodule. Docker images already contain required dependencies such the appropriate java and python libraries, the compatible JDK version, Kafka version and Debezium version.

Customization: DIM can be configured to capture, process, fuse and sink real time data from various sources. Sources, processing and destinations (sinks) are configurable via configuration files.

Trouble/Solution: -

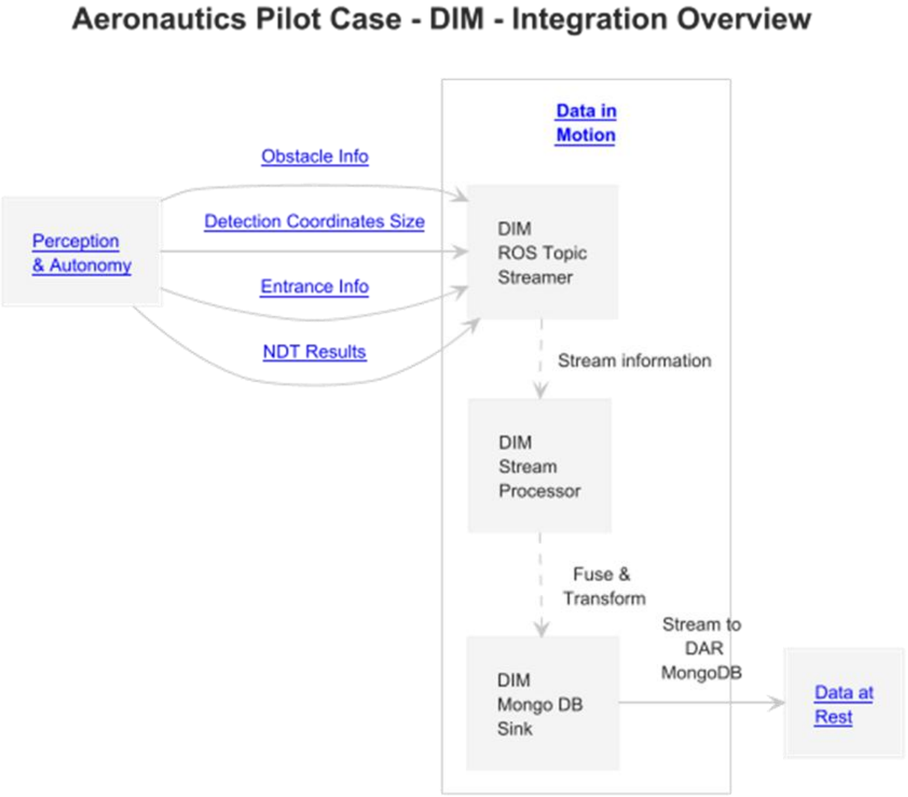


Figure 45: DIM module architecture.

Operator Training Module (OTM)

Setup: OTM module is used for offline training of the operators in a VR environment which simulates the whole process of the tank's inspection. In that way, the training of the operators is achieved in a safe environment so hands-on experience can be gained throughout multiple iterations of the training module.

Requirements: OTM module requires an AR/VR Meta Quest 3 headset, which Is capable to run developed applications directly on the headset. Also, it provides the ability to walk around the environment space without having trouble with connected cables to the headset. Furthermore, Meta Quest Touch Plus controllers are needed for the tracking of hands throughout the whole training process.

Customization: The environment scene of the application has been customized to a virtual environment for the Aeronautics pilot case, including an airplane, the RIR cart-robot, an industrial warehouse, etc.

Trouble/Solution: While the first application build was done with a previous headset that did run all computations on the PC and only visualize the results to the headset, the Meta Quest 3 does run the application locally on the headset. For that reason, multiple optimizations have been applied in order to build the application to Meta Quest 3 headset and run smoothly without dropping FPS and lagging experience.

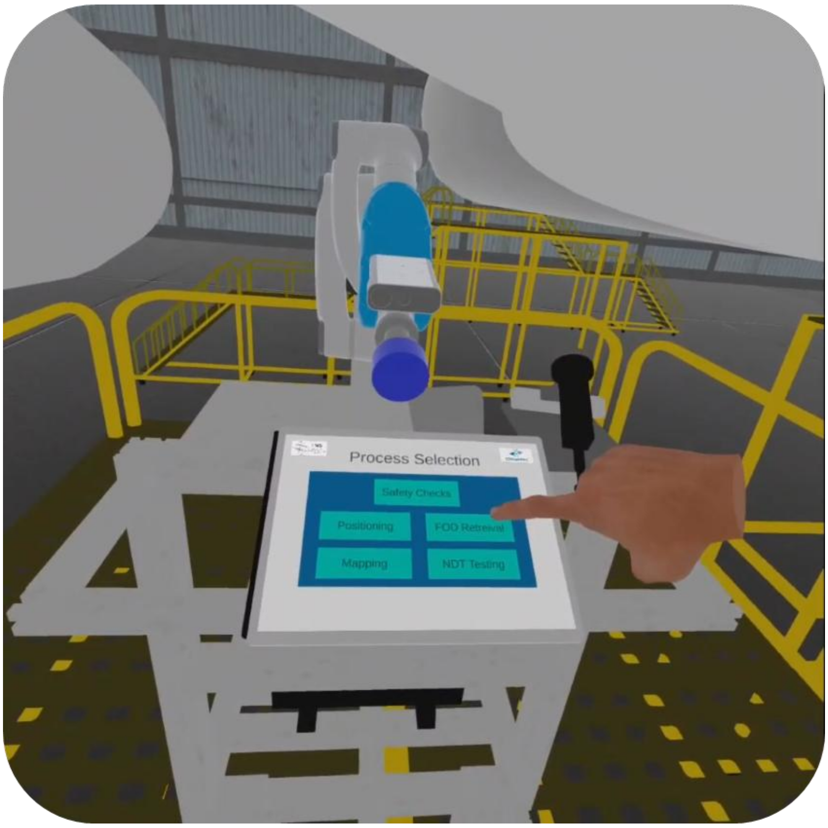


Figure 46: OTM module training environment.

4.3 OPL System Level Functionalities (SLFs)

4.3.1 High Level Functionalities

Following the layout of D2.1, details for modules features in D2.2 and D7.1 initial setups, the following are the System Level Functionalities for the Aeronautics OPL.

Table 33: High level system functionalities.

#	High Level Functionality	Short description
1	System enforces environment safety for human operation	Operators following the guidance of the AISC module performs all the appropriate checks while the system informs operator if a module indicates a failure.
2	Collaborative semi-autonomous Robot entrance in fuel tank	The operator using the cart of the RIR can guide the robot using the MACI module under the hole entrance of the wing. Using PAM module, the robot can evaluate the entrance and accurately without collisions navigate appropriately inside the wing.
3	Fuel tank scanning and representation in digital twin	For the Aeronautics use case the robot uses the PAM module to scan the wing, creating a 3D map that supports the RIR to navigate without collisions.

#	High Level Functionality	Short description
4	Semi-autonomous, collaborative FOD detection	The FOD is performed by the RIR using its end effector, while the PAM module is utilized for navigation and FOD detection purposes. Using MACI module the operator monitors the process as he/she receives sensor data, can confirm decisions, and intervene or teleoperate if necessary.
5	Semi-autonomous, collaborative NDT detection.	The NDT is performed using PAM module with its vision system while also PAM support autonomous navigation for detection. The operator can interrupt and teleoperate the process if necessary, perform manual NDT on remaining rivets, and view detected cracks using the MACI module.

4.3.2 Low Level Functionalities

4.3.2.1 System enforces environment safety for human operation

A - Operator confirms aircraft electrostatic grounding

Table 34: Electrostatic grounding confirmation.

Step #	Operation	From	To	Status
1	Execute Task Aircraft electrostatic grounding confirmation	AISC	MACI	Functionally validated
2	Instructions and prompt for electrostatic grounding confirmation	MACI	Operator	Functionally validated
3	Confirm grounding	Operator	MACI	Functionally validated
4	Confirm grounding	MACI	AISC	In progress

B - Operator confirms aircraft fuel tank purging

Table 35: Fuel tank purging confirmation.

Step #	Operation	From	To	Status
5	Execute task aircraft fuel tank purging	AISC	MACI	Functionally validated
6	Instruction and prompt for aircraft fuel tank purging confirmation	MACI	Operator	Functionally validated
7	Confirm purging	Operator	MACI	Functionally validated
8	Confirm purging	MACI	AISC	Functionally validated

C - Operator confirms oxygen replenishing completed

Table 36: Oxygen replenishing completion confirmation.

Step #	Operation	From	To	Status
9	Execute task confirm oxygen process completed	AISC	MACI	Functionally validated

Step #	Operation	From	To	Status
10	Instructions and prompt for oxygen process	MACI	Operator	Functionally validated
11	Confirm oxygen process completion confirmation	Operator	MACI	Functionally validated
12	Confirm oxygen process completion confirmation	MACI	AISC	Functionally validated

D – Module failure response

Table 37: Module failure response.

Step #	Operation	From	To	Status
13	Status	Operator	AISC	In progress
14	Pause operation	AISC	AISC	In progress
15	Inform about failure	AISC	MACI	In progress

4.3.2.2 Collaborative semi-autonomous Robot entrance in fuel tank

A - Operator guides the cobot under the fuel wing tank entrance

Table 38: Cobot guidance.

Step #	Operation	From	To	Status
1	Move cobot under wing fuel tank	AISC	MACI	Functionally validated
2	Notify operator to guide system to location	MACI	Operator	Functionally validated
3	Move cobot	Operator	RIR	Functionally validated
4	Cobot move completed	Operator	MACI	Functionally validated
5	Cobot move completed	MACI	AISC	Functionally validated

B – Collaborative robot placement under the fuel wing tank entrance

Table 39: Robot placement under the fuel wing.

Step #	Operation	From	To	Status
6	Get Entrance Relative Location	AISC	PAM	Functionally validated
7	Get Vision Data	PAM	RIR	Functionally validated
8	Identify Fuel Tank Entrance	PAM	PAM	Functionally validated
9	Calculate Relative Fuel Entrance Location	PAM	PAM	Functionally validated
10	Send Entrance Relative Location	PAM	AISC	Functionally validated
11	Configure behavior task (fuel tank entrance) collision avoidance	AISC	ARBA	Functionally validated
12	Request Execute task (fuel tank entrance) (relative location)	AISC	CRC	Functionally validated
13	Report Cost/Feasibility prohibiting	AISC	CRC	Functionally validated
14	Calculate robot realteive location	AISC	PAM	Functionally validated
15	Get relative base location indication	AISC	PAM	Functionally validated
16	Show relative base location	AISC	MACI	Functionally validated
17	Show visual cue on how to move the cobot base of success notification	MACI	Operator	Functionally validated

Step #	Operation	From	To	Status
18	Move robot base	Operator	Operator	Functionally validated
19	Show visual cue on how to move the cobot base success notification	MACI	Operator	Functionally validated

C – System generates paths for the cobots entrance to the fuel tank

Table 40: Paths generation.

Step #	Operation	From	To	Status
20	Move cobot in the Fuel Tank Entrance	AISC	PAM	In progress
21	Get visual information	PAM	RIR	Functionally validated
22	Path planning	PAM	PAM	Functionally validated
23	Planned Path	PAM	AIDT	Functionally validated
24	Visualize planned path	AIDT	AIDT	Functionally validated
25	Move robot in wing fuel tank	PAM	RIR	Functionally validated
26	Cobot in fuel tank entrance	PAM	AISC	In progress

4.3.2.3 Fuel tank scanning and representation in digital twin

A – Equip 3D Depth camera End Effector

Table 41: Digital twin scanning and representation.

Step #	Operation	From	To	Status
1	Move robot to fuel tank	Operator	Operator	Functionally validated
2	Move to tool changer position	AISC	RIR	Functionally validated
3	Release gripper	AISC	RIR	Functionally validated
4	Move to depth camera end-effector	AISC	RIR	Functionally validated
5	Get depth camera enf-effector	AISC	RIR	Functionally validated
6	Move to neutral position	AISC	RIR	Functionally validated

B – Generate Representation of current field of view

Table 42: Current field of view representation.

Step #	Operation	From	To	Status
7	Notify process starts (FuelTankID)	AISC	AIDT	In progress
8	Notify process starts (FuelTankID)	AISC	DAR	In progress
9	Get planned capture points	AISC	PAM	In progress
10	Move to next capture point	AISC	RIR	In progress
11	Get camera rotation steps	AISC	PAM	In progress
12	Rotate camera	AISC	RIR	In progress
13	Robot step, camera rotation	AISC	AIDT	In progress
14	Robot step, camera rotation	AISC	DAR	In progress
15	Capture	AISC	RIR	In progress
16	3D Data	RIR	DIM	Functionally validated
17	3D Data	DIM	DAR	Functionally validated
18	3D Data	DIM	AIDT	Functionally validated
19	Camera Point of view point cloud generation	AIDT	AIDT	Functionally validated
20	Point cloud persistence	AIDT	DAR	Functionally validated
21	Partial point cloud representation	AIDT	MACI	Functionally validated
22	Partial point cloud view	MACI	Operator	Functionally validated

C – Generate complete Fuel Tank Digital Twin

Table 43: Digital Twin generation.

Step #	Operation	From	To	Status
23	Notify process finished (FuelTankID)	AISC	AIDT	Functionally validated
24	Finalize fuel tank digital twin	AIDT	AIDT	Functionally validated
25	Save digital twin	AIDT	DAR	Functionally validated
26	Notify process finished (FuelTankID)	AISC	DAR	Functionally validated

4.3.2.4 Semi-autonomous, collaborative FOD detection

A – Equip FOD End Effector

Table 44: Semi-Autonomous FOD detection.

Step #	Operation	From	To	Status
1	Move robot to fuel tank	Operator	Operator	Functionally validated
2	Move to tool changer position	AISC	RIR	Functionally validated
3	Release gripper	AISC	RIR	Functionally validated
4	Move to FOD end-effector	AISC	RIR	Functionally validated
5	Get FOD end-effector	AISC	RIR	Functionally validated
6	Move to neutral position	AISC	RIR	Functionally validated

B – Autonomous FOD detection & Removal Task creation

Table 45: Autonomous FOD detection/ removal.

