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ARISE

All-in-one middleware for industrial
human-robotic-interaction

DELIVERABLE

D4.2 Full Description of TEF's Setup and Use Cases

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List of Acronyms

AI	Artificial Intelligence
API	Application Programming Interface
CPS	Cyber Physical System
DDS	Data Distribution Service
FSTP	Financial Support for Third Parties
GUI	Graphical User Interface
HMI	Human Machine Interface
IIOT	Industrial Internet of Things
IT	Information Technology
LED	Light-Emitting Diode
LLM	Large language Model
OS	Operating System
OT/IT	Operational Technology/Information Technology
PC	Personal Computer
PLC	Programmable Logic Controller
RAM	Random Access Memory
RGB	Red Green Blue
ROS	Robot Operating System
ROS4HRI	ROS for Human-Robot Interaction
SSH	Secure Shell
TEF	Testing and Experimentation Facility
TRL	Technology Readiness Level
VR	Virtual Reality

1. Introduction

1.1. Scope and purpose

The ARISE project hosts four Testing and Experimentation Facilities (TEFs) on industrial Human-Robot Interaction (HRI). One of the major objectives set for these TEFs is to showcase how the ARISE project tools can help end user industries and solution providers address their business problems using human-centric, AI powered, and robotics-based automation solutions. The TEFs will also help to establish the requirements for the ARISE middleware and SSH frameworks based on their exemplary cases.

To achieve that objective, each of the TEFs is going through a systemic and iterative process which includes the following major steps:

1. Selection of two major industrial challenges which are relevant to the human-robot collaboration domain.
2. Design a meaningful setup which allows to run experiments on relevant problems that are associated with the selected challenges.
3. Narrow the scope of the selected major challenges down to specific end user problems and derive a concise list of requirements from those problems.
4. Specify a collection of target capabilities which are relevant to solution providers because they enable and/or accelerate the creation process.
5. Analyze the strengths and weaknesses of ARISE project tools.
6. Design, implement and experiment on a proof of concept and solution demonstrator that runs in the TEF setup and leverages the ARISE project tools.
7. Generate feedback and new requirements for ARISE project tools and start a new iteration from step 2.

Deliverable 4.2, titled "Full description of TEF's Setup and Use Cases", represents the set-up of experimental facilities for their proposed use cases. The scope and purpose of this deliverable is to document the first major iteration of the aforementioned process. The results, lessons learned and generated feedback are essential to evolve and better prepare the hosted TEFs for giving effective support to the external experiments that ARISE will run in the next phases of the project.

1.2. Structure of this document

This document is structured in five main sections. Section 1 is dedicated to introducing the purpose and scope as well as the structure of the document.
Section 2 briefly describes the tools and enablers that will be offered by ARISE project. Section 3 represents a general description of four ARISE Testing and Experimentation Facilities detailing their infrastructure and software architecture.
Section 4 shows the roadmap of integration of ARISE framework within each TEF providing the requirements and expected results while Section 5 concludes this document.

1.3. Contribution from Partners

PARTNER AND SHORT NAME	CONTRIBUTION
POLIMI (**POL**) TEF 4 owner T4.2 leader D4.2 leader	POLIMI is responsible for the T4.2, "Initial TEF's setup", as well as the leader for deliverable D4.2. In this document POLIMI has reported the ARISE TEFs initial setup respecting the requirement and results from T4.1. In addition, a general description of POLIMI TEF as well as its roadmap in order to address the assigned challenges applied in exemplary use cases benefiting from ARISE tools and enablers have been mentioned.
CARTIF (**CAR**) WP1, WP4 leader TEF1 owner	In this document CARTIF has contributed to improvement of the structure of the document as well as describing their TEF and the journey that they will take in order to solve assigned challenges taking the advantage of project tools.
FIWARE (**FF**) WP2, WP7 leader	In this document FF has contributed to improvement of the structure of the document as well as explaining the tools that will be offered by the ARISE project.
INTELLIMECH (**INT**) WP6 leader TEF 2 owner	INT has presented its TEF infrastructure including hardware and software architecture to adopt ARISE tools with the aim of facilitating application use cases defined within the project challenges while the expected results have been depicted as well.
PAL Robotics (**PAL**) TEF 3 owner	PAL has reported their existing facilities and the steps to integrate ARISE enablers in their application use case. As a TEF, PAL also has mentioned their remapping of software architecture to include developed enablers.

