D1.3: Functional multi-robot cell

Demonstrator

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Abstract	This document supports the primary deliverables by summarizing the successful commissioning and operational readiness of the COROB project's pilot multirobot cells. It highlights key technological advancements, cell layouts, and preparations for future integration, while directing readers to the videos for a comprehensive visual demonstration of the cells' capabilities [1][2]
Keywords	Multi-robot cell, jigless welding, WAAM

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Important remarks:

- The contributors listed in this table and on the front page are the report's primary editing authors. It is important to note that all COROB partners are contributing critical technical contributions to this ongoing work.

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DMP: Data management plan

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EXECUTIVE SUMMARY

This document serves to support and complement the two videos showcasing the operational readiness of the COROB project's pilot multirobot cells. It provides concise evidence that both cells have been successfully assembled, tested, and validated, demonstrating their capability for advanced jigless welding and Wire Arc Additive Manufacturing (WAAM) in alignment with project objectives.

The document summarizes key technological advancements, cell layouts, and preparatory work for future integration, as detailed in Sections 2 and 3.

Readers are encouraged to refer to the accompanying videos for a comprehensive visual demonstration of the pilot cells' performance and readiness, as these videos represent the primary evidence of this important project milestone [1][2].

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ABBREVIATIONS & GLOSSARY

2D	Two Dimensional
API	Application Programming Interface
AAS	Asset Administration Shell
CAM	Computer Aided Manufacturing
CI/CD	Continuous Integration/Continuous Deployment
DDS	Data Distribution Service
DED	Direct Energy Deposition
DPP	Digital Product Passport
DOF	Degrees of Freedom
EGM	External Guided Motion
FSTP	Financial Support to Third Parties
GMAW	Gas Metal Arc Welding
HMLV	High-Mix Low-Volume
MLOps	Machine Learning Operations
NDT	Non-Destructive Testing
P4R	Papyrus for Robotics
PDO	Process Data Object
PLC	Programmable Logic Controller
PC	Personal Computer
ROS	Robot Operating System
WAAM	Wire Arc Additive Manufacturing

1 INTRODUCTION

The COROB project is focused on developing a flexible, cooperative, and intelligent multi-robotic system for arc welding-based manufacturing processes, specifically targeting both joining and additive manufacturing applications. The objective is to introduce new operational capabilities that enhance efficiency and flexibility in industrial production, aligning with the evolving demands of Industry 5.0.

Traditional welding methods often require custom jigs and fixtures for each part, which is especially challenging and costly in high-mix, low-volume (HMLV) production settings. The COROB project addresses this by implementing a jigless robotic welding approach. In this setup, two manipulator robots are used to precisely position and align the workpieces, while a third robot performs the welding operation. This eliminates the need for dedicated physical jigs, enabling rapid reconfiguration for different parts and geometries, and significantly increasing production flexibility. This approach reduces tooling costs, shortens lead times, and is particularly advantageous for custom or small-batch manufacturing scenarios.

The project also leverages Wire Arc Additive Manufacturing (WAAM) for the repair of high-value components. WAAM is a directed energy deposition process that uses an electric arc to melt and deposit metal wire layer by layer. The COROB system features a processing robot equipped with the WAAM torch, complemented by a rotational unit for workpiece holding and an auxiliary collaborative robot for handling auxiliary manufacturing tasks (e.g. 3D scanning, preheating, others). This integrated multi-robot cell is capable of addressing the repair of existing high-value products, with a focus on tooling.

In summary, the COROB project will demonstrate the transformative potential of cooperative multi-robot systems for both jigless welding and WAAM-based repair of high-value manufactured parts.

This document provides comprehensive evidence of the successful commissioning and operational readiness of the two pilot multirobot cells developed within the COROB project. Both cells have been fully assembled, tested, and validated, demonstrating their capability to perform advanced jigless welding and Wire Arc Additive Manufacturing (WAAM) tasks in line with project objectives. They are prepared to serve as integration platforms for the forthcoming internal and external technological developments planned in the next phases of COROB. The readiness of these pilot cells marks a significant milestone, ensuring a solid foundation for further innovation, system integration, and demonstration activities throughout the remainder of the project.

Sections 2 and 3 detail the layout of the cells, the technological advancements that have been implemented and finally the works that have been conducted to facilitate future integration of upcoming solutions.

To further illustrate the current status and operational capabilities of the pilot cells, we invite the reader to view the two accompanying videos, which provide a detailed visual demonstration of their performance and readiness.

- Jigless welding [1]
- WAAM repair [2]

2 MULTI-ROBOTIC CELL FOR JIGLESS WELDING

The integration of advanced robotics is transforming manufacturing, such as through the use of cooperative multi-robot systems for jigless welding. In this approach, two industrial manipulator robots handle the precise positioning and alignment of workpieces, while a third robot performs gas metal arc welding (GMAW). By eliminating traditional jigs and fixtures, this setup streamlines the welding process and enables rapid adaptation to different product designs.

This multi-robot configuration offers significant advantages over conventional jig-based methods. It delivers greater production flexibility, faster changeovers, and higher throughput, while maintaining a high accuracy through a combination of vision systems and advanced grippers. Additionally, automating the welding process reduces operator fatigue and exposure to hazardous environments, ultimately improving both productivity and workplace safety.

2.1 PRESENTATION OF THE LAYOUT

For the development of this multi-robot cell, the available LORTEK cell has been used as a base, which consisted of two (ABB IRB 4600-45/2.05 and ABB IRB 6700- 235/2.65) robotic arms and a Fronius welding machine for GMAW processes. Although the cell includes an external 2DoF axis, it has not been used in the COROB project, only considered for collision avoidance. Both robots were commanded by a single RW6 controller.

For the welding robot, a Doosan collaborative robot H2017 have been used to enhance the flexibility of the robot cell and explore the use of collaborative robots for welding. The robot is mounted on a mobile platform that facilitates quick adjustments and easy repositioning using a pallet truck.

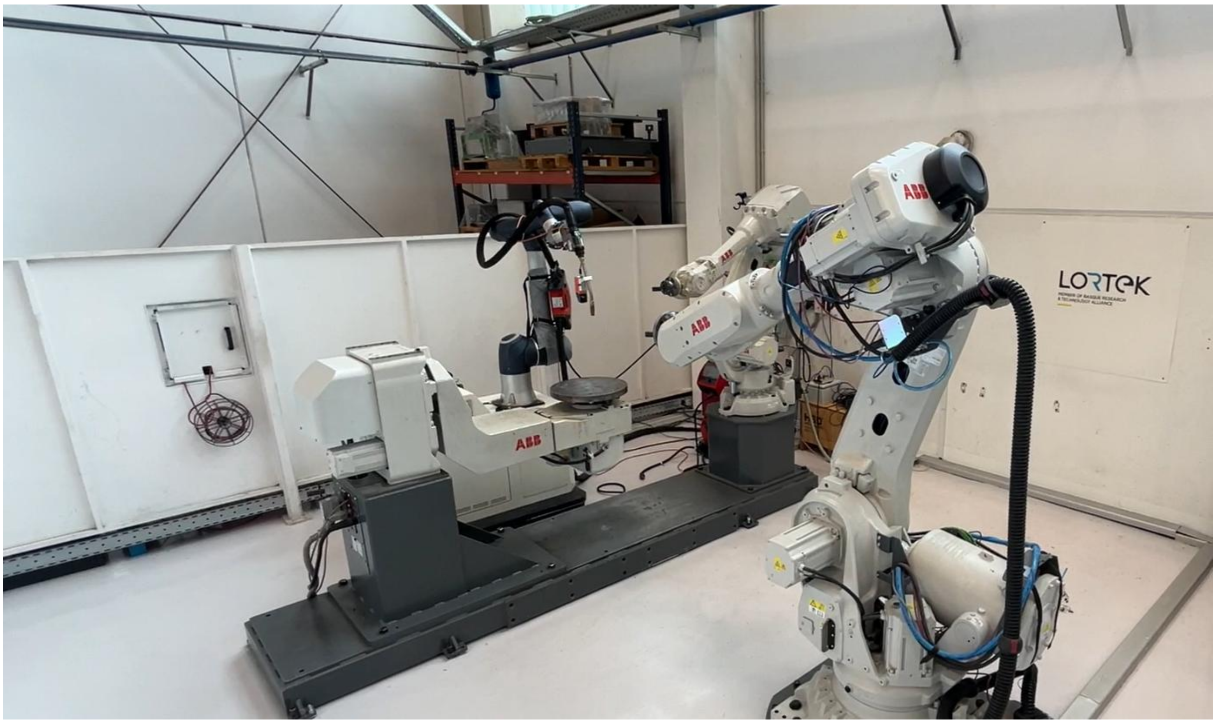

Figure 1. Final multi-robot cell layout

For the GMAW process, a Fronius TPSi system is used. The Fronius TPS400i is a state-of-the-art, microprocessor-controlled inverter power source offering flexibility and efficiency for the required application. The device provides precise control over the welding process, ensuring high reproducibility and excellent weld quality.