Step #	Operation	From	To	Status
7	Start Trajectory Visualization	AISC	AIDT	Functionally validated
8	Start Trajectory Visualization {FuelTankID, FOD}	AISC	MACI	Functionally validated
9	Start Camera view	AISC	MACI	Functionally validated
10	Generate Inspection Path {FuelTankID, FOD}	AISC	PAM	Functionally validated
11	Get Digital Twin {FuelTankID}	PAM	AIDT	Functionally validated
12	Get FOD Detection Frequency	PAM	DAR	Functionally validated
13	Create Inspection Points Path	PAM	PAM	Functionally validated
14	Send Inspection Path	PAM	AISC	Functionally validated
15	Autonomously Move To {Next Inspection Point}	AISC	PAM	In progress
16	Get Digital-Twin	PAM	AIDT	Functionally validated
17	Control sensors/orientation	PAM	RIR	Not tested
18	Get Vision data	PAM	RIR	Functionally validated
19	Autonomous path planning	PAM	PAM	Functionally validated
20	Control/Move	PAM	RIR	Functionally validated
21	Operation Status	AISC	AIDT	Functionally validated
22	Planned Trajectory	PAM	MACI	Functionally validated
23	Joint States	RIR	MACI	Functionally validated
24	Digital -Twin Visualization	AIDT	Operator	Functionally validated
25	AR view	Operator	Operator	Functionally validated
26	Operation Status	AISC	MACI	Functionally validated
27	Planned trajectory	PAM	MACI	Functionally validated
28	Joint states	RIR	MACI	Functionally validated
29	AR Visualization	MACI	Operator	Functionally validated
30	AR View	Operator	Operator	Functionally validated

Step #	Operation	From	To	Status
31	Reached inspection point	PAM	AISC	Functionally validated
32	Generate FOD plan {FuelTankID, FOD, Detection Point}	AISC	PAM	Functionally validated
33	Get DigitalTwin {FuelTankID}	PAM	AIDT	Functionally validated
34	Get FOD Detection Frequency	PAM	DAR	Functionally validated
35	Generate Detection Points	PAM	PAM	Functionally validated
36	Send detection points	PAM	AISC	Functionally validated
37	Detect {FOD, Detection Point}	AISC	PAM	Functionally validated
38	Detect Result {Occurrence, Properties, Size Estimation}	PAM	AISC	Functionally validated
39	Push {Detection Result}	AISC	DIM	Functionally validated
40	Get Context	DIM	DIM	Functionally validated
41	Request FOD Confirmation	AISC	MACI	Functionally validated
42	FOD Confirmation {Panel instructions}	MACI	Operator	Functionally validated
43	Confirms	Operator	MACI	Functionally validated
44	Confirm FOD	MACI	AISC	Functionally validated
45	Create FOD Removal Task	AISC	AISC	Functionally validated
46	Add FOD Removal Task	AISC	DWR	Not tested
47	Determine Suitability	DWR	DWR	Not tested
48	Estimate Trajectory Feasibility	DWR	PAM	Functionally validated
49	Push Detection Result	DIM	DWR	Not tested
50	{Detection Result, FuelTankID, Inspection Point,Detection Point}	DIM	DAR	Functionally validated
51	{Detection Result, FuelTankID, Inspection Point,Detection Point}	DIM	PAM	Functionally validated
52	Get FOD Plan	AISC	DWR	Not tested
53	Plan->Schedule	AISC	AISC	Functionally validated
54	Get Required Gripper	AISC	PAM	Functionally validated
55	Movement control	PAM	RIR	Functionally validated
56	Gripper control	PAM	RIR	Functionally validated
57	Move to FOD point	AISC	PAM	Functionally validated
58	Movement Control	PAM	RIR	Functionally validated
59	FOD removal	PAM	RIR	Functionally validated
60	FOD Task (Location)	AISC	MACI	Functionally validated
61	Show Task Details	MACI	Operator	Functionally validated
62	Perform Task	Operator	Operator	Functionally validated
63	Confirms	Operator	MACI	Functionally validated
64	Push FOD (Discovery/ Removal)	AISC	DIM	Functionally validated
65	Get context	DIM	DIM	Functionally validated
66	(Detection Result, FuelTankID, Inspection Point, Detection Point)	DIM	DAR	Functionally validated
67	(Detection Result, FuelTankID, Inspection Point, Detection Point)	DIM	AIDT	Functionally validated
68	(FOD Removal, EventFuelTankID, Inspection Point, FOD Point)	DIM	DAR	Functionally validated
69	(FOD Removal, EventFuelTankID, Inspection Point, FOD Point)	DIM	AIDT	Functionally validated
70	Request Teleoperation	Operator	MACI	Functionally validated
71	Request Teleoperation	MACI	AISC	Functionally validated
72	Pause Schedule	AISC	AISC	Functionally validated
73	Enter Teleoperation Mode	AISC	PAM	Functionally validated
74	Teleoperation Started	AISC	MACI	Functionally validated

Step #	Operation	From	To	Status
75	Teleoperation Menu	MACI	Operator	Functionally validated
76	Teleoperate	MACI	PAM	Functionally validated
77	Stop Teleoperation	Operator	MACI	Functionally validated
78	Exit Teleoperation	MACI	AISC	Functionally validated
79	Exit Teleoperation Mode {Parameters}	AISC	PAM	Functionally validated
80	Prepare for operation resume	AISC	PAM	Functionally validated
81	Control Cobot	PAM	RIR	Functionally validated
82	Resume Schedule	AISC	AISC	Functionally validated

4.3.2.5 Semi-autonomous, collaborative NDT detection.

Table 46: Semi-autonomous NDT detection.

Step #	Operation	From	To	Status
1	Move Robot to Fuel Tank	Operator	Operator	Functionally validated
2	Move to Tool changer position	AISC	RIR	Functionally validated
3	Release Gripper	AISC	RIR	Functionally validated
4	Move to Probe End -Effector	AISC	RIR	Functionally validated
5	Get probe end effector	AISC	RIR	Functionally validated
6	Move to neutral position	AISC	RIR	Functionally validated
7	Start planned/current trajectory visualization for (FuelTankId, NDT)	AISC	AIDT	Functionally validated
8	Start Planned/Current Trajectory Visualization for (FuelTankID, NDT)	AISC	MACI	Functionally validated
9	Start Camera view	AISC	MACI	Functionally validated
10	Generate inspection path	AISC	PAM	Functionally validated
11	Get digital twin	PAM	AIDT	Functionally validated
12	Get NDT detection statistics	PAM	DAR	Functionally validated
13	Create inspection points path	PAM	PAM	Functionally validated
14	Send inspection path, Manual DT	PAM	AISC	Functionally validated
15	Manual NDT	AISC	DIM	Functionally validated
16	Add pending manual NDT check	AISC	DIM	Functionally validated
17	Autonomously move to next inspection point	AISC	PAM	Functionally validated
18	Get digital twin	PAM	AIDT	Functionally validated
19	Control sensor/orientation	RIR	PAM	Not tested
20	Get vision data	RIR	PAM	Functionally validated
21	Autonomous path planning	PAM	PAM	Functionally validated
22	Control /Move	PAM	RIR	Functionally validated
23	Operation status	AISC	AIDT	Functionally validated
24	Planned Trajectory	PAM	AIDT	Functionally validated
25	Joint states	RIR	AIDT	Functionally validated
26	Digital twin visualization	AIDT	Operator	Functionally validated
27	AR view	Operator	Operator	Functionally validated
28	Operation Status	AISC	MACI	Functionally validated
29	Planned trajectory	PAM	MACI	Not integrated
30	Joint states	RIR	MACI	Not integrated
31	AR visualization	MACI	Operator	Functionally validated
32	AR view	Operator	Operator	Functionally validated
33	Reached inspection point	PAM	RIR	Functionally validated
34	Generate NDT plan	AISC	PAM	Functionally validated

Step #	Operation	From	To	Status
35	Get digital twin	PAM	AIDT	Functionally validated
36	Get NDT detection statistics	PAM	DAR	Functionally validated
37	Generate detection points	PAM	PAM	Functionally validated
38	Send detection points	PAM	AISC	Functionally validated
39	Detect (NDT, Detection point)	AISC	PAM	Functionally validated
40	Control detection movement	PAM	RIR	Functionally validated
41	Control unsealing	PAM	RIR	Not implemented
42	Control detection	PAM	RIR	Functionally validated
43	Detection result (Occurrence, properties, estimation)	PAM	AISC	Functionally validated
44	Detection not possible and no sealant removal is needed	PAM	AISC	Not implemented
45	Move to next inspection point	AISC	AISC	Functionally validated
46	Detection point, failure	AISC	DIM	Functionally validated
47	Detection point, failure	DIM	DAR	Functionally validated
48	Generate NDT investigation plan	AISC	PAM	Functionally validated
49	Get digital twin	PAM	AIDT	Functionally validated
50	Get NDT Detection Statistics	PAM	DAR	Functionally validated
51	Generate detection points	PAM	PAM	Functionally validated
52	Start radius detection	AISC	PAM	Functionally validated
53	Move cobot	PAM	RIR	Functionally validated
54	Control unsealing	PAM	RIR	Not implemented
55	Scan	PAM	RIR	Not implemented
56	Radius detection results	PAM	AISC	Not implemented
57	Control resealing	PAM	RIR	Not implemented
58	Push (Detection results)	AISC	DIM	Not implemented
59	Get context	DIM	DIM	Functionally validated
60	Detection Results, FuelTankID, Inspection Point, Detection Point	DIM	DAR	Functionally validated
61	Detection Results, FuelTankID, Inspection Point, Detection Point	DIM	AIDT	Functionally validated
62	Request teleoperation	Operator	MACI	Functionally validated
63	Request Teleoperation	MACI	AISC	Functionally validated
64	Pause schedule	AISC	AISC	Functionally validated
65	Enter teleoperation mode	AISC	PAM	Functionally validated
66	Teleoperation	AISC	MACI	Functionally validated
67	Teleoperation menu	MACI	Operator	Functionally validated
68	Teleoperate	MACI	PAM	Functionally validated
69	Stop teleoperate	AISC	MACI	Functionally validated
70	Exit teleoperation	MACI	AISC	Functionally validated
71	Exit teleoperation mode	AISC	PAM	Functionally validated
72	Prepare for operation resume	AISC	PAM	Functionally validated
73	Control robot	PAM	RIR	Functionally validated
74	Resume schedule	AISC	AISC	Functionally validated
75	In fuel tank	Operator	Operator	Functionally validated
76	Get pending manual NDT checks	AISC	DIM	Functionally validated
77	NDT check (location)	AISC	MACI	Functionally validated
78	Request NDT	MACI	Operator	Functionally validated
79	Perform NDT	Operator	Operator	Functionally validated
80	NDT results	Operator	MACI	Functionally validated
81	NDT results	MACI	AISC	Functionally validated
82	NDT results	AISC	DIM	Not tested

Step #	Operation	From	To	Status
83	Get context	DIM	DIM	Not tested
84	NDT results (location manual)	DIM	DAR	Not tested

4.4 Service provisioning

4.4.1 Assessment of the planned events

In the context of the Aeronautics OPL training services, the first webinars on "**Robotic inspection in confined spaces & Non-Destructive Testing**" have been designed and planned to be performed by the end of August. Due to technical issues with the RIR robot (damaged PCB), it was decided to postpone the webinars for the 14th of November 2025, where it is planned to perform the training sessions in a hybrid way.

The agenda includes presentation and interactive sessions around the following topics:

- Hazards and limitations of human inspection in confined spaces
- Challenges and CONVERGING solution overview
- Robot perception and navigation technologies
- Teleoperation and human-system interaction mechanisms
- Inspection and Non-Destructive Testing techniques

The main objective of these two back-to-back webinars is to raise awareness among industrial partners and potentially attract future partners, presenting cutting-edge robotic solutions and inspection techniques in industrial environments, and focusing on real-world applications and demonstrations.

The intended audience consists mainly of industrial employees of different roles (operators, engineers, managers), as well as technology providers, integrators, and engineering students.

4.4.2 Future work timeline

The Aeronautic OPL training services could be described, according to their focus, as technology-oriented or application-oriented, addressing the interest of a broad audience, including engineers, operators, technology providers, etc. The topics that are covered through these services are the following:

- Robot teleoperation and indirect human-robot interaction
- Digital twin in real-time process execution
- Task planning and robot programming
- Extended Reality operator training
- Robotized NDT testing
- Robotic inspection in confined spaces

By the end of the project, a series of webinars are planned to be performed covering all the above topics. On demand training services are available for interested companies, providing also the opportunity of hybrid workshops and hands-on training. The on-site sessions take place at the TF-CC premises, where the Aeronautics Pilot is hosted.

4.5 Industrial deployment

4.5.1 M48 plan and timeline

As previously agreed, due to the geopolitical situation at the country of the end user, the final deployment will occur at the premises of TF-CC. Representatives of the end user (both engineers and technicians) will visit TF-CC to perform on-site testing and assessment of the solutions. The Aeronautics pilot timeline will follow the schedule outlined below:

- **Until M39:** A first testing of the Pilot case from the end user will take place at M38 at TF-CC premises. Furthermore, integration and enhancement of the other developed modules will be performed along with data capturing.
- **From M30 to M44:** A second round of testing from the end user will take place in that period. Also, along with the captured data of the pilot and AI analysis finetuning and enhancements of the modules be performed.
- **From M45 to M48:** In the final period of the project, a final testing of the Open pilot will take place from the end user.

5 Additive Manufacturing Open Pilot Line - AIMEN

Two complementary lab-scale Open Pilot Lines (OPLs) have been established to support the additive manufacturing use case. These OPLs, one hosted at AIMEN's facilities and the other at TF CC premises, have been designed and deployed to enable the integration, testing, and validation of advanced robotic and digital technologies developed throughout the project.

The decision to implement two distinct OPLs stems from both logistical and technical needs. At AIMEN, space constraints prevented the installation of the COMAU collaborative robot. Instead, an industrial robot (already existing) is being used, allowing for the early development and testing of CONVERGING modules in a controlled, realistic industrial environment and focuses on data acquisition, simulation-based optimization, ergonomics, and traceability, also acting as a training and demonstration environment. This pilot line also serves as a dedicated training and demonstration hub, enabling the dissemination and exploitation of project results through operator upskilling and technical outreach.

On the other hand, the OPL set up at TF-CC premises hosts a COMAU collaborative robot in a setting that enables the testing and final integration of technologies requiring close human–robot interaction, such as AR/VR and adaptive control systems. All the modules developed for the PRIMA use case will be part of the OPL. This two-fold setup ensures the validation of CONVERGING technologies and supports their scalability for industrial deployment, including future implementation at PRIMA's facilities.

5.1 Value Proposition

The two developed pilot lines offer a complementary value proposition within the scope of the CONVERGING project. These pilot environments serve as realistic and flexible testbeds where advanced technologies are not only developed but also integrated, validated, and demonstrated in collaborative industrial settings.

The AIMEN-hosted OPL emphasizes robotic handling and collaborative processing of medium to large-sized parts, while also focusing on digital enablers such as data acquisition, simulation, ergonomic monitoring, and traceability. This cell, featuring an industrial robot, provides an environment for early-stage integration and evaluation of CONVERGING technologies. Furthermore, AIMEN's OPL delivers added value through training offering and technical services, facilitating knowledge transfer, skill development, and the adoption of innovative solutions by industrial stakeholders. Its open character makes it especially suited for ongoing demonstration activities and continuous improvement of modular solutions.

In parallel, the second OPL hosted by LMS within TF CC is equipped with a COMAU collaborative robot and functions as a pre-final integration environment for modules requiring close operator interaction, such as augmented reality (AR), virtual reality (VR), and enhanced HMI systems. This setup allows for the fine-tuning and final validation of those human-centered technologies that could not be tested in AIMEN's industrial setting.

5.2 Description of the current Setup

For the additive manufacturing use case two pilot lines have been deployed, including different robotic setups thus demonstrating the scalability of the CONVERGING solutions.

AIMEN OPL:

The AIMEN pilot line serves as a testbed for the integration and validation of CONVERGING modules, with a particular focus on data management, simulation, ergonomics, and traceability. The cell is equipped with an industrial robot, which required the implementation of additional safety measures to enable human interaction within the environment. To this end, the SAM (Safety-Aware Module) was integrated, complemented by a safety laser scanner to monitor operator working areas and a light curtain to ensure immediate protective actions when necessary. Beyond its role as a validation environment, the AIMEN OPL also functions as an open training and demonstration platform, providing services for the adoption of CONVERGING solutions and supporting skills development in collaborative industrial robotics.