Table 1: Partners contributions

2. ARISE Project Tools

The ARISE project is working on two major tools which aim to accelerate the creation of human centric, AI powered, and robotics-based solutions for industrial end users:

- **Tool 1: the *ARISE All-in-one middleware***, which is an integrated middleware solution with multiple tools and utilities to help solution providers reduce the costs and efforts required to design and implement complex industrial HRI projects. Main components and features of the ARISE All-in-one middleware are:
  - Vulcanexus: an open source and performance-focused ROS 2 All-in-One tool set which guarantees a fixed middleware implementation to guarantee optimized robot development. At its core, Vulcanexus brings an open and off-the-shelf middleware solution that enables distributed communications while keeping great real-time performance in terms of latency and determinism. Thus, the main role of this ARISE tool will help solution providers deal with the complexities of and minimize the efforts in configuring all the necessary elements of software integrations on top of their PLC and control unit networks.
  - DDS Enabled Context Broker Technology: the all-in-one industrial middleware must support OT/IT convergence between the distributed CPS communications enabled by Vulcanexus and those communication networks established by co-existing IIoT and industrial IT systems. FIWARE's Context Broker technology, the Open Standard API NGSI-LD, and Smart Data Models are the ARISE tools responsible for enabling the seamless interoperability between OT and IT systems.
  - ROS4HRI: The ROS REP-155[1] (aka, ROS4HRI) defines a set of topics, naming conventions, and frames that are important for HRI applications[2]. The tool contributes with a reference approach and a series of best practices to accelerate the design and implementation of HRI features which are seamlessly integrable with the all-in-one middleware.
  - Library of AI Powered components for industrial HRI: ARISE aims also to contribute AI-powered and ready-to-use robot skills for HRI as plug-and-play extensions to the all-in-one middleware. On the one hand, the library will integrate a selection of existing off-the-shelf components which are easy to integrate with all in one middleware. On the other hand, the library will integrate the novel HRI components resulting from a series of FSTP projects on industrial HRI that ARISE will carry out. The creation of the library is part of ARISE's ongoing work, and the initial list of components is intended to be published by the last quarter of 2024 when the open call process for funded projects will start.
- **Tool 2: The *ARISE SSH Framework* for human-centric and agile HRI** – a collection of specifications, recommendations, and guidelines, as well as a collection of reference

[1] https://www.ros.org/reps/rep-0155.html
[2] https://ieeexplore.ieee.org/document/9636816

use cases that aim to ensure that industrial HRI projects are safe and consider a wide range of ethics related questions throughout the lifecycle of the technologies.

The Framework is not a one-size-fits-all solution to the ethical, legal, and societal (ELS) aspects of industrial HRI, but is rather a toolkit to ensure contextualized, human-centric innovation in different use cases. Taking as its starting point the broad range of existing tools, guidelines specifications related to AI, robotics and HRI (e.g. AI-HLEG guidelines and assessment list, AI-on Demand Platform, Ethics-by-Design guidelines, DIH2 Network, DIH-HERO, RIMA Network industry approaches) the ARISE SSH Framework is developed and built up during the ARISE project with close collaboration with the project consortium as well as funded FSTP cases.

The first release of the SSH Framework, including the different guidelines, principles and specifications to support the ARISE experiments will be published by the end of 2024. The aim is to help designers effectively address some of the challenges associated with key aspects of human-centricity such as: privacy and data governance, worker safety, autonomy and agency, legal uncertainty and liability, accountability and oversight, transparency, trustworthiness, explicability, wider societal implications, gender, environmental implications, non-bias and non-discrimination, fairness, inclusion, and participation.