To accurately measure the dynamics of the process forces applied to the manipulators (and enable dynamic compensation), the two manipulator robots have been equipped with force/torque sensors. These sensors measure in all six axes, providing decoupled measurements for each axis in all dimensions, including forces and moments. Based on the range of measured forces and torques, as well as the resolution and performance, the AXIA80-DUAL SI-75-4/SI-150-8 force sensors have been selected.

Manipulator robots have been equipped with preliminary grippers as well, as the final grippers will be received through the FSTP by the end of 2025. The clamping mechanism involves direct bolting of the parts to the grippers, which is not fully aligned with the project objectives, but allow for the necessary testing while waiting for the arrival of the final grippers. It is important to note that the grippers are subjected to significant shear forces during the welding process and that any slippage or backlash in their grip will inevitably result in defects. The preliminary grippers have been manufactured using PBF and Pa12.

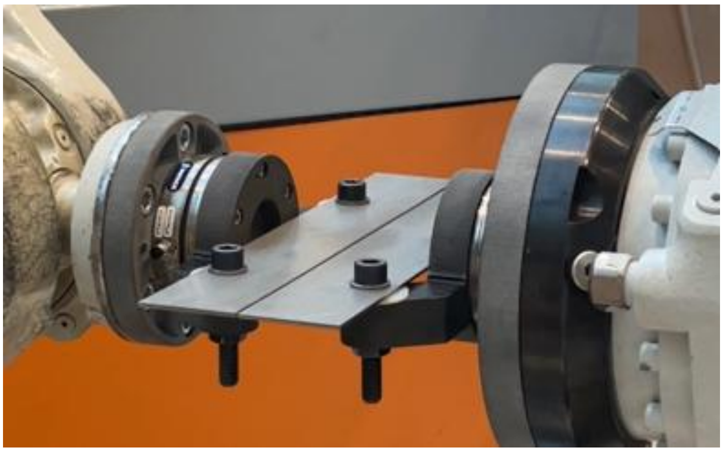

Figure 2. Preliminary grippers

Regarding the inspection system, initially, the Garmo GarLine profilometer was integrated into the welding robot. However, it has been finally replaced with the Wenglor MLZL131, which offers superior performance. The Wenglor, with its class 2 blue laser, provides enhanced visibility during welding, a wider field of view, improved Z-axis resolution, and a significantly higher maximum frequency of 4000 Hz compared to the Garmo’s. Both systems are ready to communicate with a controller via TCP/IP, so switching from one profilometer to the other was straightforward.

Figure 3. Wenglor profilometer integrated in the welding torch

To measure the cell's energy consumption, an energy meter has been installed in the electrical panel. This sensor allows real-time monitoring of the power consumed at any given moment. This data is essential to take the necessary measures to reduce consumption and achieve optimum efficiency.

Additionally, specific areas for part feeding and part placement were identified through accessibility analysis. Part feeding involves a bin picking solution where both manipulator robots take turns collecting parts for welding, while part placing consists of leaving the product in a designated bin.

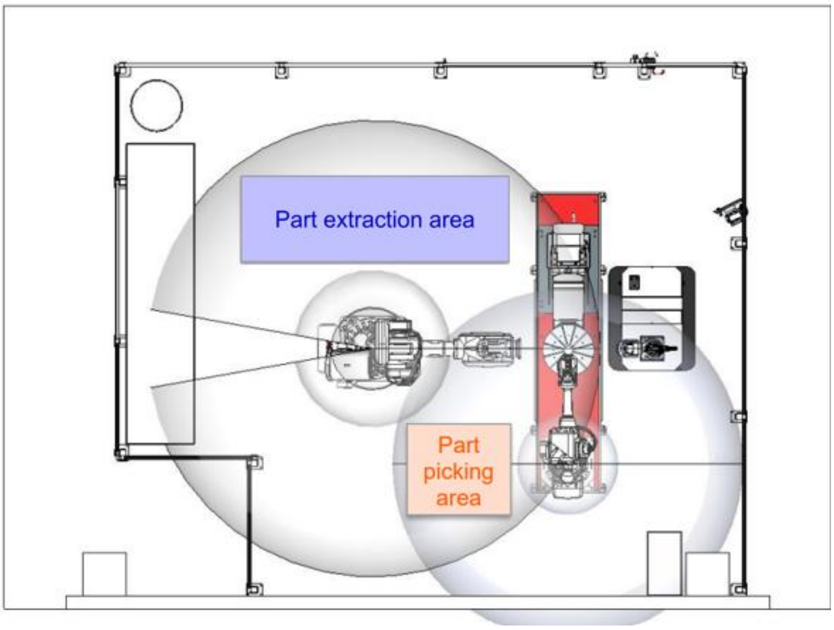

Figure 4. Picking and placing areas

Finally, the work envelope has been analysed to determine the ideal welding position that maximizes the stiffness of the manipulator robots and the dexterity of all three robots, without moving their bases. Based on the analysis, the optimal welding position is identified as the area next to the low-payload manipulator robot when it is oriented towards the high-payload manipulator robot. This conclusion is intuitive, as this position maximizes the stiffness of the low-payload robot, which was the primary criterion for this determination.

All the details of this optimization process can be found in [3].

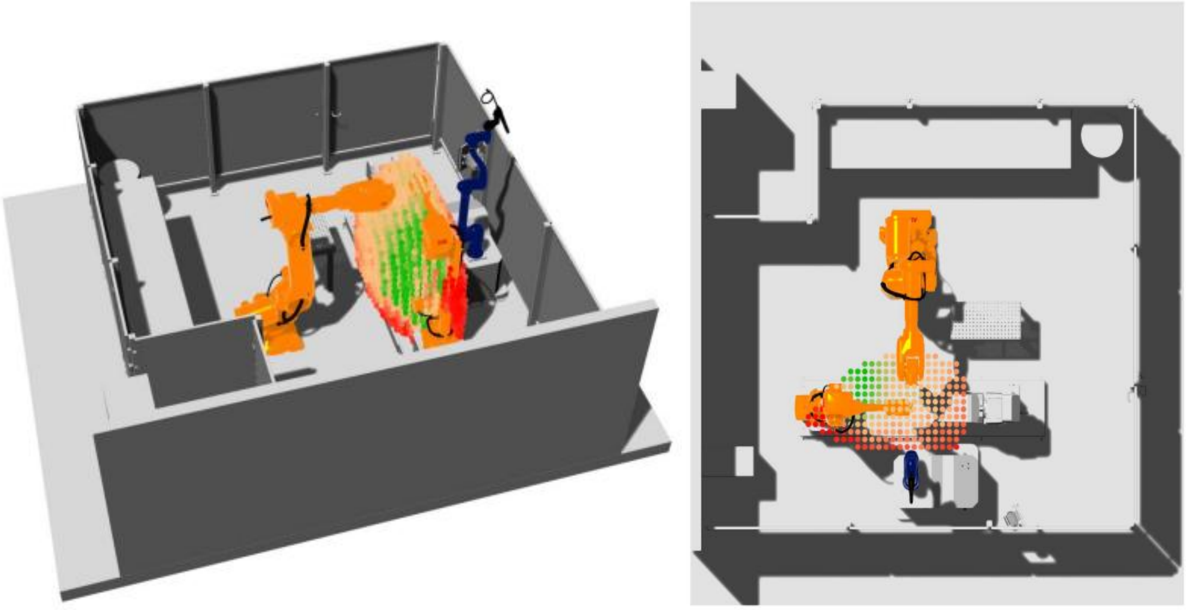

Figure 5. Result of the welding position optimization

2.2 TECHNOLOGICAL ADVANCEMENTS

The robotic cell presented incorporates advanced technological innovations, establishing a robust technical foundation to support future internal and external solutions.