Figure 47: AIMEN Open Pilot Line.

LMS OPL:

The testbed implemented by LMS provides a realistic representation of the intended industrial pilot, which will be deployed at the end-user premises in the later stages of the project. The OPL features a medium-payload collaborative robot equipped with a case-specific gripper and sensorized skin to ensure operator safety in the event of contact. The robotic cell also includes a fixture designed to resemble the metal printing machine used in PRIMA’s original production line. Additionally, the pilot line integrates all necessary robotic peripherals for both operational and cognitive functions, such as controllers, depth sensors, and safety systems. The layout further includes an AGV equipped with a 6-DOF collaborative robotic manipulator. This robot receives the prepared printed parts, which are then handed over to the operator for further processing—specifically for deburring—through HRC. The layout is presented in the figure below.

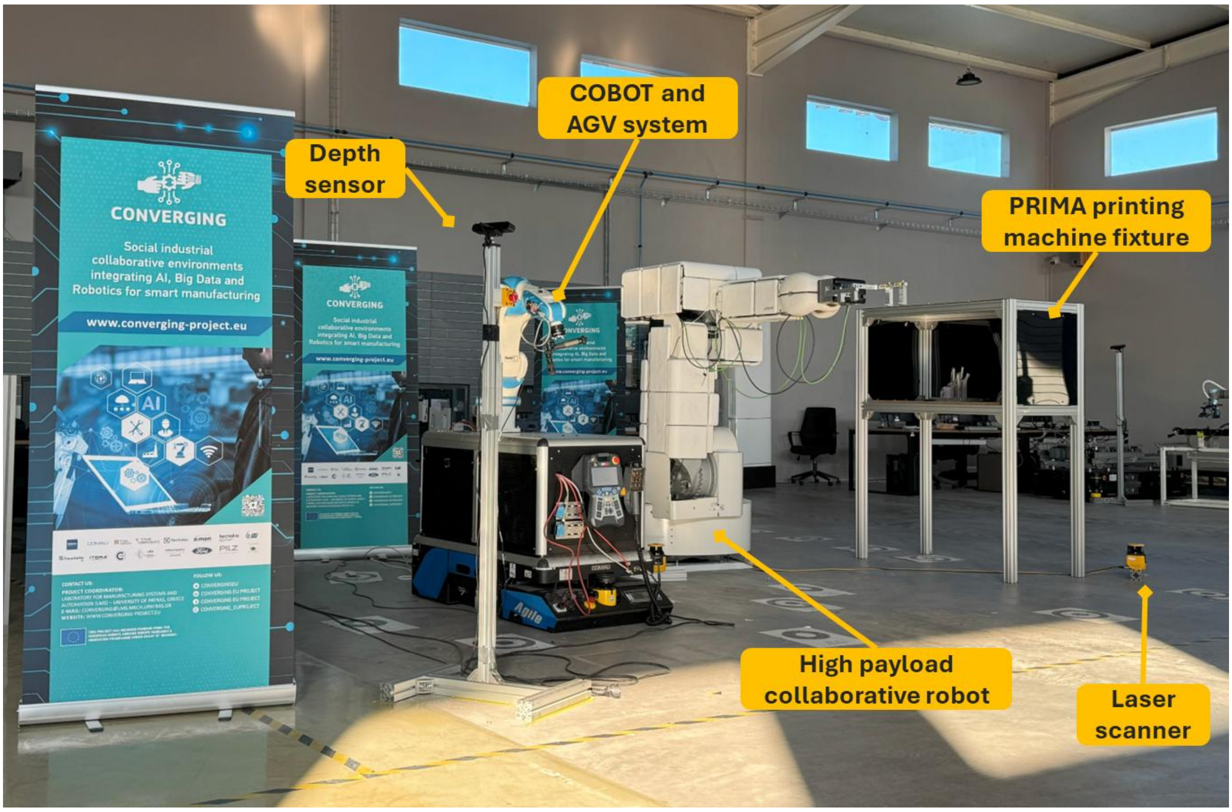


Figure 48: LMS Prima use case OPL.

5.2.1 Hardware setup

The hardware setup for AIMEN's open pilot line includes an advanced robotic cell comprised of an ABB IRB 6660-205/1.9 robot, an industrial robot designed to handle medium and large components. It is equipped with a SCHUNK EGU 80 ProfiNet gripper for precise workpiece handling and an Applied Robotics Sigma 3.1 tool changer for seamless automated tool changing.

The system operates within a chamber replica that simulates the conditions of an additive manufacturing environment and includes metal and PLA workpieces for testing.

The setup also integrates a Stereolabs ZED2i 3D camera system for enhanced vision and depth perception.

Connectivity is managed via a FortiSwitch-148F-POE Ethernet switch, ensuring seamless communication between components. Two high-performance PCs, one running Ubuntu 22 and the other running Windows 11, both equipped with Intel Core i7-13700 processors, 32GB RAM, NVIDIA RTX A4000 GPU, and 1TB NVMe SSD, provide the computing power needed for simulations and control tasks, making it an ideal environment for developing and testing additive manufacturing solutions.

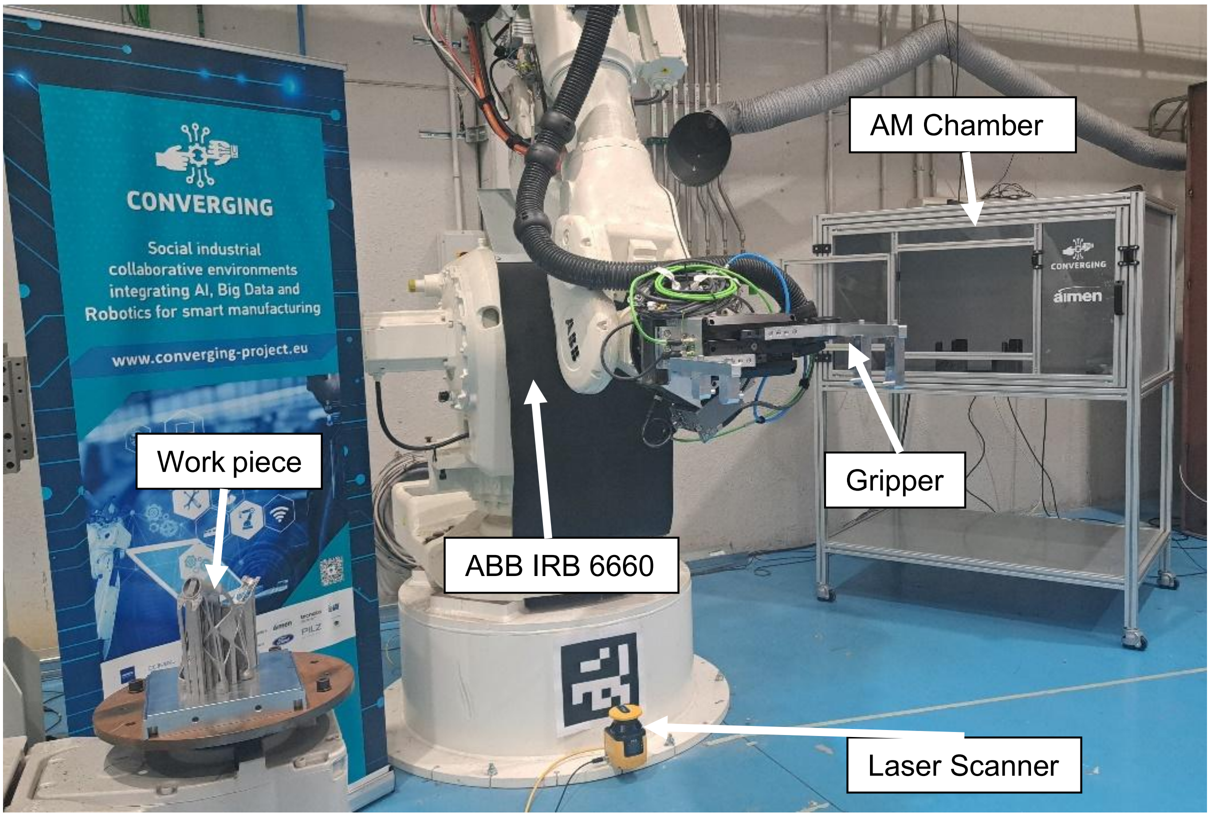


Figure 49: AIMEN OPL Hardware 1.

Figure 50: AIMEN OPL Hardware 2.

LMS OPL: The hardware components of the LMS OPL are presented below:

- Medium Payload Collaborative Manipulator:

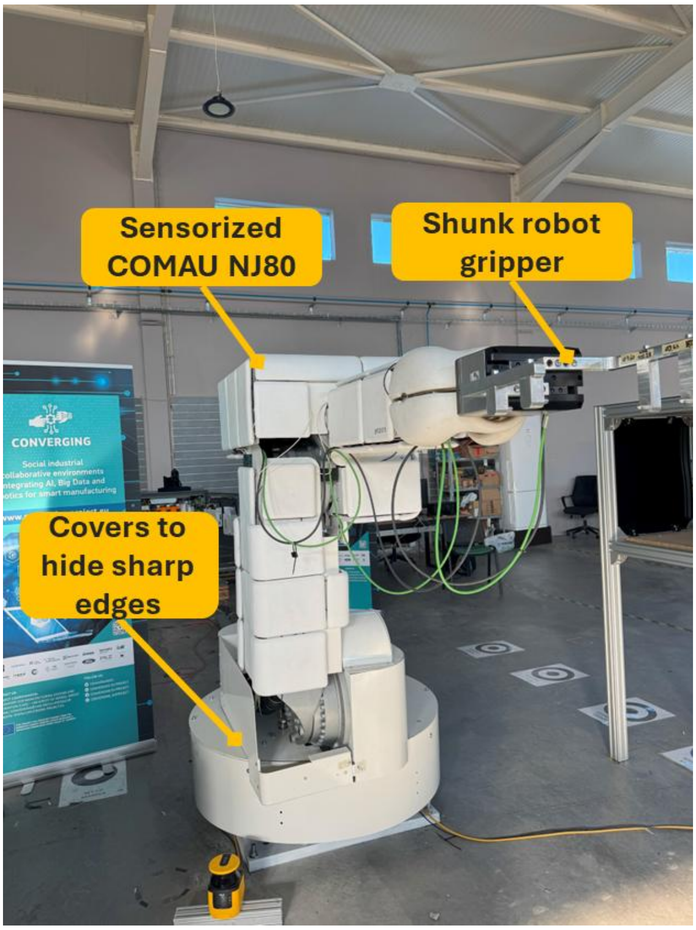


Figure 51: Comau NJ60 with safety skins.

- Mobile collaborative robot:

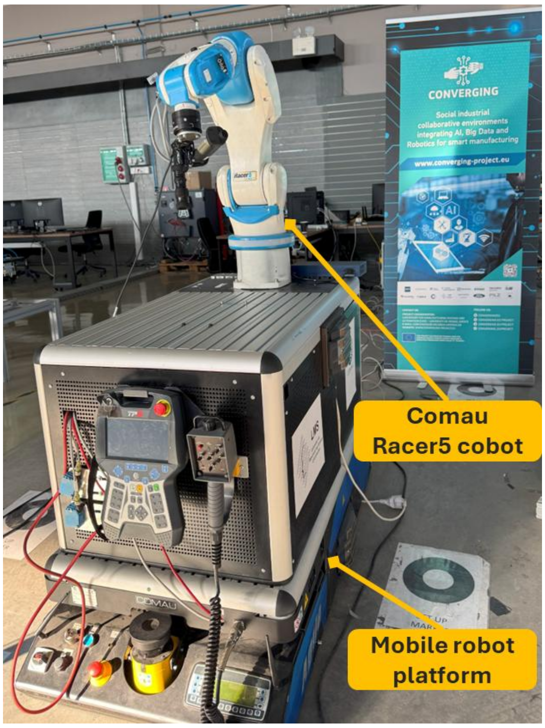


Figure 52: Comau Agile-racer5 cobot mobile robot.

- Additive chamber replica:

Figure 53: PRIMA OPL printing machine resembling fixture.

- Sensors:

Figure 54: Stereolabs ZED2i depth sensor system.

- PILZ laser scanners:

Figure 55: PILZ laser scanners.

- SAM module cabinet:

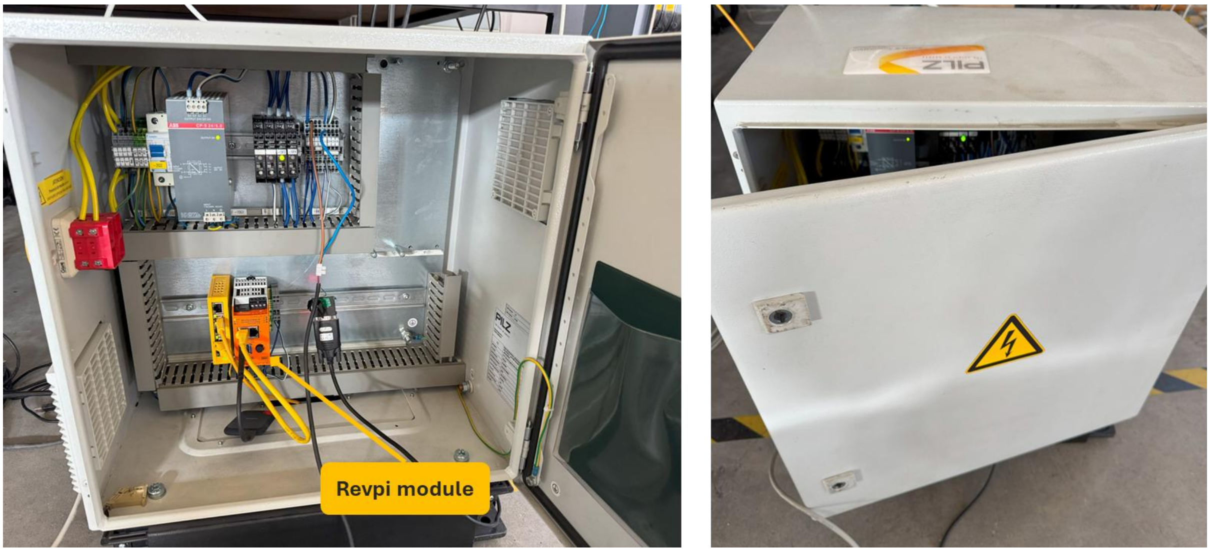


Figure 56: SAM module cabinet including RevPi.

The solution also utilizes Ubuntu 24 pc with installed ROS2 Jazzy that operates all use case related software (Digital twins, perception systems, robot control s/w etc.). Also the solution utilizes a Hololens2 headset that is responsible for executing the MACI module for human robot interaction.

5.2.2 List of active modules

AIMEN OPL: Within the AIMEN OPL, activities since M24 have primarily focused on software enhancements and the complete list of active modules are in D7.1. The main achievement has been the deployment of the Asset Administration Shell (AAS) framework, which enables the structured organization and synchronization of data across the different modules.