3. Description of ARISE TEFs

In this section, an overall description of four ARISE TEFs has been presented with focusing on hardware and software architecture hosted at each TEF.

3.1 TEF 1 - Experimental Robotic cell for Complex Picking and Dismantling Applications [CARTIF]

3.1.1 TEF Overall Introduction

CAR provides TEF1, its Pilot Factory at TRL4.5, a facility to create relevant scenarios for testing and experimentation in Human robot collaboration (HRC) context. Our facility is dedicated to advancing the field of human-robot interaction (HRI) within industrial production and logistics settings, simulating industrial production and logistics operators who engage directly with robotic systems, as well as developers seeking to innovate and optimize HRI technologies.

TEF1 provides experimental design support in designing and conducting experiments related to human-robot interaction, evaluating robot behavior adaptation algorithms, testing, or assessing the impact of collaborative tasks on productivity, this facility offers the necessary resources and expertise. The TEF's users are involved in manufacturing, assembly, and logistics operations, utilizing the facility to test and evaluate robotic systems designed to streamline production processes, developing new algorithms and control strategies for human-robot interaction, making robots more intuitive, adaptable, and collaborative and also improving efficiency and enhancing workplace safety.

Figure 1: a) Pilot cell at CARTIF b) User interacting with cobot via Hololens 2.

TEF1 offers diverse experiments and experiences aimed at pushing the boundaries of Human-robot interaction (HRI) in industrial environments as follows:

- Adapt the robot behavior to the operator's conditions: it focuses on developing algorithms and systems that allow robots to adapt their behavior based on the condition and preferences of the operator.

- Identification of complex objects to proceed with their handling: it involves developing computer vision and machine learning techniques to enable robots to identify and classify complex objects within their environments.
- Human-Robot interface using XR (Extended Reality): using extended reality (XR) technologies, to create intuitive and immersive interfaces for robot interaction, XR interfaces overlay digital information or virtual objects onto the physical environment, allowing users to interact with robots in a more natural and intuitive manner.
- Human-robot interface using natural language: it focuses on developing natural language tools that enable humans to interact with robots using spoken language commands. By understanding and interpreting natural language input, robots can respond to verbal instructions, questions, and requests from operators in real-time.

Among many possible scenarios in the ARISE project CAR will focus on two challenges: a) dismantling and/or assembly of high value-added products and (b) complex picking in warehouse environments. TEF1's overarching goal is to enhance HRI and collaboration in industrial settings, driving productivity, efficiency, and safety improvements across industries. By fostering collaborative research and development, TEF1 aims to integrate robotic systems seamlessly into existing workflows, augmenting human capabilities, and driving transformative changes in industrial production and logistics. Ultimately, TEF1 serves as a catalyst for innovation, empowering users to unlock the full potential of collaborative robotics in industrial environments.

3.1.2 Hardware Equipment

In this section it is presented a comprehensive description of TEF1 hardware infrastructure that includes mainly robots, center table, cameras, grippers, and mixed-reality glasses as follows:

1-Robots:

Figure 2: a) UR5e b) UR10e c) SCARA.

- The **SCARA THL600 robot** from Toshiba can handle up to 10 kg and reaches 600 mm. It's very handy for light-duty tasks. It can move in four directions and rotate 360 degrees, making it very flexible. The setup process is quick and easy, ensuring efficient implementation.

- Initially, the **UR5e robot** was installed, followed later by a **UR10e** around a central table. Both robots are from the Universal Robots brand and can handle 5 kg and 10 kg respectively. These types of robots are collaborative, meaning they can work alongside human operators without the need for a protective cage. Additionally, the way they're positioned around the table allows them to interact with each other, making them a great option for a variety of tasks in industrial environments.

2-Centre table:

- Both robots are located around a central table, allowing the operator to work collaboratively with the robot. LED lighting has been incorporated into this table, which can be controlled to provide alerts or indicate the operating location for the worker, as each LED is independent. Additionally, a JXCP1 linear guide has been added to the table, which is connected to the PLC and can be controlled easily and effectively through the HMI of the controller. This allows for automatic operation with the robots or manual control of the guide.