Although originally planned, it was finally decided not to use Papyrus for Robotics (P4R) for several reasons. One major challenge was the steep learning curve associated with P4R, which could have slowed down our development process. Additionally, integrating P4R with the COROB MLOps pipeline proved difficult due to its limited support for automated workflows. These workflows are crucial for maintaining efficiency and consistency in our development lifecycle.

Furthermore, our project involves working with formal models developed across multiple middleware versions, ROS distributions, which P4R doesn't effectively support. To address this, we opted for a Docker-based architecture. This approach allowed us to manage different middleware environments more flexibly and aligns well with our CI/CD requirements. It also offers better scalability compared to using P4R. While P4R is beneficial for organizing and managing project models and designs and conducting safety analysis (offering tools for tracing failure propagation, exploring fault trees, and executing risk assessments), our specific needs are better met through the proposed architecture.

Despite not using P4R, the COROB project on this use case effectively followed the RobMoSys methodology by implementing key principles like separation of concerns and model-based design. We defined distinct roles within the project, including component suppliers, system architects and integrators. Each role worked independently to ensure that different aspects of the system were developed and integrated efficiently. This role-based approach allowed for a clear separation of concerns, enabling each team member to focus on their specific responsibilities without interfering with other parts of the system. Additionally, we used formal models as the foundation for our software development, ensuring a structured and composable system architecture. Metamodels were designed to be modular and interoperable, facilitating easy integration and reconfiguration of system components. By following these principles, we maintained the core benefits of the RobMoSys approach while adapting to the specific needs and constraints of COROB.

This approach resulted on a ROS-based architecture, where each node represented a metamodel. This design choice enables better fault isolation, as it simplifies debugging and maintenance, streamlines troubleshooting and allows updates or changes without requiring modifications to the entire system. Overall, this distributed architecture enhances the flexibility and adaptability of the multi-robot cell, making it easier to integrate additional actuators or modify existing functionalities as needed.

These metamodels adhere to a common structural pattern. Control management is handled through ROS services, which function as an instruction callback mechanism, enabling external components to issue commands to individual nodes. Concurrently, data acquisition, such as sensor measurements, robot position and velocity, and system status, is published via ROS topics, facilitating real-time monitoring and inter-node communication. This structure allows the synchronization of the process issuing sequential instructions in a controlled manner. The figure below shows a simplified representation of the pattern:

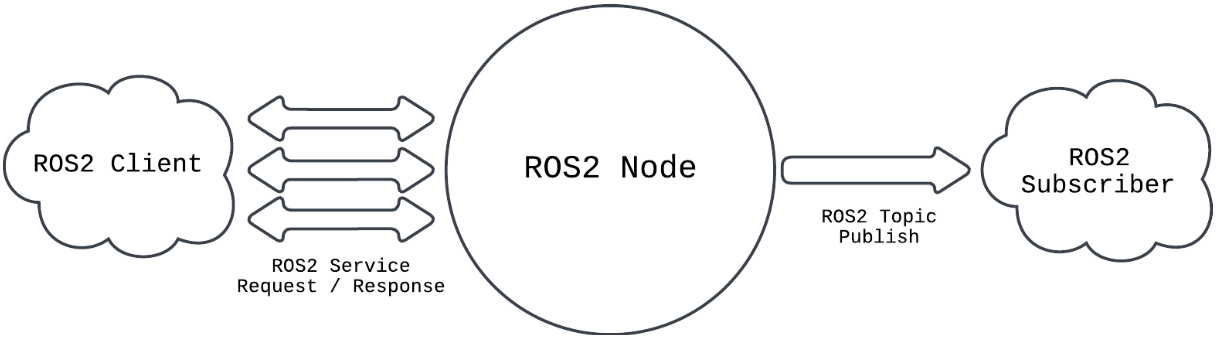

Figure 6. ROS nodes' structural pattern

This integration is a critical process, ensuring seamless communication and synchronization between the different components of the system. In order to provide a clearer understanding of the proposed overall architecture of COROB project, the following diagram illustrates all the subsystems and their interactions. This visual representation highlights how the developed controller, Trajectory Manager, platform and other solutions work together to achieve a coordinated operation.

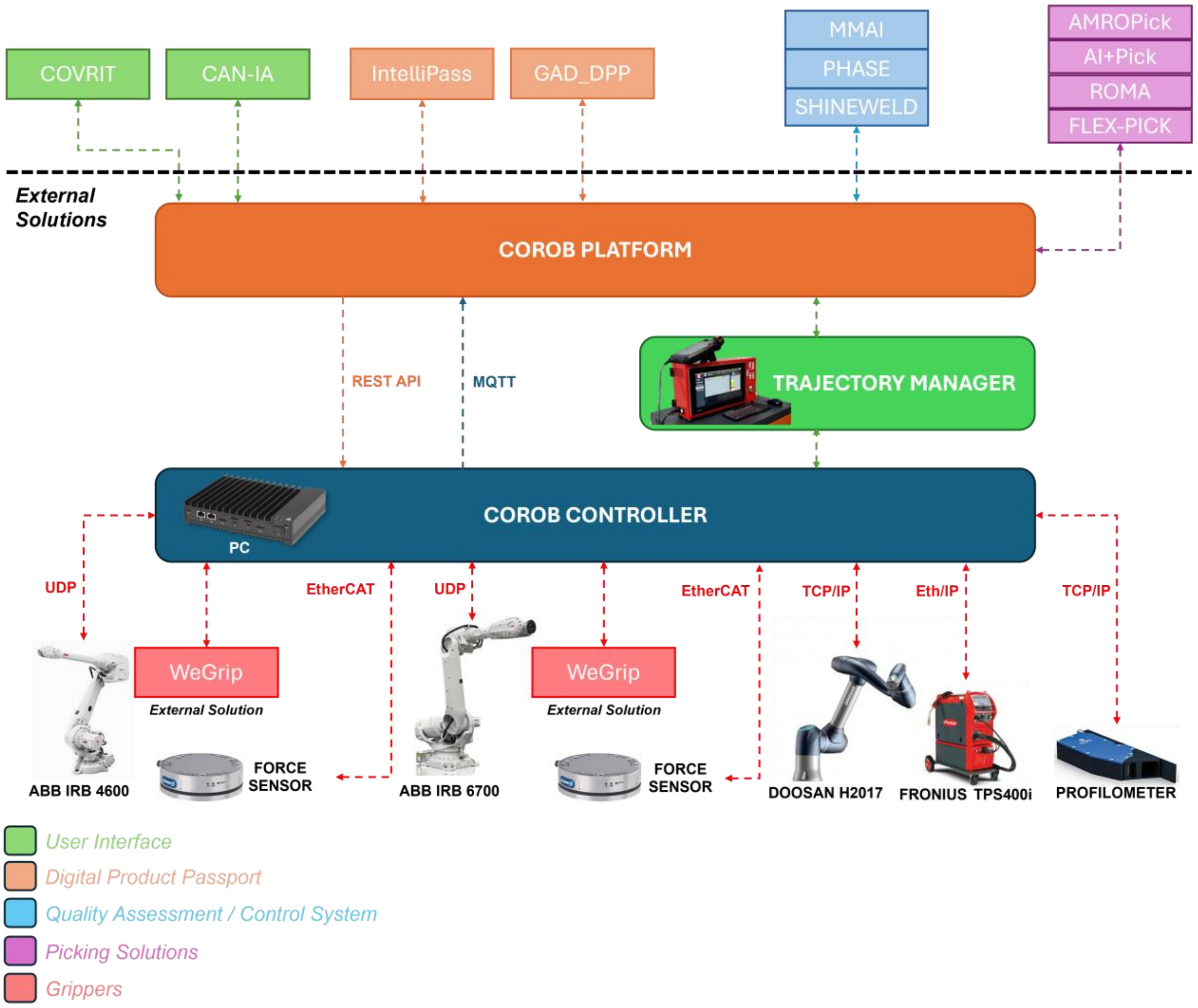

Figure 7. COROB arc welding use case architecture

To enable the communication and commanding with the rest of the subsystems, the controller seamlessly integrates the several ROS nodes. Below, a resumed description of them is presented. It is important to note that the manipulator robots' grippers node has not been developed in the current phase of the project, as the gripper solution is still in the design stage.

- **Manipulator Robots:** The motion control of both ABB robots has been implemented using External Guided Motion (EGM), provided by ABB, to enable real-time trajectory adjustments from external commands. Unlike traditional RAPID programming, which relies on predefined motion commands, EGM supports high-frequency updates (up to 250 Hz) of position and velocity, allowing the robots to respond dynamically to changing conditions. These models have been inspired by the outcome of the European project ROSIN [4].