In the AIMEN OPL we modeled in AAS both the robot data structure and the operator body parts (e.g., data originating from the PAM module). An AAS server was deployed to register these data entities, and a DataBridge component was implemented to synchronize data between the DIM and the AAS server. The DataBridge splits incoming Kafka messages into individual variables and pushes each value into its corresponding AAS property.

Although this initially appeared straightforward, setting up the DataBridge revealed several challenges. For each Kafka message, the DataBridge configuration required splitting every single key of source message into a separate JSON configuration file. Additionally, supporting files such as *source*, *destination*, and *routes* also needed to declare JSON objects for each variable. Even in the relatively simple AIMEN OPL scenario, this resulted in almost 400 variables and therefore nearly 400 JSON files which made the debugging phase extremely time-consuming and error prone.

To mitigate this, we decided to model the DataBridge itself within the AAS.

In this new approach, the entire DataBridge configuration—routes, transformers, data sources, and sinks is described in a standardized, machine-readable format. The software we developed now reads the AAS of the DataBridge, including all relationships between protocols and properties generating automatically the complete required configuration files instantaneously.

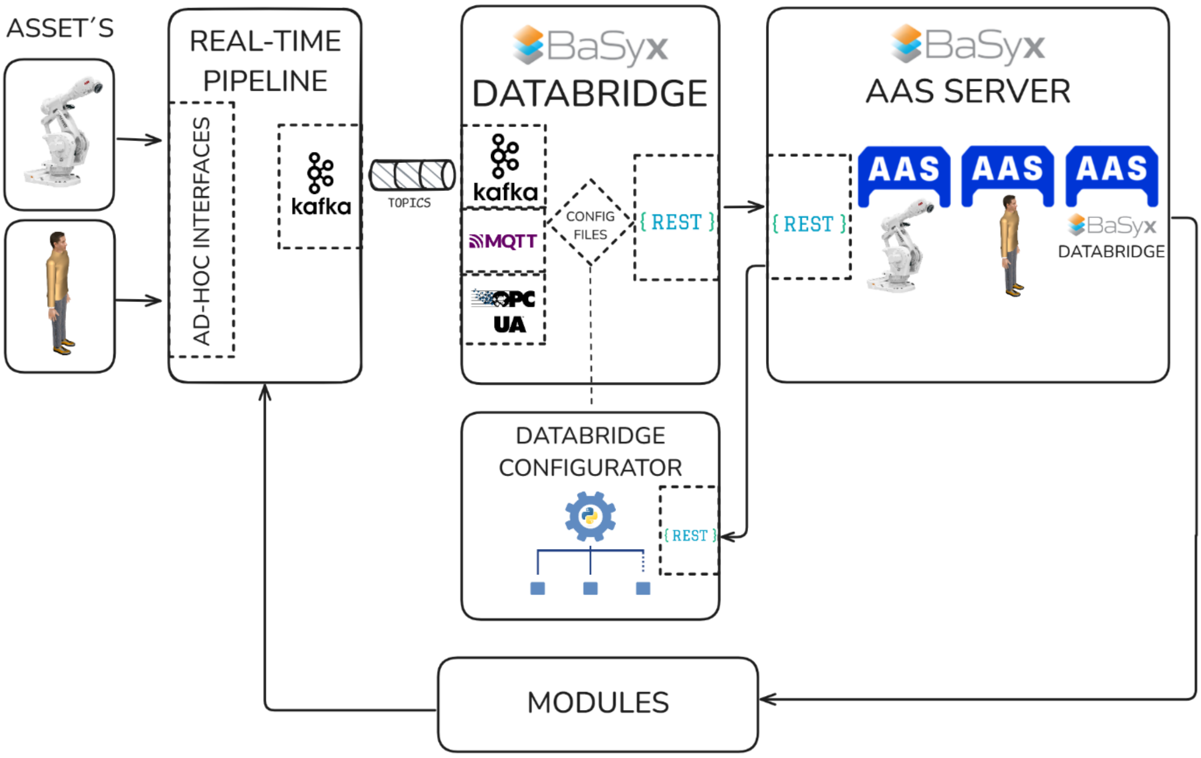


Figure 57: AAS framework architecture.

This solution makes the integration process far more scalable, standardized, and portable across different assets and communication protocols. It also simplifies testing and debugging, since any changes made in the AAS can automatically update the configuration files, reducing time and errors. The main trade-off is that the initial modeling effort of the DataBridge and its relationships is more demanding, but once completed, the system becomes reusable and interoperable across different use cases.

Currently, the DataBridge has been modeled for the AIMEN OPL, but it will be necessary to extend this approach to the other use cases. By modeling the DataBridge AAS for each pilot, the relationships between the different assets and their variables can be formalized, ensuring data integration and interoperability across all CONVERGING scenarios.

The DIM has been updated to improve data exchange across the modules. DIM integrates Kafka topics, which are consumed by the DAR module, enabling real-time monitoring and analysis. The following modules are currently active and contributing data streams:

- UXE: Provides data on ergonomic cost and joint states to support operator well-being and efficiency analysis.
- PAM: Delivers detailed tracking information of operator body movements to enhance safety and human–robot collaboration studies.
- MPCM: Publishes robot joint states to monitor robotic performance and ensure accurate synchronization with production tasks.
- SAM: Reports safety events and normal events to strengthen workplace safety monitoring and event logging.
- AIDT: A plugin was developed within the VIS software to receive updates from the DAR AAS Framework, enabling real-time ingestion of operator pose and body-part data. The next step is to publish the ergonomic score into the AAS platform and visualize it live within the real-time simulation.

LMS OPL: In parallel, at the LMS OPL all modules relevant to the PRIMA use case have now been deployed and are fully operational within the pilot environment. The summary of the involved modules and technologies for the PRIMA use case are summarized in the figure below:

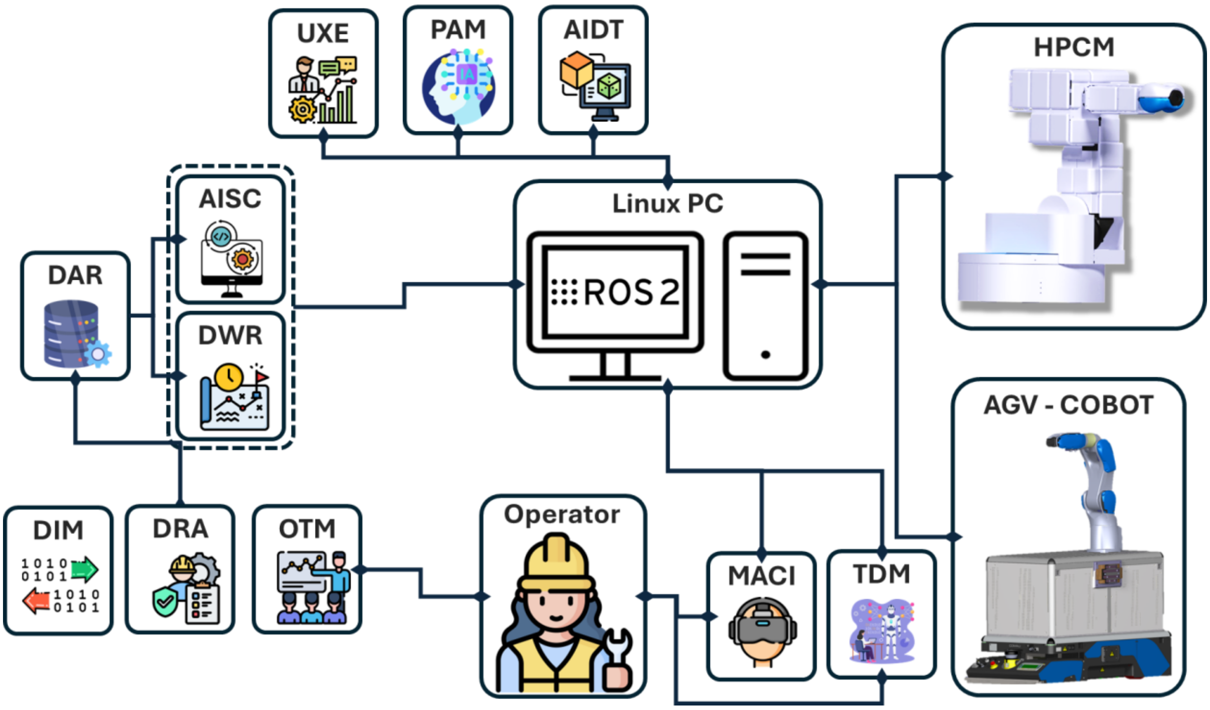


Figure 58: Active modules for PRIMA use case.

Medium Payload Collaborative Manipulator (MPCM)

Setup: The main setup of the MPCM consists of the Comau NJ60 robot with collaborative capabilities, integrating the Robosafe Safety software from COMAU. This s/w includes all the appropriate safety functions that can allow the robot to be placed in HRC environments. Additional features of the MPCM include the installation of the safety sensorized padding, that allows the robot to be included in HRC applications where tight coexistence in shared spaces between humans and robots takes place. Lastly, the MPCM is equipped with a SCHUNK EGU 80 ProfiNet gripper, that undertakes the task of safely picking and manipulating the printed part around the workspace.

Requirements: Requirements among other include the developed Comau ROS driver appropriately modified to be compatible with ROS2 jazzy. Also, based on the use case the robot system includes the appropriate collaborative configuration in its safety software, to include the safety functions of sensor skin collision detection etc.

Customization: No customization was required for the PRIMA use case, as the module was dedicatedly developed for this scenario.

Trouble/Solution: A number of issues were faced with MPCM during integration for the PRIMA use case, e.g. due to the sensorized padding, the cable management was difficult, as cables were touching the sensors triggering a safety emergency stop, interrupting the proper functioning of the robot. These have been overcome now.

Figure 59: MPCM.

Perception and Autonomy Module (PAM)

Setup: The setup of PAM module for PRIMA case, consists of a Stereolabs Zed2i sensor, that is placed around the workplace, properly towards adequate workspace coverage. Using a check board extrinsic calibration of the sensor is performed, assuring the proper data sharing within the ROS2 framework. The main data shared in this context are point cloud, depth, rgb and skeletal data; human related data are utilized specifically for ergonomic evaluation and robot pose adjustments towards improved ergonomy.

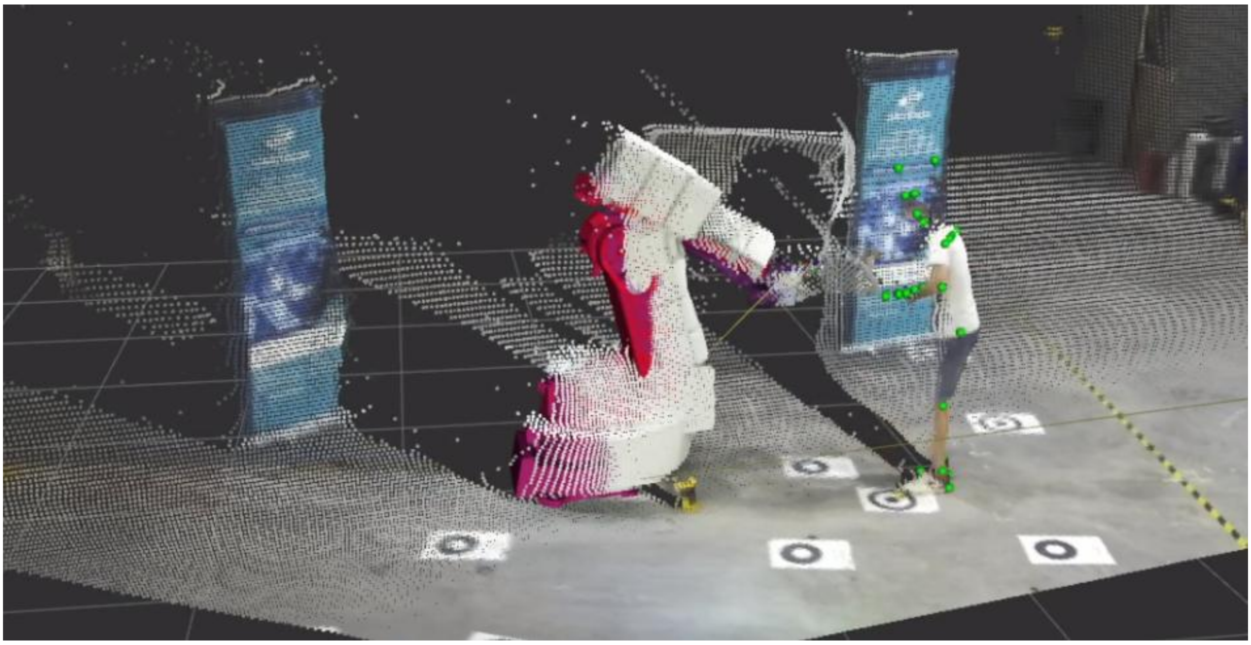


Figure 60: PAM human tracking and spatial data.

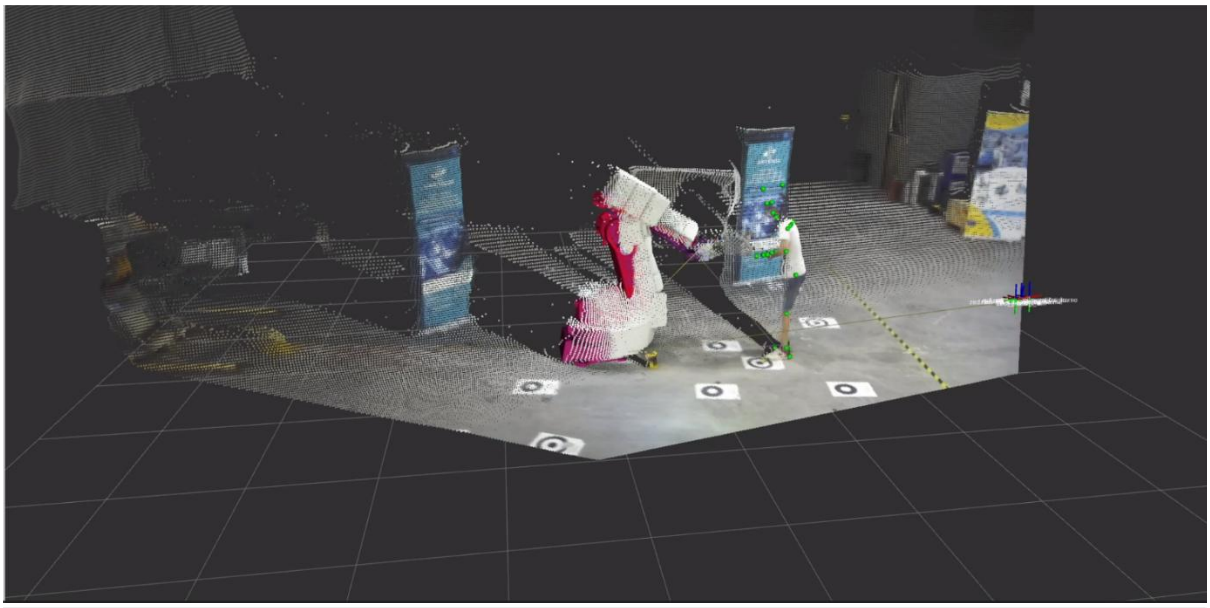
Requirements: The requirements for this module are the sensor which is the Stereolabs ZED2i, and a Ubuntu PC running ROS2 Jazzy, with installed the ZED sdk, ZED ROS2 drivers, CUDA 12.xx and the PAM module s/w itself.