3-Cameras:

Figure 3: Intel RealSense D435 b) Sick Visionary-T Mini c) KT&C KNC-hms6330 d) Luxonis OAK-D PRO W POE.

- The **Intel RealSense D435 camera** is known for its ability to accurately capture detailed three-dimensional environments. It uses depth sensors and stereoscopy to measure distances between objects and create point clouds. Widely used in industries and for tasks such as quality control, it excels in task automation. It can detect depths from 0.3 to 3 meters and is highly accurate, especially at 2 meters. The camera produces high-resolution depth images and RGB images, and it is small and easy to connect to devices using a USB-C cable.

- The **SICK Visionary-T Mini depth camera** delivers accurate three-dimensional data essential for determining object volume. It's notable for its Python integration, making programming and accessing its functions easier. With a balance of resolution and speed, it captures up to 30 full-resolution 3D images per second. Its compact and robust design suits various industrial applications, with a wide operating temperature range and IP65/IP67 protection. It uses industrial Gigabit Ethernet for efficient 3D data transmission and offers additional software solutions like 3D object detection and image processing.

- The **KT&C KNC-HMS6330 IP** camera provides a feed at 1080p of the robotic cell. The camera is placed in one of the walls pointing downward to the centre table.

Additionally, this camera can be used for security purposes, capable of recognizing individuals or detecting if someone has entered the robots' working range.

- The **OAK-D PRO W POE** camera from Luxonis is another depth camera with active stereo capabilities with an on-device Neural Network inferencing and Computer Vision capabilities. As for FOV, the camera provides 150º for the central RGB camera and 150º for stereo depth image.

4-Grippers:

- The **OnRobot VGP20 vacuum gripper** is a tool specifically designed for palletizing boxes. Being an electric vacuum gripper, it eliminates the need for pneumatic systems, resulting in increased efficiency and flexibility in load handling. With the ability to suction a variety of boxes with different shapes and porous surfaces, it provides great versatility. Despite being electric, it can handle loads of up to 10 kg when paired with the appropriate robot. Its easy setup and compatibility with various robot brands make implementation quick and straightforward. In our application with the UR10, we have safely handled loads of up to 7 kg, thanks to its suction loss detection features that ensure safe operation.

Figure 4: VGP20 Vacuum Gripper.

- The **Robotiq Hand-E Gripper** is a versatile solution for grasping objects of various shapes. Its simple setup allows for adjusting the gripping force, making it suitable for handling delicate objects with precision. With power and control integrated into a single cable, it easily connects to the robot, as in our case with the UR5. Additionally, it comes with an adapter that extends its gripping range, allowing for easy manipulation of larger pieces. With built-in safety features, such as loss of grip detection, it offers reliable and safe operation in industrial applications.

Figure 5: Robotiq Hand-E Gripper.

5-MR Glasses: Microsoft Hololens 2

Microsoft HoloLens 2 is a leading augmented reality device designed to deliver an immersive and collaborative experience. Featuring a high-resolution holographic display that provides crisp and detailed visuals, HoloLens 2 offers an expanded field of view of approximately 52 degrees horizontal and 42 degrees vertical. This device is equipped with advanced sensors, including high-precision depth sensors, high-definition RGB cameras, and an integrated eye-tracking system. These features enable precise and natural interaction with three-dimensional holograms, as well as detailed spatial scanning of the physical environment. The gesture tracking technology of HoloLens 2 allows users to manipulate holograms with intuitive gestures such as tapping and swiping, facilitating design and collaboration tasks. Additionally, the device supports eye tracking, enhancing interaction and navigation precision.

Figure 6: Microsoft Hololens 2.

3.1.3 Software Architecture

In this section it is presented a comprehensive description of TEF1 software components that includes programming frameworks, operating systems and libraries used for the creation of the prototype applications for HRI.