- **Welding Robot:** As in the case of the manipulator robots, a full external motion control has been implemented for the Doosan cobot, using the DRFL (Doosan Robotics Framework Library) API. It provides a ser of interface for controlling and interacting with any Doosan robot, enabling users to programmatically manage robot movements, configurations, and feedback data remotely at a frequency up to 1 kHz).

- **Force Sensors:** This node collects the data measured by the force sensors, enabling configuration management tasks such as zero-offset calibration. It manages the EtherCAT communication protocol between the controllers and sensors, using the PDO (Process Data Object) approach, as it is optimized for high frequency data acquisition.

- **Profilometer:** This node integrates a profilometer's into the welding system, which plays a vital role in the alignment of the workpieces on the welding position and welding quality inspection. It is based on a TCP/IP communication protocol and handles the connection with the device, and controls laser activation/deactivation, as well as manages device's configuration parameters. The use of metamodels permitted to successfully integrate the new model after the former profilometer resulted out of service.

- **Welding Sources:** It controls the welding process by activating or deactivating the welding source and acquiring the electrical parameters in real-time during the welding process. Additionally, it supports the management of other generic signals and the collection of status data. It is important to note that this node supports two different welding sources: a *Fronius TPS 400i* and *Synerbot 4000 Advanced*. This dual-source node enhances this controller's vendor agnostic capability and provides higher efficiency rate, due to limited equipment availability. It must be highlighted that very few success stories can be found in the literature, such as the ROSWELD project [5].

- **Platform Interface:** This node main propose is to acquire all the data published by the rest of the nodes, restructure it according to the platform's necessities, and send it via MQTT, which is a lightweight, publish-subscribe messaging protocol.

- **Supervisory:** It is the omniscient node of the system, as it oversees and synchronizes the entire process, issuing sequential instructions to the aforementioned nodes in a controlled manner. Furthermore, it will interface with the Trajectory Manager, receiving the mentioned instructions sequence list.

Each node has predefined control instructions or commands that will manage the workflow of the process. Considering the described nodes and the interface with the Trajectory Manager and Platform, the following ROS-based architecture diagram is presented, showing the instructions defined to each node, the data published into ROS topics and the interface with the other solutions.

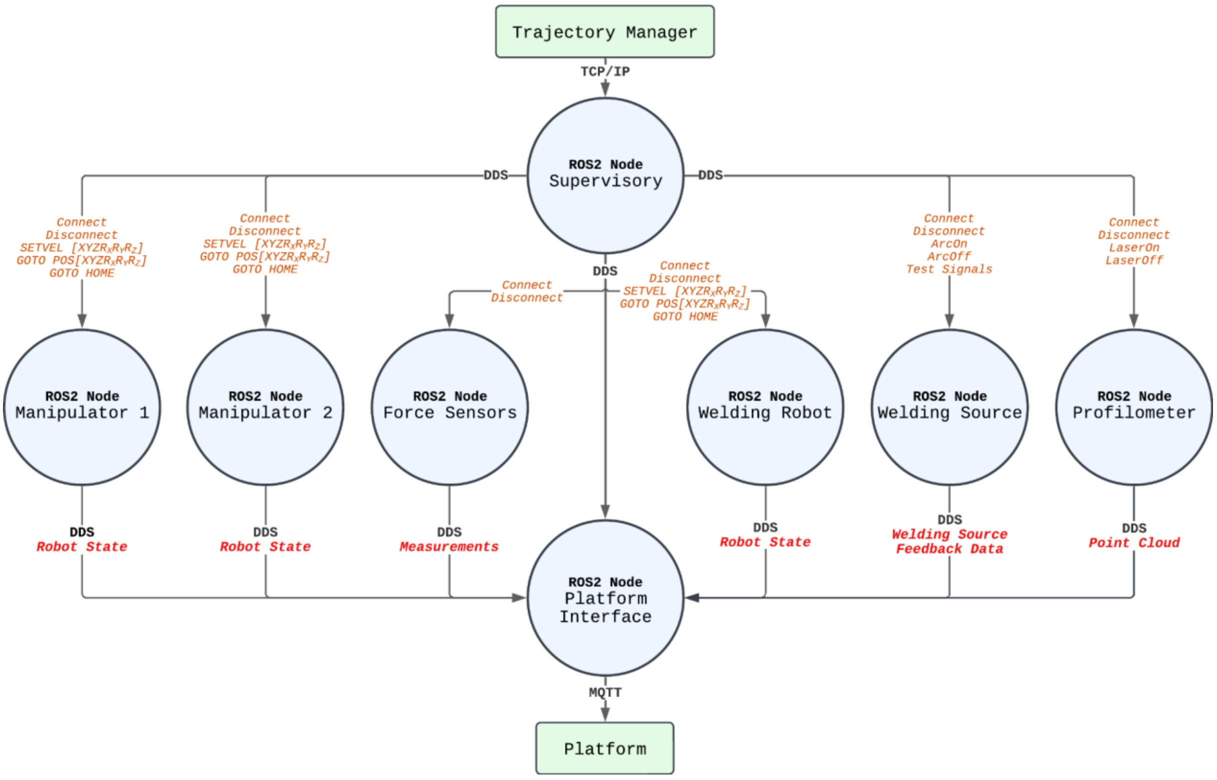

Figure 8. ROS2-based architecture diagram

Finally, a basic control node has been developed to synchronously operate the cell until the final control system is deployed in further stages. This node consisted of classical control algorithms in a cascade configuration.

2.3 FUTURE WORKS

At the time of drafting this document, a vendor agnostic coordinated movement and welding control has been developed. The controller synchronizes the movement of 18 axes, comprising the three six-axis robots, and integrates the other processes involved. However, the ambition of COROB goes beyond just synchronization, but fully integrated cooperation, where the actions of one robot affects the others and vice versa.

During jigless welding, the two manipulators cooperatively manipulate a workpiece exposed to dynamically changing forces. The two manipulator robots need to oppose these forces to precisely ensure the position within tight tolerances. Built-in robot control algorithms fail in this task.

To do so, an adaptive impedance control will be deployed in the arc welding use case. Impedance control regulates the force and motion of the robots simultaneously. However, due to the dynamical nature of the process, the impedance control to be deployed need also to dynamically adapt. A reinforcement learning algorithm will be trained to optimally tune the impedance parameters on the fly.

The transition from the presented movement synchronization algorithm to an adaptive impedance control will be facilitated by our controller metamodel architecture. This design approach allows for the seamless integration of the new control strategy without necessitating a complete system overhaul. The metamodel not only streamlines this update process but also provides flexibility for future enhancements, resulting in a more adaptable and robust control system. In addition, MLOps will be integrated with RL for continuous autonomous learning. The MLOps pipeline will enable the RL agent to process live environmental interactions without manual intervention, transforming the control system from a static implementation into an adaptive learning organism.

As presented before, the current cell status is also ready to communicate with the COROB platform, that will be integrated in further stages. The platform will serve as a centralized hub for collecting, processing, and managing data from various components within a manufacturing environment. This is achieved using connectors that interface with different devices and systems, ensuring seamless data flow with the legacy equipment. The platform also excels in data visualization and analytics, providing dashboards that display information in user-friendly formats.