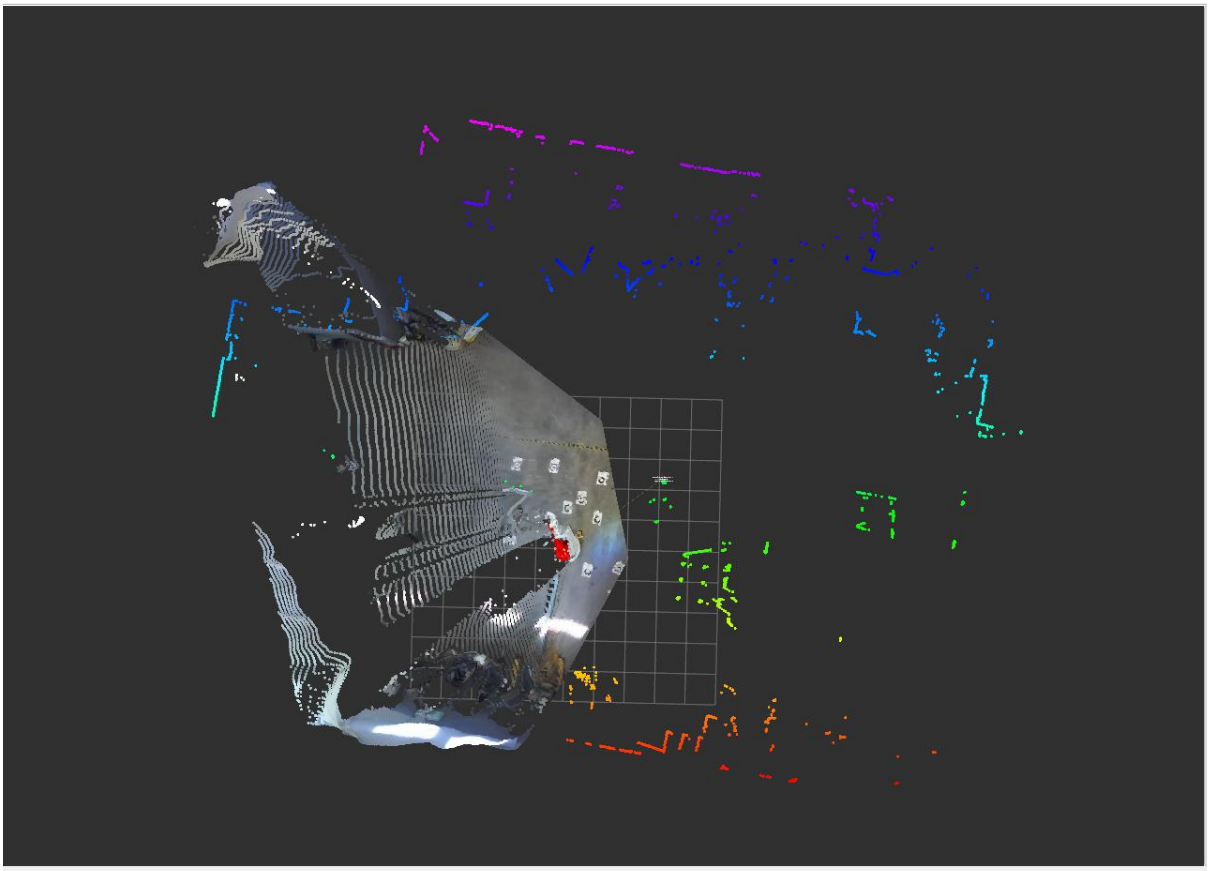
Customization: The customization for PAM module in PRIMA use case involves the sensor calibration generating a specific calibration config file and the fixture where the sensor is mounted. Additional customization involves the PAM module s/w modification from the initial ROS1 version to ROS2.

Trouble/Solution: One challenge faced during the development of the PAM module was the tuning required in the Stereolabs ZED ROS driver. Additional modifications were necessary to parse skeletal data in a way that matched the Azure Kinect ROS driver, enabling a unified format for human skeletal data publishing. This consistent format allowed for easier expansion of the PAM module.

AI Digital Twin (AIDT)

Setup: The Digital Twin is a replica of the physical cell on the digital world. The Digital Twin provides information on the operator of the configuration of the robots, future planned trajectories safety sensor's output and provides the planners of the robot of the environment of the cell. The Digital Twin is using the ROS2 framework for the communication with the robot, a number of motion planning libraries for the planners, such as the OMPL, PILZ industrial planner and Nav2.





Requirements: The digital Twin in order to function it requires a PC that Ubuntu 24.04 has been installed as an operating system, the ROS 2 jazzy full version that consists of MoveIt and RViz2, the Nav2 library for the SLAM of the mobile robot, the robot’s drivers for the communication with the robots.

Customization: The Digital Twin consists of a level of customization on the things are visualized at any giving moment. The operator can select what the digital twin can visualize, such as the sensors point cloud, the transformations that exists on the cell etc.

Trouble/Solution: The main issue that occurs during the development is the visualization and synchronization of multiple robots on the same cell. The robots needed to provide and received data independently from each other the digital twin in order for the visualization of the robot's current state to be correct and the planners to get the correct configuration of every robot. In order to address that issue every robot got a unique configurations and namespaces that eliminated the need for duplicate scripts for every robot. Also, due to the heavy network traffic and multiple nodes that needed to communicate with each other the addition of a Discovery server, for the FastDDS protocol, was needed to reduce the time that the nodes needed to discover the desired nodes using only the default peer-to-peer communication.

AI Station Controller (AISC)

The AISC is responsible for the integration and orchestration of CONVERGING modules in the Additive Manufacturing Pilot Case. The AISC is implemented using an actor-based approach [10] and supports the human-centric architecture of CONVERGING [11]. Using a Production Plan graph data structure that describes the production process, the AISC can request a specific execution plan from the DWR and execute it by using the API of the integrated modules for instance the MPCM for requesting robot related task execution or the MACI for the interacting with the operator. It can also respond and take decisions or actions based on the data stream coming from modules like the SAM or PAM.

In addition, the AISC monitors the execution and the integrated modules, providing a real-time view of the current status in multiple levels and different visualizations formats such as a tabular or a dynamic graph view.

Finally, it gives the user control over the whole process, providing pause, resume and cancel functionalities.

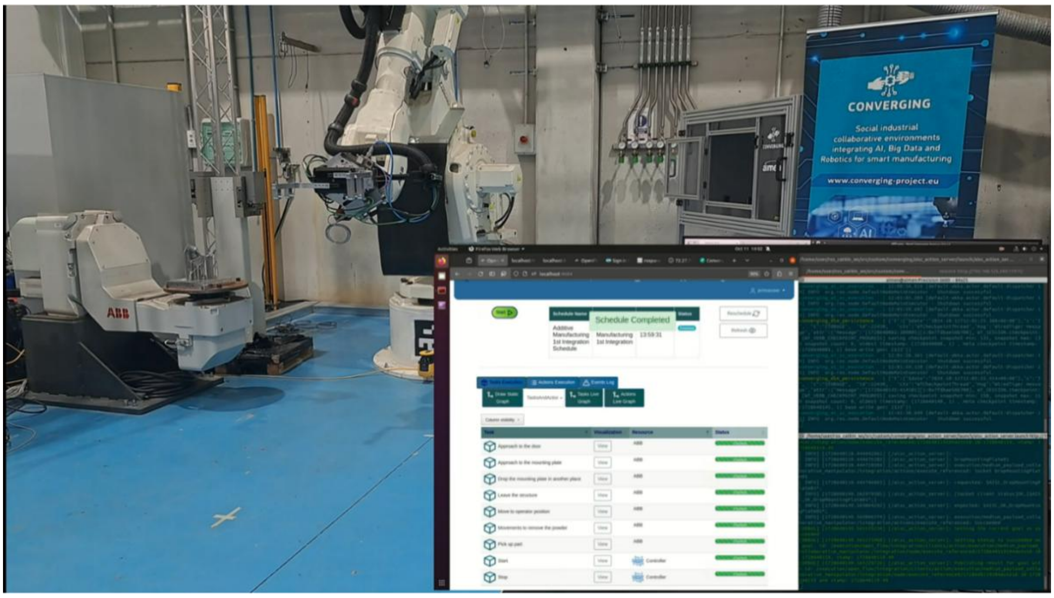


Figure 61: AISC of PRIMA case.

Setup: The AISC is packaged as a docker image and distributed via the private CONVERGING docker repository

Requirements: The AISC requires network connectivity with all resources that need to be integrated, and a docker environment.

Customization:

Deployment and integration customisation in module level is implemented by a docker-compose and a set of environment variables listed in a dedicated file. Both files are stored in a specific file in the integration architecture repository in the project's github.

In addition, the Knowledge Repository of the AISC has also been populated by all the required information that describe the OPL data, such as the Production Plan, available modules, graph names of their Actions, Services and Topics.

Data In Motion (DIM)

The DIM module, captures, fuses, processes and sinks data from SAM, PAM, UXE, MPCM and AISC modules to the DAR module. In particular it captures detection results from PAM, ergonomic cost and joint states from UXE, robot and tool state from MPCM, execution status from AISC and safety data from SAM. Data are contextualised, transformed and pushed them to DAR in real-time.

Setup: The DIM is packaged as a docker image and distributed via the private CONVERGING docker repository

Requirements: The DIM requires network connectivity with all resources that need to be integrated, and a docker environment.

Customization: The DIM uses a Kafka backbone for scalability and fault tolerance, in the scope of the OPL multiple configurations were created to demonstrate the scalability. The customization requires the configuration of the source to be monitored, which are the graph names of the ROS topics and details of the SAM database to be captured by CDC (Change Data Capture). All customization is stored in docker compose files, environment variable files (.env) and a json file that are stored in the integration architecture repository of the CONVERGING Github.

Dynamic Work Reorganization (DWR)

Setup: The DWR module generates plans in JSON format, which are stored in session history and downloaded to the user's machine. The output is a high-level task process containing sufficient information for generating lower-level actions in the agent component. The system requires a Node.js environment with MongoDB connection and an API key for accessing the Gemini API.

Requirements:

The system requires internet connection for communicating with external LLM and LMM APIs. It needs a video description of the case process with clear demonstration of required tasks and all available resources.

Customization:

To ensure compatibility between the task planner and the execution phase from OMPL, the JSON output plan is transformed using a custom script to match the schema required by the OMPL API route for plan addition. For AISC compatibility, simulation agents must be defined with skills corresponding to real resources. The video input should be custom-made for each specific case.

Trouble/Solution: The output plan structure differs from the OMPL plan structure, which requires lower-level actions instead of the high-level actions generated by TPC. The solution involves using the available high-level JSON data and passing it through custom simulation agents (robot and human) with specific skills to generate lower-level actions. The data is then transformed to a format compatible with the OMPL API.

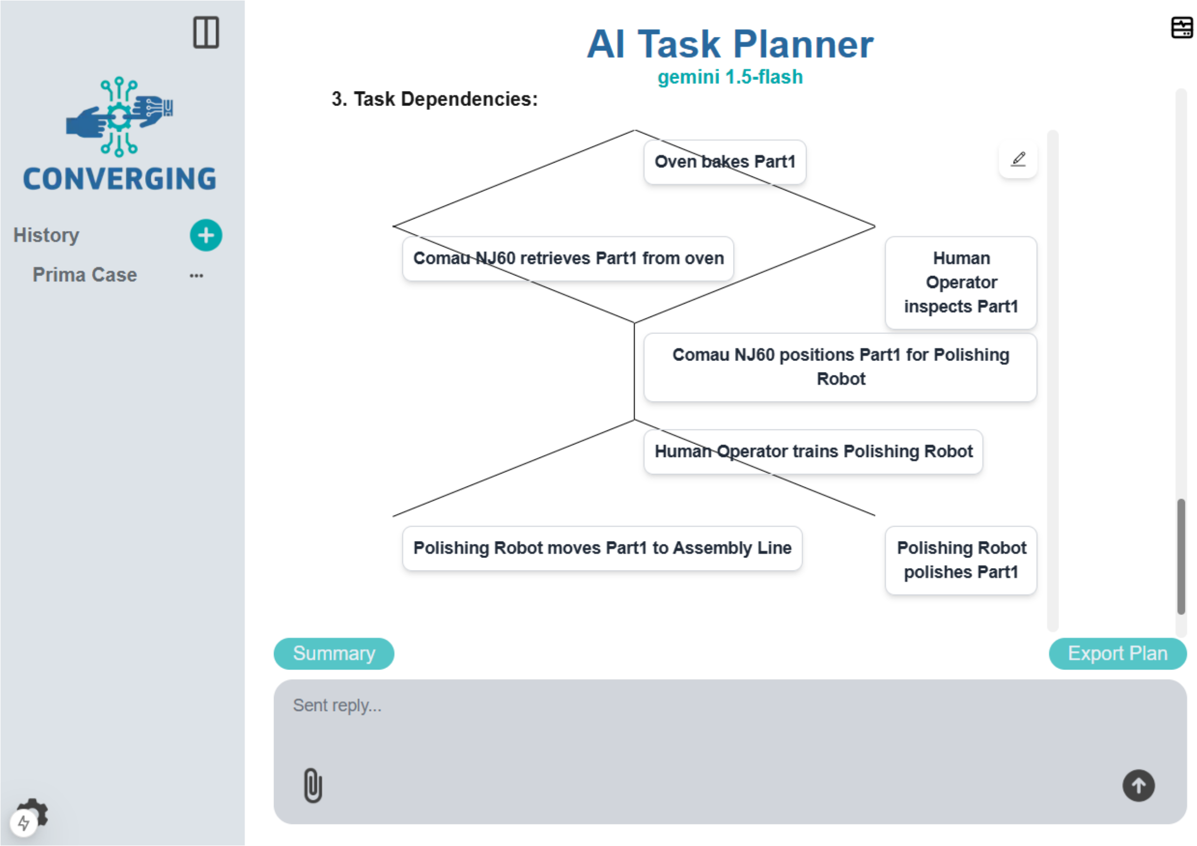


Figure 62: TPC on process of handling the prima case. Showing the tasks ordering that has extracted.