ROS, Python (3.8.5), OpenCV, YOLO Ultralytics, Tensorflow, Pyrealsense2, Docker), Unity, s.

- **ROS (Robot Operating System)** is a software development environment for robots that uses a communication model based on the publisher-subscriber pattern. This model allows different robotic components, called nodes, to exchange information efficiently and in a distributed manner. ROS is an open-source platform, which means that its source code is publicly available and can be modified and improved by the developer community. This characteristic fosters collaboration and innovation in robotic system development, making ROS a powerful and versatile tool for researchers and developers worldwide.

- **Docker** is an open-source platform that enables developing, shipping, and running applications in lightweight, portable containers. These containers encapsulate everything needed to run an application, including code, dependencies, and runtime environment, ensuring consistent behavior across different environments. Docker simplifies container management through a client-server architecture, allowing developers to create and deploy applications quickly and efficiently. Additionally, Docker provides features like volumes that allow for persisting data between containers and the host system. In our case, we use Docker to create containers from ROS images, enabling us to develop, test, and deploy robotic applications in a reproducible and scalable manner. Docker's capability to manage and orchestrate containers makes it a valuable tool in modern software development and deployment.

- **Unity** is the graphics engine used to design and develop mixed reality applications that integrate with Microsoft HoloLens 2. The programming language used in this environment is C#. However, Unity's interface allows you to program instructions in an easy and intuitive way. Unity is a powerful tool for creating immersive experiences and interactive content, leveraging its robust rendering capabilities and physics engine. It supports a wide range of platforms, including augmented reality (AR), virtual reality (VR) and traditional games. Developers can use Unity to build complex scenes, integrate 3D models and animations, and implement interactive behaviors with ease.

General schema of the devices

This diagram shows the interconnection of all the devices we have in the cell and how they are interconnected with each other, including the protocols they use.

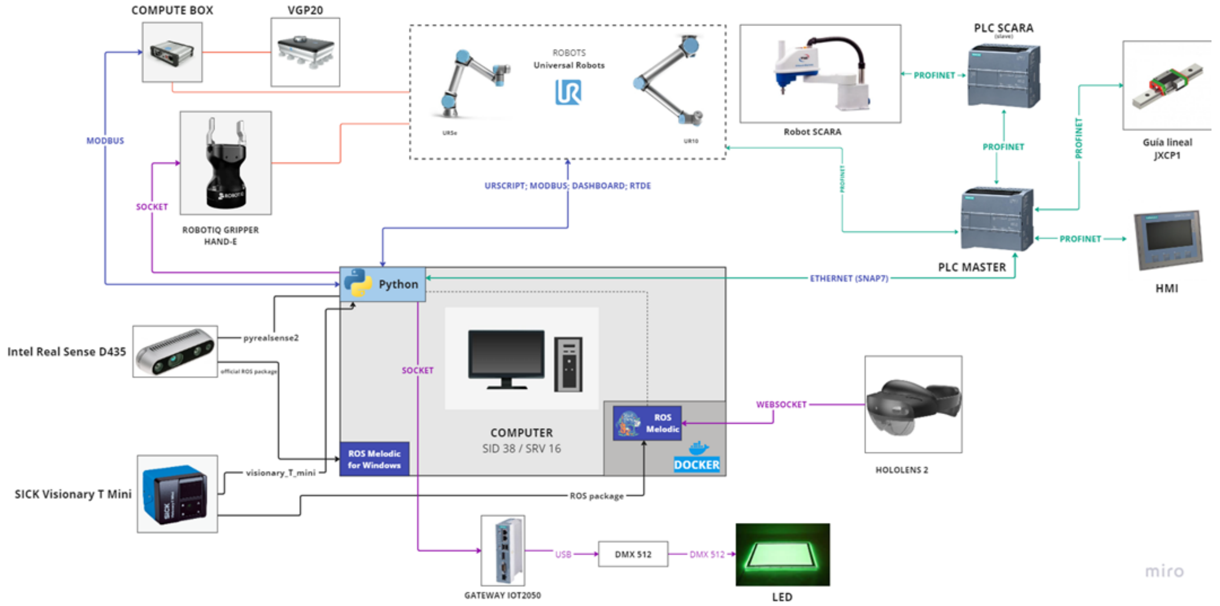

Figure 7: Connection architecture between CARTIF's pilot cell devices.