The integration of the platform will allow future interconnection of multiple internal and external solutions, following the architecture presented in

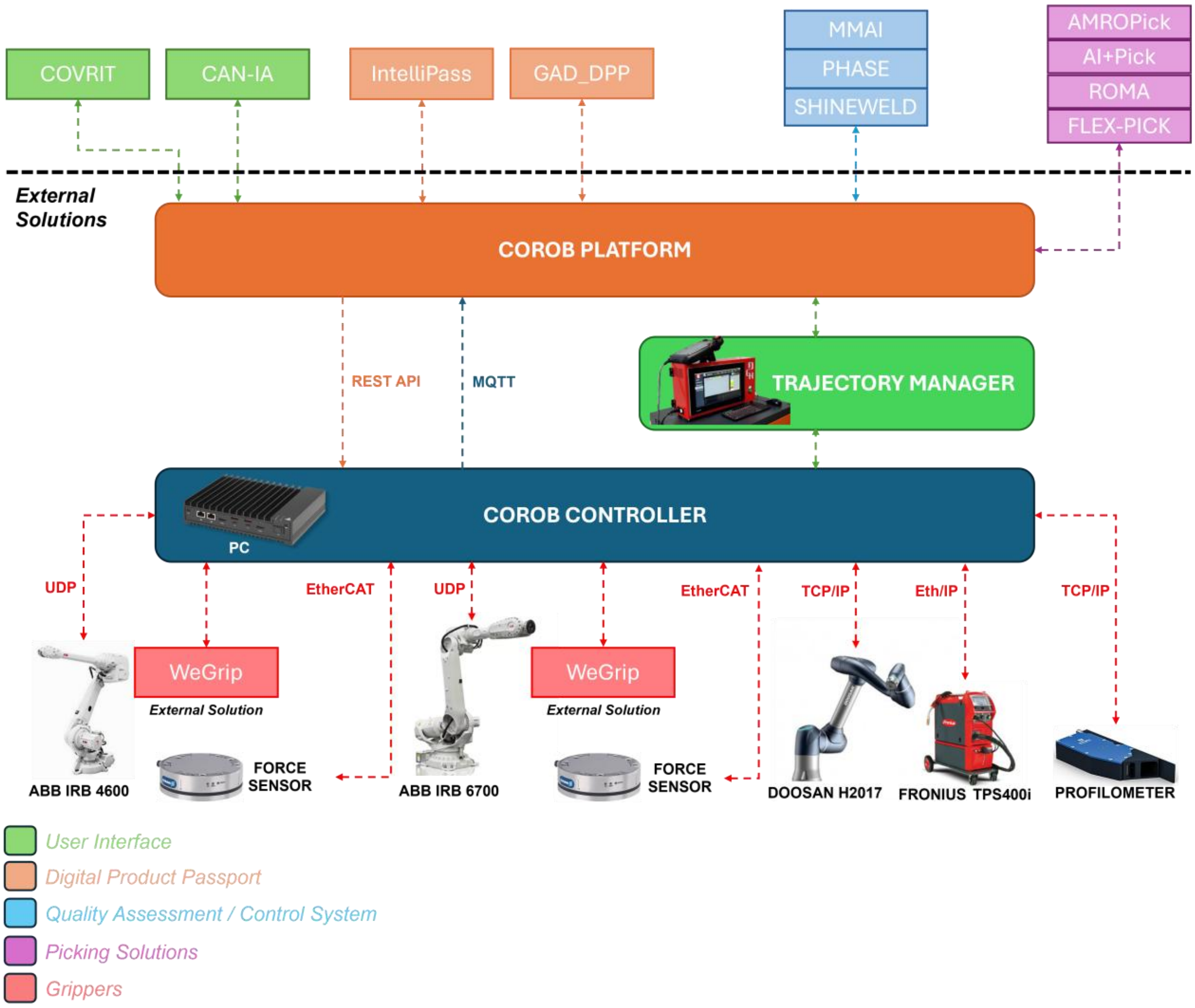

Figure 7. The external solutions proceed from the beneficiaries of the two open calls. Being:

- COVRIT and CAN-IA user interfaces. These two solutions consist of a traditional user interface and a virtual reality environment that will let the operators interact with the cell in a user-friendly manner.
- IntelliPass and GAD_DPP digital product passports.

- PHASE, SHINEWELD and MMAI quality inspection methods. These methods represent different solutions for welding quality NDT. They leverage advanced AI models with the inputs coming from high-speed cameras, spectrometers and electrical parameters to provide anomalies in process time.

- AMROPick, AI+Pick, ROMA and FLEX-PICK provide different solutions for precisely picking the parts to be welded.

Finally, the **Trajectory Manager** will assists in the generation and parameterization of robotics programs, enabling the automatic creation of robot trajectories in real time. It is designed for high-density line robot programs and provides real-time 3D representation of robots. It will allow for easy updates of code in the robot program and real installation to the simulator with a single click. Additionally, it will convert simulated trajectories into real ones seamlessly, analysing reachability conditions. The main power of this software is that it can be managed by non-expert operators in the production process.

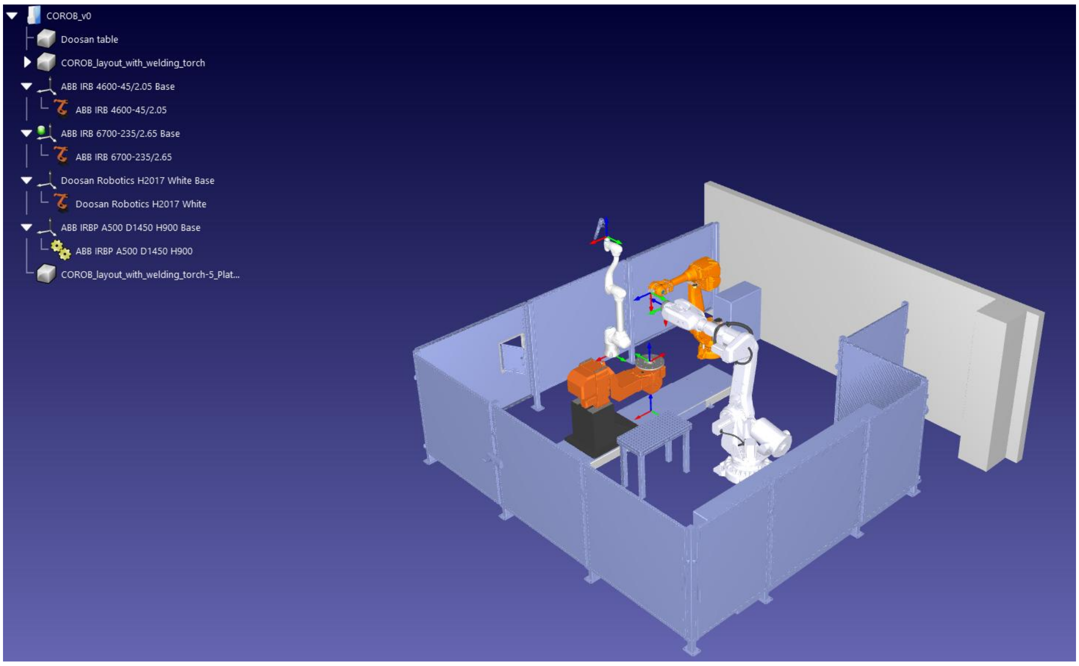

Figure 9. Preliminary simulation in TM

3 MULTI-ROBOTIC CELL FOR WAAM REPAIR

3.1 PRESENTATION OF THE LAYOUT

Repairing of tools has traditionally been performed through welding processes or cladding. The latest years, Direct Energy Deposition (DED) Additive Manufacturing (AM) / DED-AM has been employed for repairing of high-value products. Specifically, WAAM can offer several advantages such as high-deposition rates and with optimized configurations minimized local heat input, in a wide range of materials, using lower-cost fillers in comparison with other AM processes.

The second use case deploys COROB solution for the development and demonstration of a Multi-robot cooperative WAAM (Wire Arc Additive Manufacturing) solution for repairing existing, large-scale, and high value components by additive manufacturing, contributing to resource savings, enhanced circularity, and reduction of costs.

This solution includes the use of a Main Industrial robot for the WAAM operations, a rotational unit to withhold the workpiece, a Collaborative Robot for the auxiliary manufacturing operations, a WAAM system, a 3D scanner, coordinate referencing devices and the use of commercial and custom-developed software tools, for the generation of the trajectories to be followed by the robots.

The current state of high-mix low-volume (HMLV) market scenario requires constant changes in jobs, materials, and machines. Therefore, the WAAM use case needs to be built upon flexible and intelligent manufacturing principles, allowing the fast adaptation of process and processing equipment, in order to assure first-time-right products, with optimal manufacturing efficiency, at the highest quality.

The challenges that have been identified in a high-level and will be solved through COROB for the WAAM use case are categorized in the pre-processing, processing, and post-processing phases.

The pre-processing challenges rely to the digitalisation and coordination of the necessary information in order to generate the repair toolpaths.

The WAAM processing flexibility relies mainly on the toolpath generation, therefore on software perspectives, as well as that if the processing head is compact enough to be manipulated freely in tight areas, with a high level of dexterity. During WAAM processing, monitoring of the process is necessary as it is hard to trace-back any defects due to the repaired area of the workpiece being formed in a layer-by-layer manner specially in detecting sub-surface imperfections after the product has been repaired.

Finally, the post-processing phase involves mainly the evaluation of the quality of the repaired product.