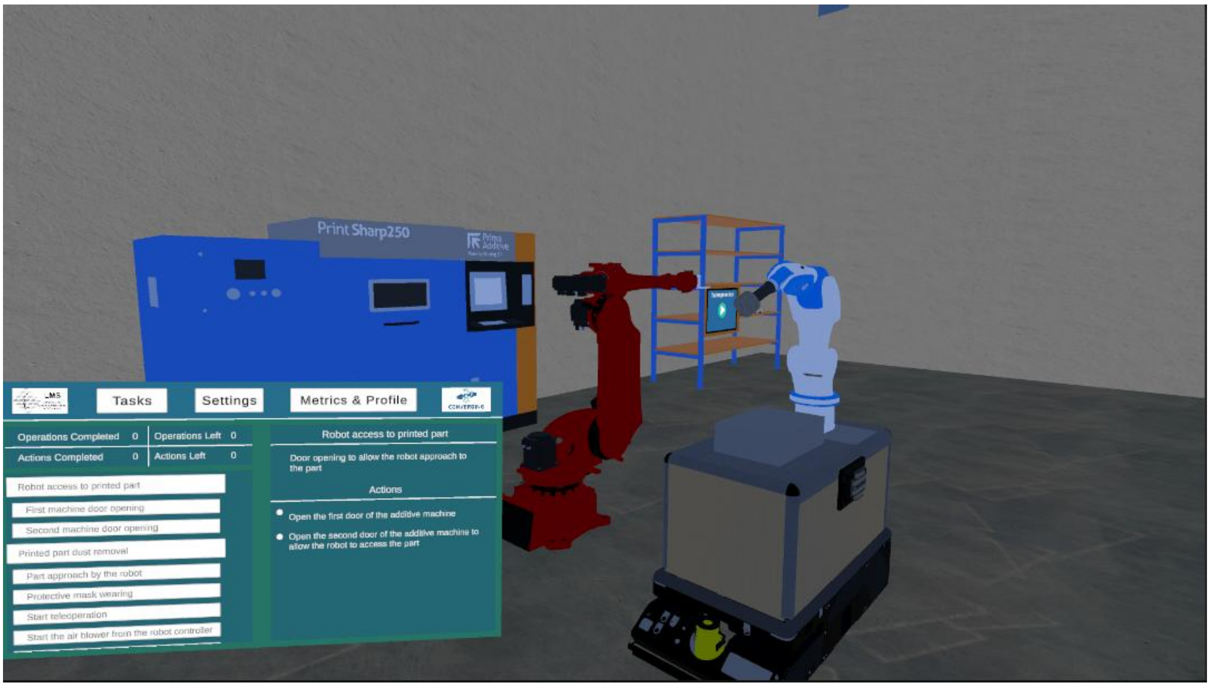
Operator Training Module (OTM)

Setup: Under the OTM module, operator's training applications are implemented for the different use cases utilizing VR technology. The module provides seamless, immersive and most of all safe training conditions for operator, while it drastically reduces training expenses and minimizes the downtime required for on-line training.

Requirements: Requires a Meta VR headset with the paired controllers, a Windows computer for the installation of the applications to the headset. To install the applications, the Meta Quest Developer Hub application is required, which is free.

Customization: Development of new interactions on the VR environment, such as touchscreen functionality for the tablet, robot tool change and cart push (for the positioning action where the cart is aligned with the entrance of the tank). Finally, visual indications for the buttons of the interface where developed to guide the trainees through the interface of the MACI application via the VR training application.

Trouble/Solution: A minor trouble faced during the development of the VR training application, was the previous headset LMS used for the development and testing, which was an HP Reverb G2 headset. This headset is wired and requires a capable computer to efficiently run the VR application. The headset's cord limited the movement of the trainee (both translation and rotation), and there was always a risk of tripping on the cord. This was "fixed" by switching to the standalone headset (a headset which has an onboard computer, eliminating the need for an external computer) Meta Quest 3. To be able to deploy the application first developed for the HP headset on the Meta headset, a switch to Android build platform on the Unity project of the application was required. Moreover, modifications on the code responsible for reading and writing to external files were made, such as the instructions' texts and the action lists files, as well as the files containing the statistics of the different trainees, since the Meta headset is an Android device, where the files are not easily accessible like they are when using a Windows device.



Robot access to printed part

Door opening to allow the robot approach to the part

- Open the first door of the additive machine
- Open the second door of the additive machine to allow the robot to access the part

Figure 63: Operator Training Module POV in virtual environment.

Safety Assessment and Monitoring Module (SAM)

Setup: The SAM module setup consists of an integrated layout with PILZ PSEN laser scanners that monitor the safety area, a safety PLC that evaluates scanner signals and performs required safety functions, the main SAM module cabinet containing the RevPI, and a local router that connects relevant network devices.

Requirements: The integrated solution for the PRIMA use case requires establishing a common network between the safety PLC, RevPI, ROS2 PC, and robot. It also needs internet connectivity for online SAM analytics and updates.

Customization: The LMS testbed customization includes a router and multiport ethernet switch connecting all network devices with internet access for the RevPI's cloud functionality. A custom ROS2 package was developed to read a 16-bit Modbus/TCP register from the PLC and republish the data to both ROS and MQTT. It publishes the raw word as UInt16 on a ROS topic and decodes key bits (laser scanners, airskin, E-STOP, reset) to JSON format on an MQTT topic. Additional information is shared throughout the ROS system using a package built by PILZ.

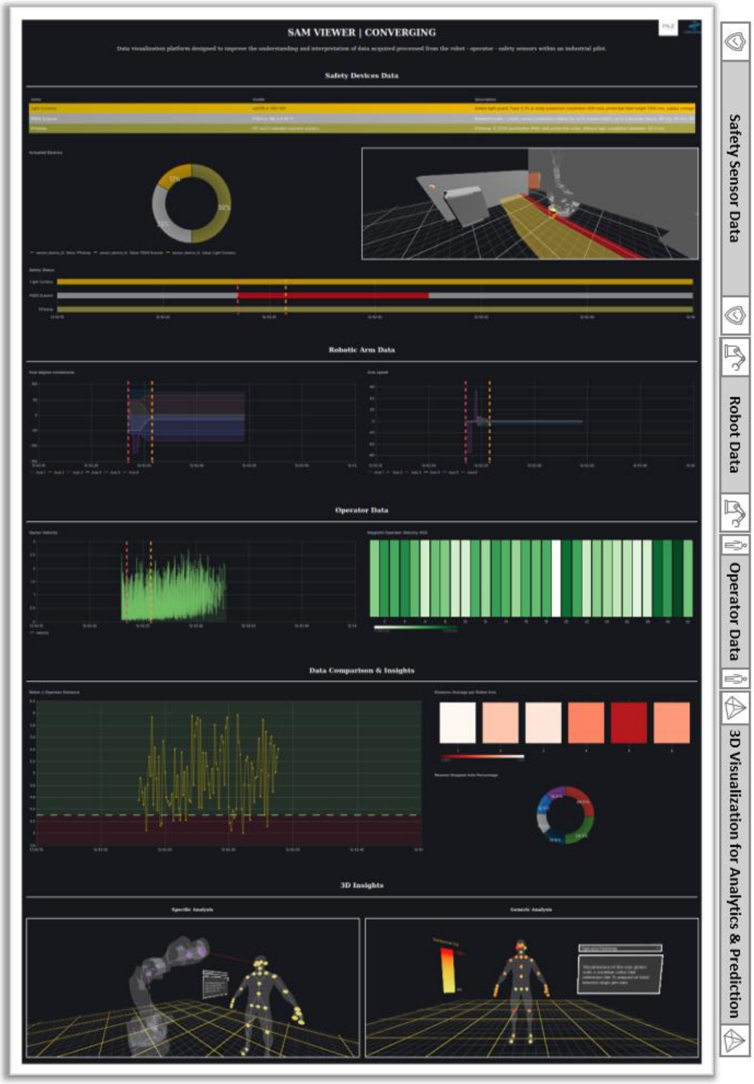


Figure 64: SAM UI.

Trouble/Solution: The SAM modules were initially based on the PSS4000 safety PLC, but the robot control only supported Profisafe fieldbus for safety functions - a protocol not available on the PSS4000. This required reformatting the network architecture and configuring a different communication pipeline.

Multi Actor Contextual Interfaces Module (MACI)

Setup: The setup of MACI module consists of the development of an AR application ran on an AR headset, that provides the operators with robots and process related information, as well as task instructions, visualization of the future robot trajectories, robot interaction capabilities and ergonomic data visualization.

Requirements: An AR headset is required - LMS uses the HoloLens 2. A local network with Wi-Fi is required as well so that the headset can exchange data with the computer that runs

ROS as well as send commands to it. A computer with professional Windows license is also required to deploy the application developed in Unity to the HoloLens headset. The Visual Studio software is also required for the computer that deploys the application on the headset. Finally, a QR code that is used for calibration is required. The QR code is placed on the physical cell and is used to calibrate the virtual NJ60 robot's position with the actual robot's position.

Customization: The only customization required for the MACI module in the PRIMA case, was the use of MRTK to enable the AR interactions, which allow the operator to press buttons on the virtual screens like they were real touchscreens.

Trouble/Solution: No troubles were faced.

Figure 65: MACI module - PRIMA OPL

Teaching by Demonstration Module (TDM)

Setup: The TDM module setup for the PRIMA use case consists of a mobile robotic manipulator with an F/T sensor mounted on the robot manipulator. A specifically designed handling device is placed on top of the F/T sensor, allowing the operator to teach the robot appropriate motions. Robot control is achieved through a ROS2-based package that receives published F/T sensor data and uses the Comau ROS driver with a PID controller to enable operator movement and trajectory recording. The AIDT module receives these recordings to replicate robot motion during the final deburring process.

Requirements: The hardware requirements for this solution include the mobile robot, the F/T sensor and its controller, and a PC running ROS2 with all robot control drivers installed. The software components are the ROS2 driver for the F/T sensor, the ROS package for translating F/T sensor data to motion, and the Comau ROS driver.

Customization: Customization involves defining the F/T sensor's specific pose within the robot URDF to properly translate F/T sensor data to motions. Additionally, robot wiring adjustments were performed to pass hand guidance device signals for the enable and record buttons between the robot controller and robot flange.

Trouble/Solution: -

Figure 66: TDM module - PRIMA OPL

Use Experience and Ergonomics Module (UXE)

Setup: The UXE module setup for the PRIMA use case consists of sensors that capture the pose of the operator. The sensor data are being analyzed and processed, aiding to the calculation of operator ergonomic score in real-time. Then the robot pose is being altered to improve ergonomics.

Requirements: The hardware requirements for this solution include the Kinect sensors.

Customization: Apart from the calibration of the sensors for the PRIMA setup as well as insertion of the robot data, no additional customization was needed.

Trouble/Solution: -

5.3 OPL System Level Functionalities (SLFs)

5.3.1 High Level Functionalities

The system can coordinate robotic production resources through the execution of schedules that outline necessary actions, their order, dependencies, and potential conditional pathways. The AI Station Controller (AISC) orchestrates these actions by factoring in real-time conditions, allowing for condition-based execution and corrective measures as needed.

AISC interacts DWR to optimize task sequencing based on real-time feedback and operational conditions. By continuously updating resource and task statuses to higher-level planning systems, AISC ensures smooth coordination between human operators.

The system employs an automated disassembly algorithm that identifies the optimal sequence of actions for part removal. This sequence can be dynamically reorganized based on real-time conditions. The schedule is stored in the DAR module, and the process can be simulated and executed through the UI.

The SLFs for the PRIMA use case as defined in the initial stages of CONVERGING have been slightly modified to fit better the needs of the end user and results in more functional and better manufacturing process. The new slightly modified high level functionalities are summarized in the aggregate table below:

Table 47: High level functionalities description.

#	High Level Functionality	Short description
1	Semi-autonomous AM part removal from bed	This functionality enables the automated removal of parts from the additive manufacturing (AM) bed while minimizing operator interaction. It enhances safety by preventing direct exposure to powder dust, reducing health risks of the operator
2	Supports removal operations in ergonomic position	This functionality enables the operator to remove the supports of the AM part which is presented to the operator’s ergonomic position by analysing the skeleton data and ergonomic scores and providing cognitive support.
3	Semi-autonomous placement on milling station & post-processing	This system facilitates the automatic transfer of the part to the AGV milling position, for robot polishing trajectory teaching and post-processing operations.

5.3.2 Low Level Functionalities

As mentioned also in Section 5.3.1, the low-level functionalities have been partially modified as needed to follow up and adapt with the high-level functionalities updates.

5.3.2.1 Semi-autonomous AM part removal from bed

Table 48: Semi-autonomous AM part removal from bed.

Step #	Operation	From	To	Status
Robot performs dusting of the remaining powder on the part.				
1	Behaviour: Task: {Dust powder}, Operator{id}, Details	AISC	ARBA	Functionally validated
2	Notify dust powder	AISC	MACI	Functionally validated
3	Notify dust powder	MACI	Operator	Functionally validated
4	Execute dust powder request	AISC	CRC	Functionally validated
5	Current position	MPCM	MACI	Functionally validated

6	Planned trajectory	CRC	MACI	Functionally validated
7	Visualize cobot	MACI	Operator	Functionally validated
8	Control cobot	CRC	MPCM	Functionally validated
Operator teleoperation of Robot is available in case of complex geometries.				
9	Request teleoperation	Operator	MACI	It was agreed with the end user that this is of a low priority and will be implemented as a last feature.
10	Request teleoperation	MACI	AISC	
11	Pause schedule	AISC	AISC	
12	Enter teleoperation mode	AISC	PAM	
13	Teleoperation started	AISC	MACI	
14	Teleoperation menu	MACI	Operator	
15	Teleoperate	MACI	PAM	
16	Stop teleoperation	Operator	MACI	
17	Exit teleoperation	MACI	AISC	
18	Exit teleoperation mode (params)	AISC	PAM	
19	Prepare for operation resume	AISC	PAM	
20	Control cobot	PAM	MPCM	
21	Resume schedule	AISC	AISC	

5.3.2.2 Supports removal operations in ergonomic position

Table 49: Supports removal operations

Step #	Operation	From	To	Status
System can identify and locate single parts and their supportive plate.				
1	Task: {Identify Part}, Operator: {Id}	AISC	ARBA	Functionally validated
2	Control behavior	ARBA	CRC	Functionally validated
3	Start task: {Identify Part}	AISC	CRC	Functionally validated
4	Control cobot	CRC	MPCM	Functionally validated
5	Identify part pose	AISC	PAM	Not tested
6	Visualize detected part	AISC	MACI	Not tested
7	Visualize part	MACI	Operator	Functionally validated
8	Part Pose	AISC	DIM	Functionally validated
9	Get context	DIM	DIM	Functionally validated
10	{Location, Part, Task, Pose}	DIM	DAR	Functionally validated
Robot presents part to operator in ergonomic position to proceed with support removal.				
11	Task: {PresentPart}, Operator: {Id}	AISC	ARBA	Functionally validated
12	Get Ergonomy Details: {Present Par}, Operator: {Id}	ARBA	UXE	Functionally validated
13	Behavior & Ergonomy details	ARBA	CRC	Functionally validated
14	Enable robot trajectory visualization for robot	AISC	MACI	Functionally validated
15	Execute present part task request	AISC	CRC	Functionally validated

5.3.2.3 Semi-autonomous placement on milling station & post-processing

Table 50: Semi-autonomous placement on milling station & post-processing.