Connection of the devices connected to the computer

This following diagram provides a more detailed overview of all devices that can be controlled through the computer:

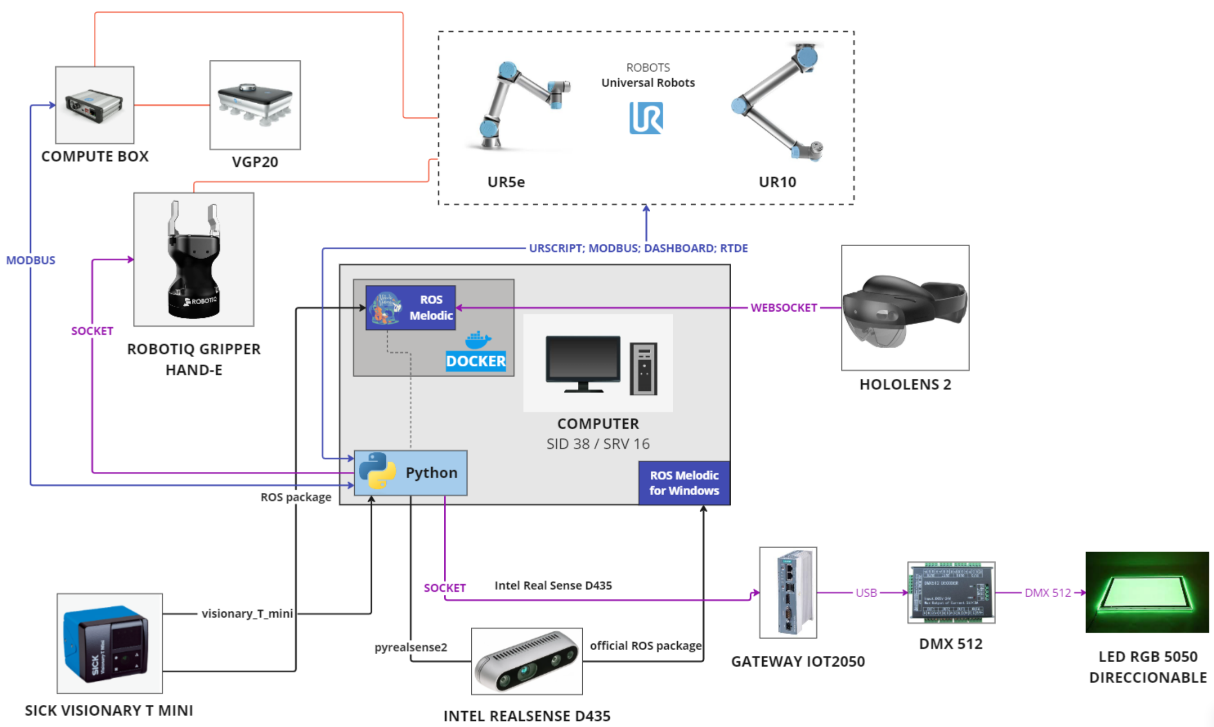

Figure 8: Connection architecture between CARTIF's pilot cell devices (detailed).

Profinet network

This shows the Profinet connections of all devices with the PLCs, and these in turn with the PC. The Profinet network establishes connections between all devices and the PLCs, which, in turn, communicate with the PC. For PLC software, Siemens SIMATIC S7-1200 PLCs are programmed using the TIA Portal, enabling comprehensive and efficient control of these devices.