The multi-robot COROB WAAM use case cell, first consists of a 6 DOF industrial robot, the YASKAWA GA50 which is responsible for gripping the WAAM torch and executing the WAAM process.

The GA50 robot is designed for applications that require high precision and path accuracy. It provides a payload of 50 kg and a high reach of 2,038 mm, which allows processing of large workpieces. In combination with the advanced Sigma-7 servo drive technology and tolerance-optimized precision gearboxes, this manipulator achieves very high positioning and path accuracy paired with high mechanical stiffness [6]. A 2 DOF rotary table, the DK-250 [7] with 250kg of payload has been selected to position and withhold the workpiece to be repaired.

Next, the UR10 collaborative robot has been selected for the auxiliary manufacturing operations, where human oversight and decision-making is still necessary. This initially includes the 3D scanning, the coordinate referencing and a preheating system that will be supplied from the 2nd COROB open call.

For the WAAM process, the Power Wave® S500, with a separate wire feeder made by Lincoln Electric will be used [8]. Initially due to hardware availability the COROB WAAM use case has been deployed with the use of a GYS WAAM machine.

For the WAAM use case there was freedom in the positioning of the robotic infrastructure. Therefore, the available working space as well as the dexterity of the YASKAWA GA50 that is responsible for the execution of the WAAM process, must be maximized in the workpiece area. This will allow freedom in the generation of geometrically complex WAAM toolpaths. Furthermore, the working envelope of the YASKAWA GA50 should be placed in a way to ensure scalability of the proposed solution to other workpiece placements (e.g. large workpieces positioned on the floor).

The dexterity of a robot performing a manufacturing process that involves complex and continuous toolpaths is significantly important. Calculating and analysing the dexterity of a robot in a manual manner, is really difficult and mentally overwhelming for humans. Therefore, to define the area with the highest level of dexterity and reachability of the YASKAWA GA50 robot and to accurately position it in relation to the rotary table (workpiece area), a layout optimisation tool that has been developed within COROB has been used (for more details see our latest publication [3]).

The results from the layout optimisation procedure demonstrated that the robot shall be lifted by 400mm on the Z-axis while the horizontal distance of the robot's base centreline, with the rotational unit center point should be on approximately 1500mm. In colormap are depicted in Figure 10 the results per point in the reachability map (see more details in [3]).

Lower-level dexterity points that are located in the higher heights may be mitigated, by using the two extra DOF from the rotary table, by repositioning the workpiece through tilting and rotating it, to a higher dexterity point, through the CAM software.

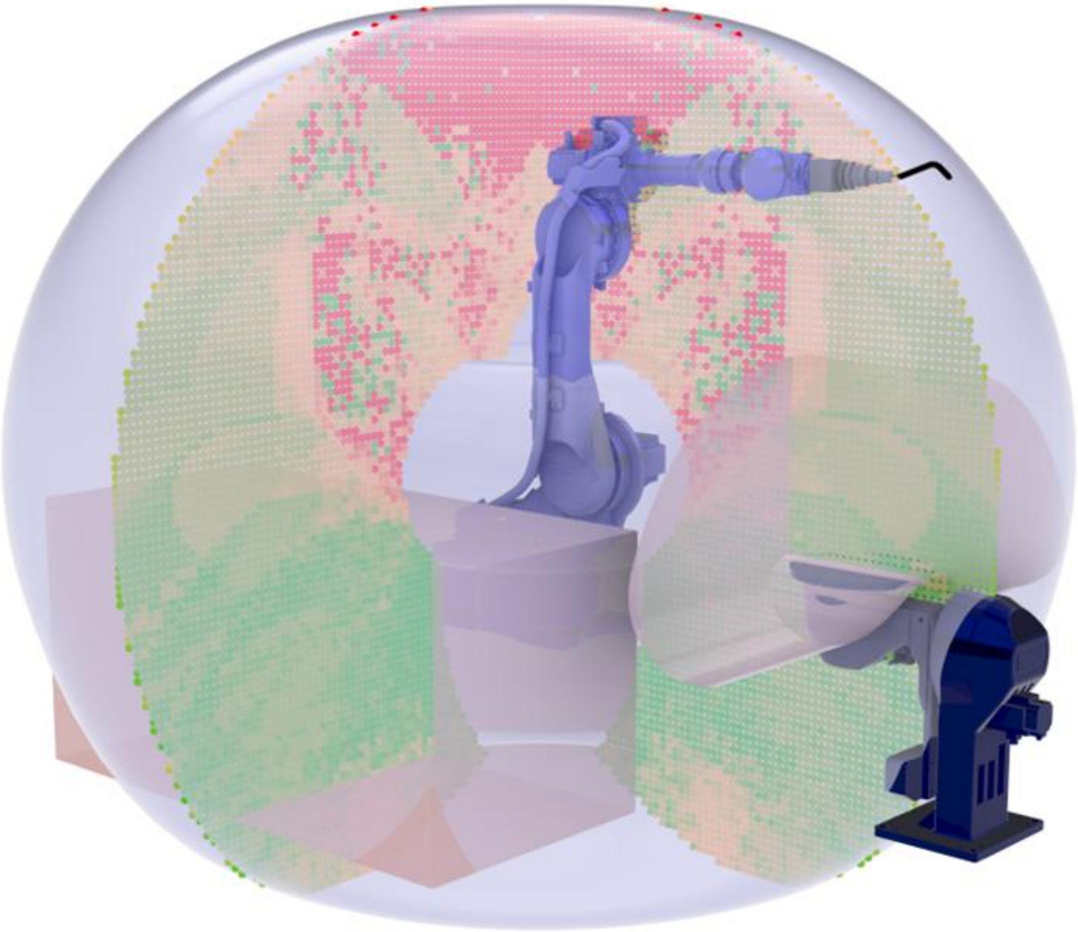

Figure 10: WAAM use case layout optimisation results

The mounting of the robot should be as rigid as possible to minimise vibrations during rapid acceleration movements. To ensure the robot remains stable during operation, particularly during rapid movements, and to minimize vibrations that could affect process stability, a high-quality robot pedestal was used to elevate the robot as well by 400 mm, satisfying the optimisation positioning needs.

For the cobot, it should be able to reach the workpiece area in order to conduct its auxiliary tasks. Its dexterity is not critical. Its reachability is sufficient to access the workpiece; however, it must be elevated along the vertical (Z) axis to bring its base closer to the workpiece plane. To ensure flexibility in positioning along the Z-axis, the base will have an automatic mechanism to adjust the height of the cobot so it can handle the different sizing of the workpiece.

Additionally, the cobot should be able to be positioned in a way to satisfy its operational requirements but not interfere the operation of the YASKAWA GA50 robot. Therefore, a movable base through caster wheels has been designed, so that the cobot can freely be moved in the processing area. An initial 3D printed gripper has as well been designed and manufactured for the conduction of the initial tests. The design of the gripper will be updated and finalized during the integration of the external solutions.

The designed layout of the cell for the WAAM use case is illustrated in Figure 11, while the physical layout of the cell is presented in Figure 12.