Step #	Operation	From	To	Status
Identify part pose on the AGV				
1	Move to Location	AISC	AGV	Not tested
2	Notify AGV incoming	AISC	AGV	Not tested
3	Notify AGV Coming	MACI	Operator	Not tested
4	Identify part pose	AISC	PAM	Not tested
Robot moves recognized part up on AGV milling station				
5	Behaviour (Move Part, OperatorId, PartId)	AISC	ARBA	Functionally validated
6	Enable Trajectory Visualization	AISC	MACI	Functionally validated
7	Start Task (Move Part, PartId, PartPose)	AISC	CRC	Functionally validated
8	Task cost estimation	CRC	AISC	Functionally validated
9	Notify Part Movement	AISC	MACI	Functionally validated
10	Notify Part Movement	MACI	Operator	Functionally validated
11	Planned Trajectory	CRC	MACI	Functionally validated
12	Visualize trajectory	MPCM	MACI	Functionally validated
13	Visualize trajectory	MACI	Operator	Functionally validated
14	Task Guide and teach robot	AISC	MACI	Functionally validated
15	Notify Task	MACI	Operator	Functionally validated
16	Behaviour (Teach Robot, OperatorId, PartId)	AISC	ARBA	Functionally validated
17	Start Task (Teach Robot, PartId, PartPose)	AISC	CRC	Functionally validated
18	Enable Teaching Mode	AISC	MACI	Functionally validated
19	Enable Teaching Mode	MACI	Operator	Functionally validated
Operator guides the robot to perform post-processing procedures				
20	Behaviour (Post Processing, OperatorId, PartId)	AISC	ARBA	Functionally validated
21	Notify Post Processing Starts	AISC	MACI	Functionally validated
22	Operator performs polishing trajectory	Operator	CRC	Functionally validated
23	Enable Trajectory Visualization	AISC	MACI	Functionally validated
24	Start Task (Post Processing, PartId, PartPose)	AISC	CRC	Functionally validated
25	Planned Trajectory	CRC	MACI	Functionally validated
26	Visualize trajectory	MPCM	MACI	Functionally validated
27	Visualize trajectory	MACI	Operator	Functionally validated
Operator inspects part				
28	Start Inspection	AISC	MACI	Functionally validated
29	Start Inspection Task	MACI	Operator	Functionally validated

Step #	Operation	From	To	Status
30	Inspection	Operator	Operator	Functionally validated
31	Inspection results	Operator	MACI	Functionally validated
32	Inspection Results	MACI	AISC	Functionally validated

5.4 Service provisioning

5.4.1 Assessment of the conducted webinars

This report provides a detailed analysis of two recent webinars organized to foster knowledge sharing on advanced industrial topics. The sessions aimed to engage professionals in key areas of robotics and Industry 4.0 technologies. The report evaluates each webinar in terms of registration, attendance, feedback, participant satisfaction, and improvement opportunities. It also includes qualitative insights from participants and lessons learned to enhance future events.

5.4.1.1 High Payload Robots: Safe Human-Robot Interaction (Link)

5.4.1.1.1 Attendance Overview

The webinar had 14 registered participants, out of which only 43% attended. This attendance rate is relatively low, indicating a gap between initial interest and participation. Possible reasons could include conflicting schedules, insufficient reminders, or lack of dissemination.

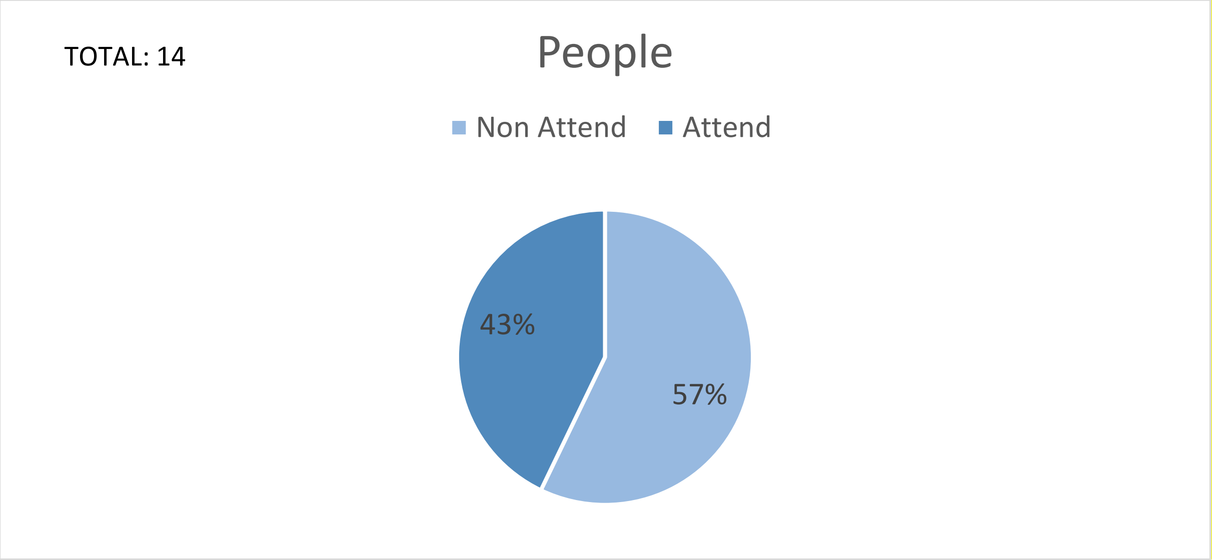


Figure 67: Attendance chart Human-Robot Interaction Webinar

5.4.1.1.2 Feedback Participation

Among the attendees, 4 participants submitted feedback, representing about 67% of those who attended. While this response rate is acceptable relative to the actual attendance, the overall sample size is very small, which limits the statistical significance of the results.

5.4.1.1.3 Satisfaction and Quality Assessment

Feedback results show high satisfaction levels across all surveyed aspects:

- Training goals and objectives were clear.

- The content met participants' expectations.
- Overall quality of training and teaching by instructors was rated highly.
- The balance of presentations, discussions, and practical content was positive.
- Learning environment and training duration were well rated.

Importantly, there was no negative feedback recorded. All responses were categorized as Very Satisfied or Extremely Satisfied, indicating that the content quality and delivery were strong for those who attended.

5.4.1.1.4 Net Promoter Score (NPS)

The NPS analysis shows:

- Promoters: 2
- Passives: 2
- Detractors: 0

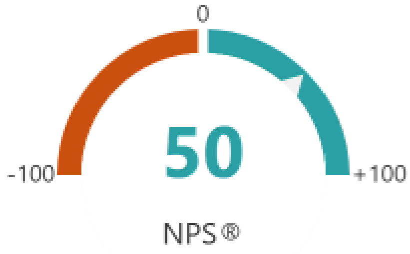


Figure 68: NPS Score Human-Robot Interaction webinar

The resulting NPS is 50, which is considered good and indicates a likelihood of positive word-of-mouth. However, the small sample size (4 responses) makes this result less conclusive.

5.4.1.1.5 Post-Event Reach

The recorded session was uploaded to YouTube and has received 56 views so far, extending its reach beyond the live audience.
Video link: Watch on YouTube

5.4.1.2 Unlocking Industry 4.0: Mastering Asset Administration Shell Modelling (Link)

5.4.1.2.1 Attendance Overview

The webinar attracted 17 registered participants, but only 24% attended live.

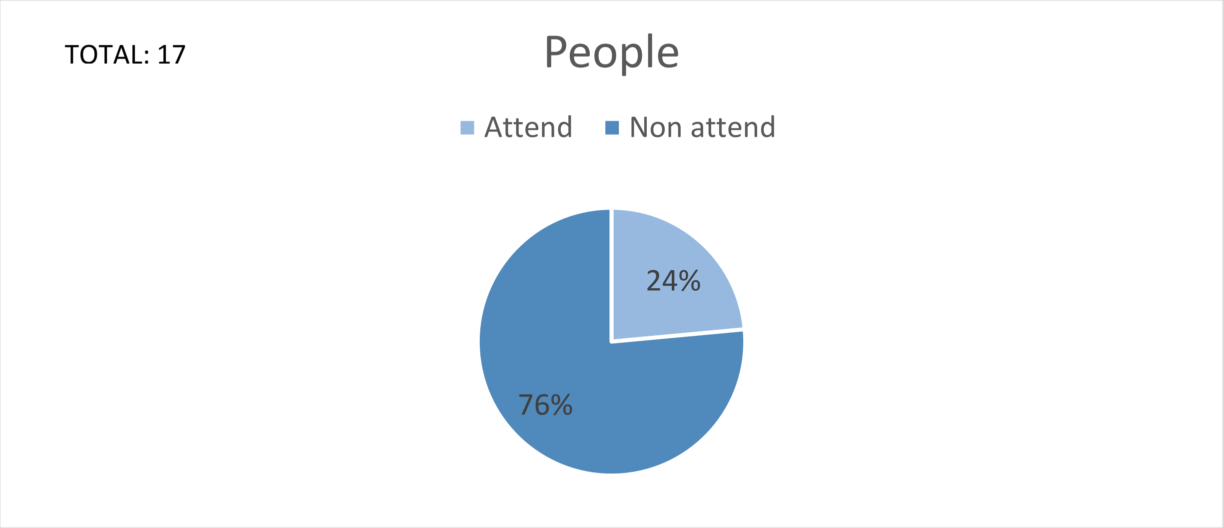


Figure 69: Attendance Chart AAS Webinar.

5.4.1.2.2 *Feedback Participation*

Although the sample size was small, the following sections present the key findings for completeness.

5.4.1.2.3 *Satisfaction and Quality Assessment*

The collected responses indicate very high satisfaction levels across all evaluation areas, including:

- Clarity of training objectives and content
- Overall quality of the session
- Teaching quality of the instructor
- Balance of presentations and discussions
- Relevance of the learning environment and training duration

All responses were rated as Very Satisfied or Extremely Satisfied, confirming that the webinar content and delivery met participants’ expectations and provided value.

5.4.1.2.4 *Net Promoter Score (NPS)*

- Promoters: 3
- Passives: 0
- Detractors: 0
- NPS: 100

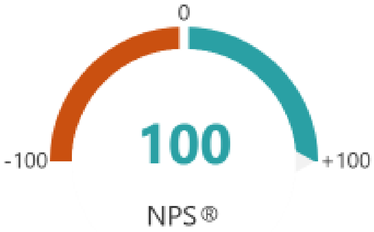


Figure 70: NPS Score AAS Webinar

This is an excellent score, reflecting that participants would strongly recommend this training to others.

5.4.1.2.5 Qualitative Feedback

What did participants like most about the training?

- *“Very clear presentation of AAS and hands-on session allowed for a good overview of AAS.”*
- *“Emilio’s training was really clear.”*
- *“The clear explanation of the three types of AAS and how they support interoperability across systems and partners in the value chain.”*

These comments highlight the clarity of explanations, the quality of instruction, and the value of including a practical perspective.

How could the event be improved?

- *“Might be out of scope but could be interesting to have a hands-on short session with the participants.”*
- *“Maybe some exercises to make in group.”*
- *“Include hands-on exercises for configuring real-time data updates using tools like Data Bridge or connecting AAS with external protocols (e.g., MQTT or OPC UA).”*

The main improvement request is clear: participants want more interactivity and practical exercises, especially related to real-world integration scenarios.

Additional suggestions for improvement

- *“Make something interactive.”*
- *“Add a section on troubleshooting common issues or best practices for integrating AAS with existing systems.”*

These suggestions reinforce the idea of moving towards a more hands-on and problem-solving oriented format in future sessions.

5.4.1.2.6 Post-Event Reach

Although live attendance was low, the recorded session uploaded to YouTube has accumulated 92 views (as of now). This indicates continued interest in the topic and extends the value of the event beyond the live session.
Video link: Watch on YouTube

Within the AIMEN OPL, two consulting and technical services are planned to support companies in the adoption of the Asset Administration Shell (AAS) framework. These services aim to accelerate the digitalization of assets and provide a practical pathway towards interoperability and integration in industrial environments.

Table 51: Technical services.

Topic Title	Description	Duration	Tentative Dates	Format
Use of AAS for Assets Digitalization	Consulting to evaluate feasibility and benefits of AAS for asset digitalization; includes roadmap and recommendations.	4h (multiple sessions)	Q4 2025	Remote
Assets Modelling and Digitalization (PoC)	PoC using open-source tools (Package Explorer, BaSyx) for asset digitalization via AAS implementation.	8h (multiple sessions)	Q4 2025	Remote / OPL

The first service, “Use of AAS for assets digitalization”, is designed to evaluate the feasibility and benefits of applying the AAS framework in specific use cases or scenarios. The service guides organizations in assessing their requirements, objectives, and expected outcomes from digitalizing assets. It covers the evaluation of particular scenarios, the implementation process of AAS, and the creation of digital representations of physical assets. The outcome includes a feasibility analysis and a tailored set of recommendations, complemented by a roadmap for AAS adoption aligned with business goals. The service also ensures compliance with international standards and best practices. Delivery is organized through remote sessions with engineering experts, structured into short modules to facilitate knowledge transfer.

The second service, “Assets modelling and digitalization”, provides a proof-of-concept (PoC) to transform existing physical assets into digital twins using open-source tools such as Package Explorer and Basyx. This service focuses on the practical implementation of AAS for asset digitalization and demonstrates, through the PoC, the benefits of interoperability and data exchange. It also emphasizes flexibility and scalability by tailoring the digitalization approach to the specific requirements of each organization, while keeping the solution extensible for future growth. Importantly, the service requires assets to be already monitored as a prerequisite and may involve remote access to IT infrastructures. The delivery format combines presentations and hands-on sessions using Ubuntu-based environments and open-source software, targeting technicians, engineers, and software developers.

5.4.2 Future work timeline

To ensure the adoption of innovative technologies in industrial environments, a structured roadmap of future trainings, consulting services, and technical demonstrations have been defined. These initiatives are designed to address key areas such as asset digitalization, collaborative robotics, advanced automation, and safety standards.

Each activity is planned with a clear objective: to equip professionals with actionable skills, accelerate digital transformation, and foster safe and efficient human-robot collaboration. The following table summarizes the available sessions, their scope, expected duration, and format.

Table 52: Available sessions on demand.

Topic Title	Description	Duration	Format
Use of AAS for Assets Digitalization	Consulting to evaluate feasibility and benefits of AAS for asset	4h (multiple sessions)	Remote

Topic Title	Description	Duration	Format
	digitalization; includes roadmap and recommendations.		
Assets Modelling and Digitalization (PoC)	PoC using open-source tools (Package Explorer, BaSyx) for asset digitalization via AAS implementation.	8h (multiple sessions)	Remote / OPL
Basic Concepts on Robot Safety	Overview of collaborative robot safety standards (ISO/TS 15066), risk assessment, SSM, and hand-guiding techniques.	4h	Converging OPL
Collaborative Robots	Introduction to collaborative robots with a live plasma cutting demonstration; safety and efficiency benefits explained.	1h	Shipbuilding Demonstrator
Basic Training in Robot Programming	Foundational training in robot programming, movement, and applications; includes practical exercises.	4h	Converging OPL
3D Projection Systems	Overview of projection systems for shipbuilding; includes calibration, stitching, and localization techniques.	1h	Shipbuilding Demonstrator
AI Perception Systems in Robotic Cells	Training on AI-powered detection systems for robotic cells; includes gesture recognition, object detection, and SSM implementation.	1h	Converging OPL

5.5 Industrial deployment

5.5.1 M48 plan and timeline

The AM pilot will follow a phased transition from open pilots to industrial deployment:

- **Until M42:** A complete setup is deployed at TF-CC premises, featuring the COMAU collaborative robot, a case-specific gripper, and supporting hardware modules. This setup serves as a pre-final validation environment, enabling the integration of modules that require close human–robot interaction (HRC), AR/VR-assisted workflows, and ergonomic monitoring.

- **On M43:** The COMAU robot and associated hardware modules will be transferred to PRIMA's premises, where the final pilot line will be assembled.