Within our CAR TEF, PLCs facilitate the execution of cyclic operations for robots and the concurrent operation of linear guides. Operators can visualize and control these processes from both the PC and the HMI located within the cell. The TIA Portal framework offers engineers a user-friendly environment for developing automation solutions. It provides a range of tools and features for streamlined programming and configuration of PLCs. With its intuitive interface and robust functionality, TIA Portal simplifies the process of designing, commissioning, and maintaining PLC systems, ultimately enhancing productivity, and reducing time-to-market for industrial projects.

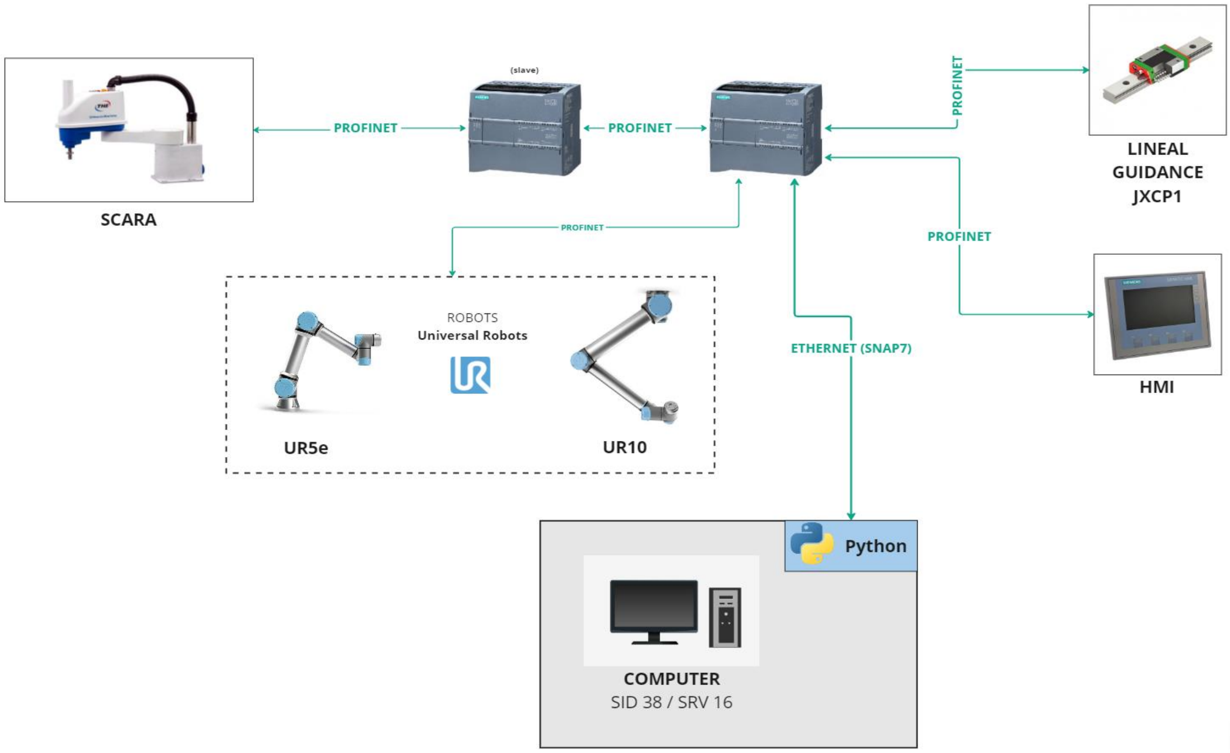

Figure 9: PLC connection architecture.

3.1.4 Interoperability aspects/Communication protocols

The communication framework within our TEF is primarily geared towards facilitating seamless interaction between operators and robots through mixed reality, as well as object and pose recognition in space. Additionally, it encompasses robotic cell control using natural language commands.

Moreover, the communication with the devices connected to the PLC is conducted via PROFINET, a widely used industrial communication protocol known for its high-speed and real-time capabilities, facilitating efficient data exchange between PLCs, HMIs, drives, and other industrial devices, ensuring smooth integration and optimal performance within the industrial network. This enables flexible and reliable control of manufacturing processes, thereby enhancing productivity.