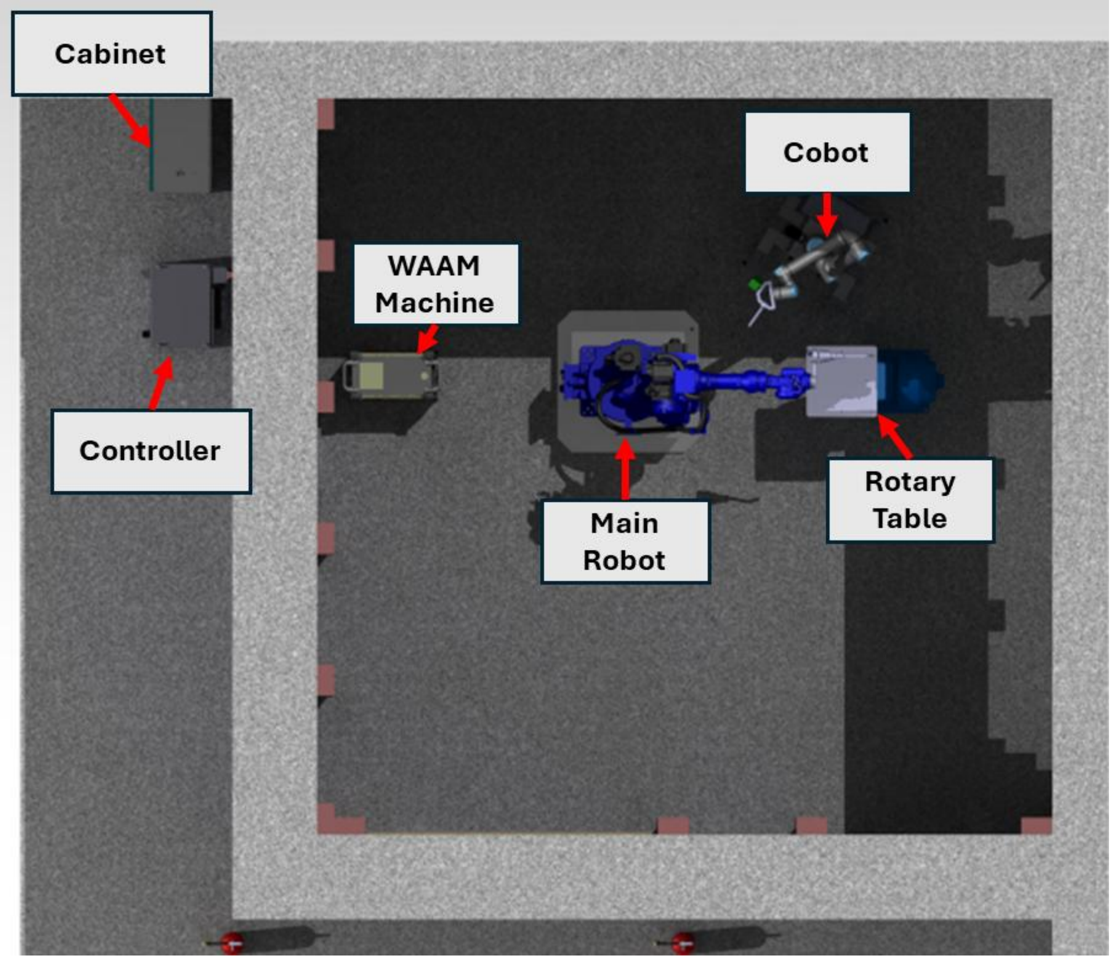

Figure 11: WAAM Cell Layout - Top View

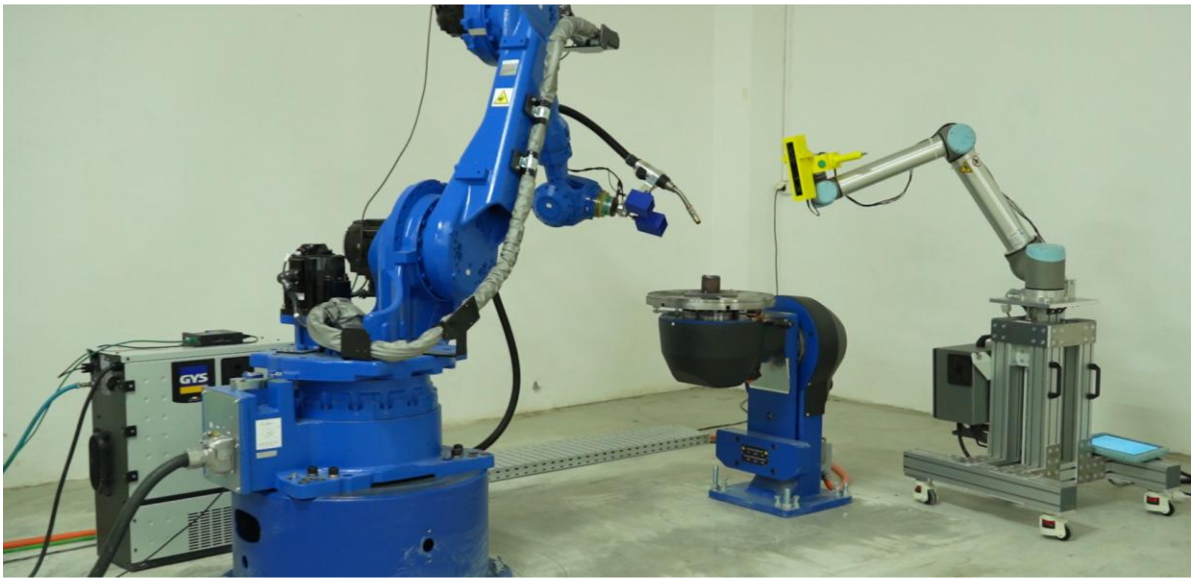

Figure 12: COROB WAAM use case physical layout

For monitoring the process an initial set of sensors have already been installed in the cell, a thermal and an optical camera. The thermal camera allows the assessment of features related to the heat input of the process, thus how heat is distributed, etc., while the optical camera allows the generation of optical features that can be better utilized to assess geometrical information. Additional sensors to monitor the process will be installed later on through the external solutions provided by SMEs, funded by the COROB Open call. The cameras have been integrated in close proximity with the torch, as presented in Figure 13.

Figure 13: Initial sensor location - WAAM use case

3.2 TECHNOLOGICAL ADVANCEMENTS

Within the first 18 months, efforts have been placed on investigating current practices both in terms of hardware and software related to the WAAM use case, to subsequently design, deploy and operationally verify a multi-robot phygital infrastructure that is able to accommodate the project's internal and external developments, leveraging data and AI technologies as its foundation.

The core of the technological advancements in this use case is the redistribution and redesign of the WAAM workflow, in alignment with the Industry5.0 principles. In industrial practice, manufacturing operators typically specialize in either robot operation, or process knowledge, but rarely both. This use case, targets operating audience with relative process knowledge (e.g. welding) rather than requiring them to be robot and AI experts. Rather than relying on fully automated processes, that would require extensive programming skills and resources, the human flexibility is leveraged where it provides the most value.

At the end, this approach is expected to reduce the time and the effort required to reconfigure to new product variations, as a response to the high-mix-low-volume manufacturing scenarios of repairing high value products through WAAM.

The overall architecture of the WAAM use case is presented in Figure 14.

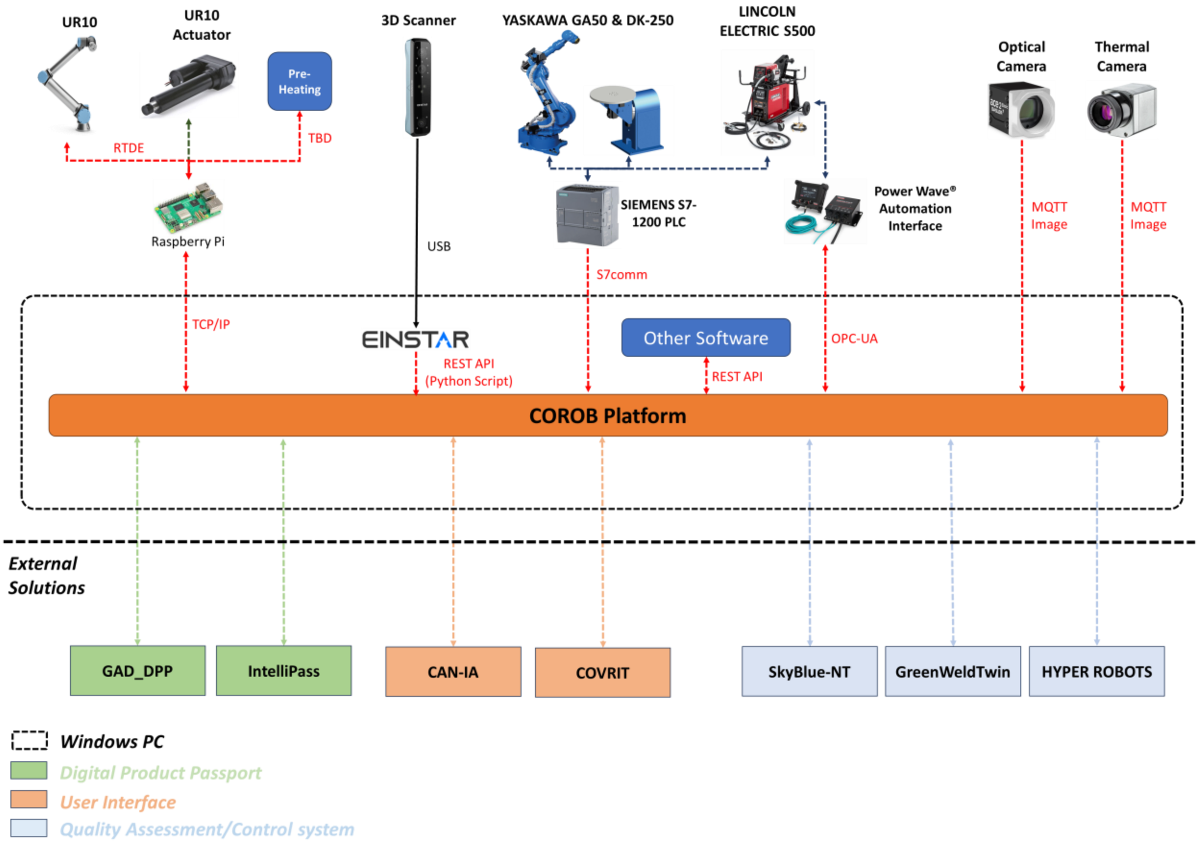

Figure 14: COROB WAAM use case architecture[1]

For enabling data interoperability and cross-operation of different assets, the COROB AAS-based platform is deployed, where legacy equipment is connected to it through the appropriate data connectors (MQTT, OPC-UA, REST, etc.), that is responsible for handling, storing, and managing data interactions, ensuring interoperability and seamless interactions across these.