- **From M44 to M48:** The software modules (simulation, SAM safety module, XR operator support, traceability, and data services) will be progressively deployed and integrated at PRIMA to complete the transition to a fully operational industrial pilot.

6 Human factors and operator engagement methodology

The integration of robotic systems into manufacturing environments presents not only technological challenges but also critical human factors considerations. Successful adoption of such systems depends largely on operators' trust in the technology, their readiness to adapt, and their ability to interact effectively with new tools and processes. In recognition of these challenges, the CONVERGING project has performed a line of user engagement activities (reported in D5.1-D5.3) and is developing an acceptance training self-paced online program and final validation protocol that provides a structured, user-centred approach to support operator preparedness, foster acceptance, and enhance performance across the project's pilot environments. The design of acceptance training and final validation program is kept structurally identical across four use cases, however, the use case specific elements are being integrated to address the key human factors.

6.1 Current process challenges

FORD

The sanding process relies heavily on tacit knowledge that operators develop over years of experience, which is difficult to transfer to robots. In workshops (D5.1–D5.3), operators stressed that people will remain essential for tasks requiring judgment and expertise, while robots should focus on the physically demanding work. Simply adding automation does not guarantee less strain, as poor ergonomics can replace one type of discomfort with another. Operators also raised concerns about trust, acceptance, and job security, pointing to the need for open communication, participatory design, and user-centred implementation.

ELUX

Assembly tasks create both physical strain and mental fatigue. Operators highlighted in D5.3 that robotic systems could reduce task variety and autonomy if they shift people into passive monitoring roles, leading to skill loss and lower engagement. Many also expressed worry about job security. To succeed, automation should be introduced as a tool that supports wellbeing and performance while also opening opportunities for skill development and career growth (WP7).

IAI

Robotic inspection can improve safety by removing operators from confined and poorly lit spaces, but remote operation increases cognitive demands. Trust in the technology depends on clear communication about system limits and decision-making. Feedback from WP5 workshops stressed the importance of reliability and transparency. For adoption to succeed, designs must deliver ergonomic benefits while ensuring operators remain engaged and confident in the inspection process.

PRIMA

Working with hazardous print powders causes stress, while removing supports from printed parts often requires awkward and uncomfortable postures. Operators noted in D2.1 and D5.2 that creativity and autonomy in design are central to job satisfaction. If robots reduce these meaningful aspects of the work, resistance is likely to grow. Collaborative robots that adapt to operator posture could ease physical strain while still preserving the creative and satisfying parts of the job.

6.2 Acceptance training

Acceptance training is provided to show operators how their input directly shaped the development of the technology, to increase their knowledge and engagement with the new systems, and to acknowledge and thank them for their essential role in the process. Acceptance training is grounded in four key objectives. First, it aims to build operator acceptance by making the robotic systems more transparent and relatable, clarifying their role in day-to-day tasks. Second, it familiarises operators with the modified workflow, introducing the practical implications of automation on their responsibilities. Third, it promotes confidence in the use of advanced technologies, such as virtual and augmented reality interfaces, which are increasingly embedded within human-machine interactions. Lastly, the methodology supports the transition of critical manual and tacit skills into semi-automated contexts, ensuring that operator expertise continues to inform quality assurance and decision-making processes.

To meet these objectives, a self-paced online training program was developed and tailored to each pilot use case. The training is approximately 20 minutes in duration and is delivered through a combination of narrated videos, illustrative infographics, and knowledge-assessment quizzes. The content is informed by prior user engagement sessions and reflects the specific cognitive, physical, and organisational challenges identified at each pilot site. While the training content varies by use case, all modules consistently introduce the CONVERGING solution from a human factors perspective, distinguish between automated and manual tasks, define the evolving role of the operator, and explain both the benefits and anticipated challenges of human-robot collaboration.

A key feature of the training programme is its focus on operator engagement in system design. Operators are introduced not only to the robotic applications but also to the human factors that shaped those solutions. The training includes an overview of the original manual processes, highlighting key difficulties, and explains how these have been addressed through iterative co-design with operator input. Operators are also shown how their feedback influenced the final system design, reinforcing their agency in the development process. Below are the outlines of the acceptance training content for all four use cases

6.2.1 FORD - Structure of the Acceptance Training Programme

Module 1: Welcome and System Overview (3 minutes) - Introduction to the training goals, system context, and collaborative approach adopted in CONVERGING.

Module 2: Refresher – Manual Polishing Essentials (3 minutes) - Review of foundational manual techniques, such as left palm sanding, fingertip precision work, and tactile inspection. This module reinforces the continued importance of operator expertise in evaluating robot-assisted work.

Module 3: Understanding the Robot’s Role (3 minutes) - Explanation of how the robot performs repetitive polishing using pre-learned demonstrations and adaptive AI. The operator’s responsibilities in supervising quality, reassigning tasks, and validating final outcomes are outlined. Robot communication methods, including visual indicators, audio cues, and screen notifications, are also presented.

Module 4: Using the Interface (3 minutes) - Guidance on the interactive interface, including task control, feedback mechanisms, and error reporting.

Module 5: Working in a VR Practice Environment (3 minutes) - Introduction to a simulated practice environment designed to allow safe familiarisation with robot operation in a virtual setting.

Module 6: Safety, Comfort, and Collaboration (2.5 minutes) - Focus on ergonomic design, shared control between operator and robot, and psychological aspects of collaboration.

Module 7: Final Quiz and Certificate (2.5 minutes) - A brief knowledge check followed by certification to validate operator understanding and readiness.

6.2.2 ELUX Structure of the Acceptance Training Programme

Module 1: Welcome and System Overview (3 minutes) – Introduction to training objectives, system capabilities, and the collaborative development process adopted in the CONVERGING project.

Module 2: Physical and Cognitive Challenges (3 minutes) – Overview of fatigue from repetition, awkward postures, and poor ergonomics, explaining how these informed the robot's design.

Module 3: Smart Robot Introduction (3 minutes) – Presentation of the robot as a collaborative assistant capable of projecting instructions, operating within safety zones, and supporting—but not replacing—operator decision-making.

Module 4: Interface and Task Management (3 minutes) – Demonstration of alerts, step reminders, and feedback tools, with guidance on using voice commands, smartwatch, and touchscreen input methods.

Module 5: Safety, Regulations, and Job Design (3 minutes) – Discussion of safety protocols, regulatory requirements, and strategies for framing the robot's introduction as an achievement and upskilling opportunity.

Module 6: Operator Role and Motivation (3 minutes) – Emphasis on maintaining creativity, recognising operator expertise, and ensuring task variation to avoid monotony.

Module 7: Final Quiz and Certificate (2.5 minutes) – Short knowledge check followed by certification of readiness.

6.2.3 IAI Structure of the Acceptance Training Programme

Module 1: Welcome and System Overview (3 minutes) - Introduction to the training objectives, the role of teleoperation in the inspection process, and the collaborative development approach adopted in the CONVERGING project.

Module 2: Current Process and Operator Challenges (3 minutes) - Overview of key risks in the manual inspection process, including posture-related strain, blind inspections, and potential injury. The module explains how these challenges informed the system's design priorities.

Module 3: Smart Robot and Inspection Capabilities (4 minutes) - Presentation of the robot's inspection functions and how the operator remains the final decision-maker. Examples are given of how the system identifies potential issues for operator review.

Module 4: Using the Remote Interface (3 minutes) - Guidance on marking suspected defects for further investigation and effectively navigating the remote inspection interface.

Module 5: Ergonomics and Safety Improvements (2 minutes) - Explanation of how the system removes operators from confined tank spaces, reducing risks of claustrophobia, strain, and injury, while redefining the operator's role as a remote inspector.

Module 6: Trust and Acceptance (3 minutes) - Strategies for building trust in the robotic system, including repeat validation of results and transparent communication of system capabilities and limitations.

Module 7: Final Quiz and Certificate (2.5 minutes) - Short knowledge check to confirm understanding, followed by certification.

6.2.4 PRIMA - Structure of the Acceptance Training Programme

Module 1: Welcome and System Overview (3 minutes) - Introduction to the training objectives, additive manufacturing process context, and the collaborative design approach adopted in the CONVERGING project.

Module 2: Current Challenges in additive manufacturing Tasks (3 minutes) - Overview of physical strain during support removal and part inspection, with emphasis on how these challenges informed the design of the robotic system.

Module 3: Human-Robot Collaboration Concept (3 minutes) - Presentation of the operator’s role as a designer and quality validator, illustrating how collaboration ensures high product standards while leveraging operator expertise.

Module 4: Interface Walkthrough and Communication (3 minutes) - Demonstration of how AR/VR tools are used to view robot activity and monitor task progress, along with guidance on issuing commands via voice and gesture input.

Module 5: Enhancing Creative Aspects (2 minutes) - Explanation of how robotic assistance enables a shift from repetitive manual work to creative problem-solving, encouraging innovation and process improvement.

Module 6: Safety, Trust, and Transition Strategy (4 minutes) - Discussion of safety protocols and the importance of gradual trust-building, ensuring that operators have confidence in the robotic system before full deployment.

Module 7: Final Quiz and Certificate (2.5 minutes) - Short knowledge check followed by certification to confirm readiness for collaborative Additive Manufacturing work.

Through this training, the CONVERGING project reinforces a participatory approach to technology deployment, emphasising the critical role of operator involvement in system development. By acknowledging and addressing human factors early in the design process and continuing through to implementation, the project seeks to ensure not only effective human-robot collaboration but also sustainable operator engagement, wellbeing, and trust in the future of automated manufacturing.

6.3 Validation of the developed process from Human Factors perspective

Finally, to validate the developed robotic process an experimental study will be completed once the demonstrators will be deployed on the use case premises and operators will have the opportunity to try it out. The studies structures are equivalent across PRIMA, FORD, and ELUX use cases: shared design, participant sampling, measurement tools, and procedures. The IAI use case requires adaptations due to geopolitical constraints that may limit on-site testing with operators. For IAI, supplementary baseline data will be collected in the Cranfield

University laboratory (A320 wing inspection) and archival ergonomic data will be integrated to strengthen the analysis.

Across all use cases, the validation builds on the literature review and human factors outlined in Deliverable D2.1 as well as additional factors that emerged from operator engagement activities in WP5.

6.3.1 Design

The validation will adopt a within-subjects design where participants will complete tasks under both a control (manual process) and experimental (robot-assisted process) condition. Counterbalancing will be applied to mitigate order effects. For the IAI use case where direct access to IAI operators is limited, additional baseline data will be collected at the Cranfield University laboratory using motion capture during an equivalent wing inspection task (an A320 wing is available in the facility). Existing archival ergonomics and task performance data from the industrial aerospace facility will also be integrated. Ideally, final validation will involve IAI operators on-site; however, these supplementary datasets will serve as baseline references if access is restricted.

6.3.2 Participants

The study will recruit approximately 10 to 16 participants per use case. Participants will vary in age, gender, and experience level to ensure generalisability of findings.

6.3.3 Materials

The following tools will be used to assess participant responses:

- System Usability Scale (SUS) [1]: A 10-item measure assessing perceived usability of the robot-interface system.
- Trust in Industrial Human-Robot Collaboration Scale [2]: A validated 10-item Likert scale assessing trust in collaborative robotic systems.
- Body Part Discomfort Scale [3]: A visual tool allowing participants to indicate discomfort in nine body regions.
- NASA Task Load Index (NASA-TLX) [5][6]: A multidimensional scale capturing workload across six dimensions.
- User Experience Questionnaire (UEQ) [7][9]: A 26-item tool assessing affective and cognitive dimensions of user experience.

6.3.3.1 Physiological Measures:

- Heart Rate and Electrodermal Activity (EDA): Recorded via a wrist-worn device to track mental workload and emotional arousal. Elevated EDA and heart rate are associated with increased cognitive load and discomfort [4][8].

6.3.3.2 Behavioural Measures:

- Motion Capture (G6 Systems by Synertial): Used for ergonomic analysis.
- Video Observation: Task performance will be video recorded to quantify errors, task steps, and completion times.

6.3.3.3 Qualitative Data

Short semi-structured interviews will capture process aspects that matter to operators but may not appear in the quantitative results. Topics will include retention of tacit knowledge, trust development, role satisfaction, and perceived impact on workflow and productivity.

6.3.3.4 Procedure

Participants will perform the designated task twice: once using the manual process (control) and once using the CONVERGING robotic solution (experimental condition). Self-report questionnaires, physiological recordings, and behavioural data will be collected in both conditions.

The procedure includes:

- Baseline physiological and motion data collection.
- Task execution under control and experimental conditions (counterbalanced).
- Completion of self-report measures after each condition.
- Semi-structured interviews completion.

6.3.3.5 *Analysis*

Statistical analyses will include repeated measures comparisons across conditions using physiological, behavioural, and self-report data. The goal is to identify significant differences in usability, workload, trust, physical strain, and task performance between manual and robot-assisted conditions. Thematic analysis of interviews will provide context for the quantitative results, highlighting practical considerations for refining the system before wider deployment.

7 Next Steps

This section sumarizes the next steps outlined in the individual open pilot sections, providing a cohesive plan for moving forward. Each open pilot continues to follow a specific service provisioning plan, tailored to its unique context, with the objective of ensuring continuity and effective deployment.

With the project approaching its final stages and the deployment of operating industrial pilots at the premises of production end users, a first plan has been started during this period in collaboration with the end users to guarantee a smooth and structured transition from the open pilot network to the industrial pilots.

This deliverable includes an initial plan of the final demonstrators and information from the end users to support the necessary preparations for the delivery of robots and installation of the industrial pilots. With the exception of the IAI use case—where, due to the ongoing situation in the Middle East, the industrial validation will be done at TF-CC's premises. A dedicated integration period will be allocated to bring the pilots online and fully operational.

In line with this, all technical improvements, updates, and upgrades implemented in the open pilots to adapt them for the production environments from now on will also be documented within WP7, in the future Deliverable 7.3.

8 Conclusion

The current operating status and execution of the CONVERGING Open Pilots reflect significant advancements in the deployment and validation of smart, reconfigurable manufacturing systems. Each Open Pilot Line has evolved considerably since the last reporting phase, incorporating updated hardware and software modules, executing critical service provisioning tasks, and applying human-centered design principles through operator training and human factors studies.

The Automotive, White Goods, Aeronautics, and Additive Manufacturing pilot lines have each addressed unique sector-specific challenges by integrating advanced robotics, AI, and collaborative technologies into real-world industrial scenarios. These implementations not only demonstrate technical feasibility but also highlight tangible benefits in terms of process efficiency, worker ergonomics, and operational safety.

Importantly, the first draft transition plans toward Industrial Pilots mark a critical milestone in the CONVERGING roadmap. These plans provide early visibility into how the current pilot setups will evolve into full-scale demonstrators at the end-user premises, offering a clear path to industrial adoption.

Overall, the CONVERGING Open Pilots Network continues to validate its strategic approach, showing strong alignment with industry needs and the broader goal of accelerating smart manufacturing adoption in Europe. With continued refinement, service provisioning, and stakeholder engagement, the project is well-positioned to deliver impactful Industrial Pilots in the upcoming phases—laying the groundwork for a more flexible, resilient, and sustainable manufacturing ecosystem.

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