The cell, except for the collaborative infrastructure, is operated through a Siemens PLC, which manages the core equipment control. To enable access to process data and interaction with software tools for the WAAM process, a dedicated connector has been developed that attributes data from the PLC and links it to the COROB AAS-based platform that is installed in a PC. This interface allows data to be accessed for process monitoring, analytics, or other functions as requested. In parallel, it enables the easy integration of additional tools, and supports the deployment of new functionalities, thus providing a flexible and scalable digitalization approach on the cell.

A RaspberryPi serves as the middleware for interconnecting the different assets of the collaborative infrastructure (UR10 cobot, UR10 height level adjustment actuator, preheating solution-to be funded as external solution from the 2nd COROB open call) with the COROB platform. A height level adjustment actuator is used to expand the cobots reachability map. Data transmission to the network is enabled from the RaspberryPi to the Windows PC where the COROB platform is installed.

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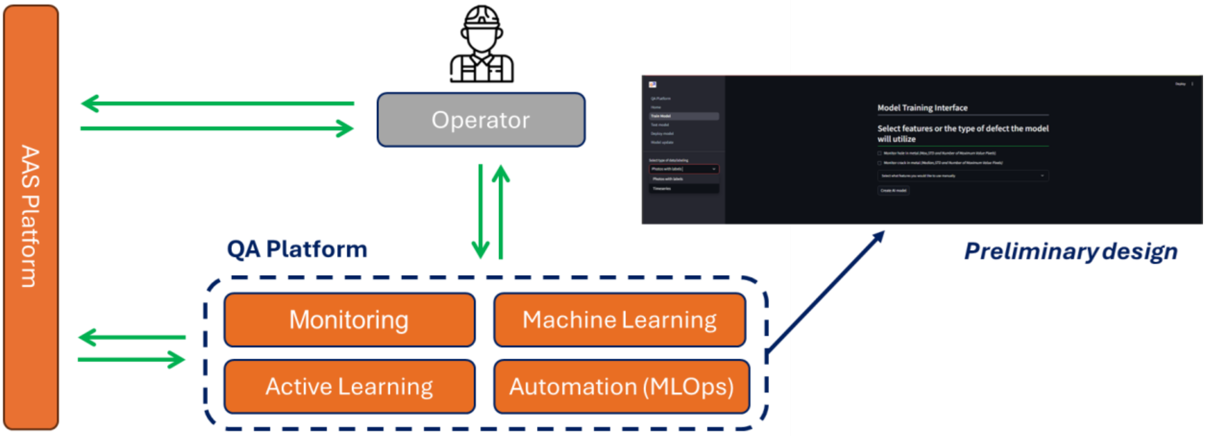
[1] The use case architecture is represented with the LINCOLN WAAM machine, with which at the end will be finally deployed.

The 3D scanner [9] includes rather than the hardware, its own vendor-specific software for operation. The data extracted from the 3D scanning solution are the generated point clouds, that are further processed in other software tools, for process planning. These point clouds will also be part of the product's Asset Administration Shell (AAS) and Digital Product Passport (DPP), providing the digital representation of the product across its lifecycle of repair. A custom script will retrieve the latest point cloud and connect it to the AAS via REST-triggered workflow events.

Furthermore, the use case integrates multiple sensing elements that can provide real-time data to generate insights on the WAAM process. An initial set of AI models for process monitoring will be developed. Active Learning functions will be subsequently integrated to enable interaction with the process monitoring models, to utilize operator's critical thinking and expertise, into refining the accuracy of the models over time.

These models and the Active Learning methods are wrapped in a digital tool, namely the Quality Assessment (QA) platform, that utilizes MLOps Level 2 strategies to enhance CI/CD capabilities. The operation of this platform is not only tailored for Data Engineers or Machine Learning experts. The overall design considers the non-expert nature of the user (manufacturing operator/expert) and simplifies both the creation and training of the models, as well as the creation of continuous automation. Figure 15 depicts the workflow between the operator and the QA platform as well as the COROB AAS platform.



Model Training Interface

Select features or the type of defect the model will utilize

Figure 15: Interaction diagram between the operator and the two platforms

The utilization of the collaborative robot for auxiliary tasks, makes the system easier in use, as well as more flexible, as it allows easily the integration of additional systems, such as NDT. Unlike industrial robots, cobots are not complex in programming, usually operated through simple user interfaces. Cobots are as well equipped with built-in safety systems, allowing humans to safely work around them. This means that operators can still intervene, when necessary, e.g. when 3D scanning errors occur, without the need for extensive reprogramming.

Regarding the WAAM process, its flexibility is directly tied to the process and path planning capabilities. Typically, either vendor specific CAM tools are provided for operating a WAAM cell, or through the use of existing commercial tools. Rather than replacing existing technologies, COROB complements these through deploying Human-focused sub-technologies for intuitive robot path planning that significantly simplify the process planning and lowering the skills barrier for wider adoption.

Additionally, a layer height control system will be installed as an external solution funded through the COROB open call, that will override the stand-off-distance of the robot from the workpiece, in case over or under material deposition is detected.

At the end, the operation of the cell will be conducted through a human-friendly user interface that guides the operator in a step-by-step workflow.

3.3 FUTURE WORKS

At this stage we have reached a key milestone, where the phygital WAAM use case main infrastructure has been operationally verified. Preliminary designs of the internal and for most of the external solutions already exist. Already some of the internal solutions are ready for initial integration and testing.

The next steps will focus on further refining the needed process development of the WAAM process for quality, where the operating process windows that ensure process quality, efficiency and repeatability will be established.

In parallel, efforts will be placed on finalizing, deploying and testing the human-focused process planning tools. The AI based process monitoring models will be tested and initially validated. Subsequently the Active Learning schemes will be integrated into the MLOps Level 2 CI/CD pipeline.

The different WAAM use case assets will be interconnected and made interoperable with the COROB Digital Platform. The different external solutions on the topics of DPP, User Interfacing, Quality Assessment and a solution for layer height control for managing over or under deposition of material will be integrated, tested and validated in the use case.

Initially few test cases will be defined internally within the consortium for an initial, small-scale validation. Following this, an open invitation will be extended to external end users to select one or more application scenarios, relevant and challenging to the use case, to be tested and validated across the complete COROB WAAM use case workflow.

4 CONCLUSIONS

The main conclusion of WP1 is that the two use cases are ready to integrate the COROB solution. The two robotic cells are prepared to enable cooperation between the robots and to support the integration of AI models for process improvement. In addition, the use cases are configured to capture data and transmit it to the platform, which will enable data-driven decision-making and ensure traceability. The cells are also ready for the integration of external challenges to be developed in the next phases.

Regarding UC1, starting from a existing robotic cell, the system was thoroughly transformed by incorporating a collaborative robot and deploying a complete ROS2-based control framework. As a result, the cell's operational approach has been entirely redesigned, now offering a fully modular and flexible architecture with increased control over its components.

In relation to UC2, the work began from scratch with the construction of a completely new robotic cell, composed of various robots and devices. Starting from the initial design phase, the cell was successfully deployed and prepared for the integration of internal and external COROB solutions.

4.1 LESSONS LEARNT

A key lesson from this phase has been the critical importance of close collaboration between project partners, which enabled effective integration of new technologies and rapid problem-solving in both use cases. Additionally, early planning for testing, data capture, and future integration proved essential for successfully deploying both the upgraded and newly built robotic cells.

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