Furthermore, the Snap7 software is employed for PC communication, serving as a software library responsible for writing to the corresponding data bases of the PLC. Snap7 facilitates communication between the PLC and external devices, such as PCs, for monitoring, control, and data logging purposes. This ensures seamless management of PLCs in industrial environments, contributing to smooth and accurate operation. The communication framework can be separated as follows:

Interaction between operator and robot through mixed reality

Human-robot interaction is made possible by processing the messages posted on ROS topics. The mixed reality interface running on Microsoft Hololens 2 communicates with the message broker via the websocket client-server protocol provided by the ROS rosbridge_suite package. Various scripts handle the sending and receiving of data to generate the necessary instructions for the collaborative robot. Communication between these scripts and the robot is done using the Universal Robots RTDE library.

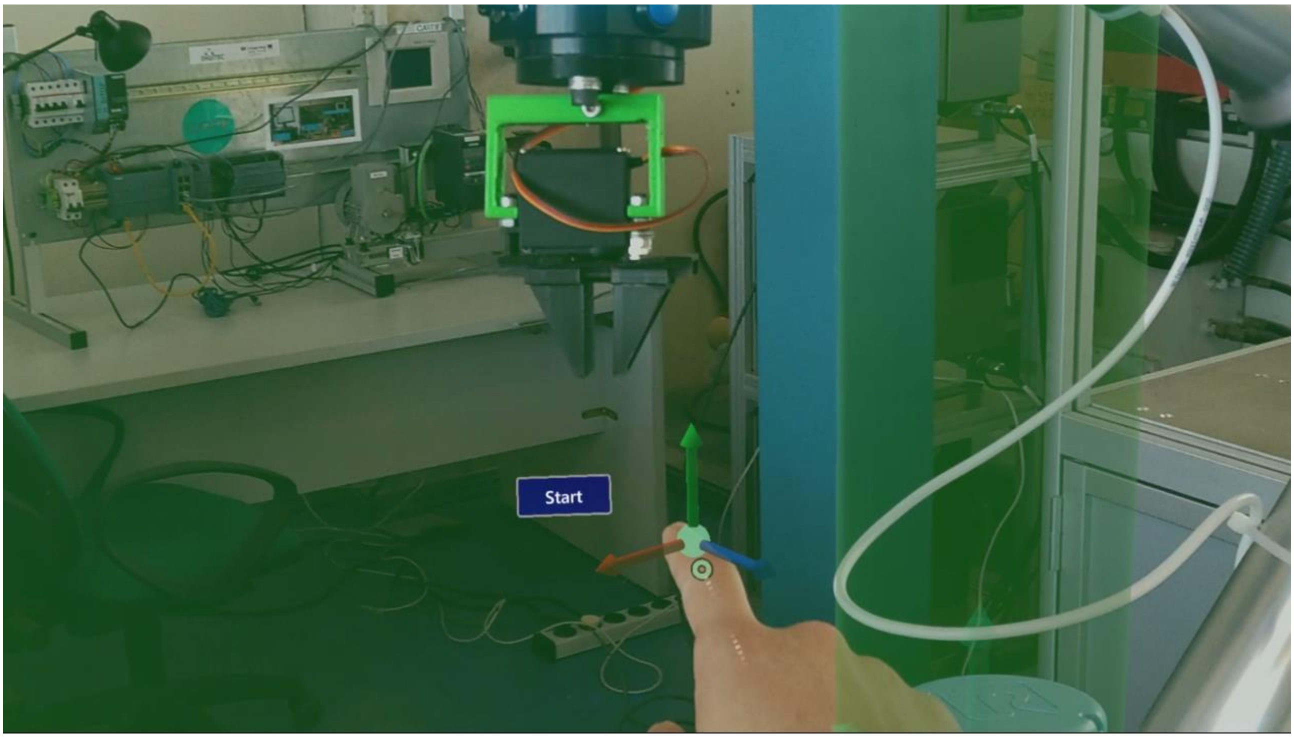

Figure 10: User indicates a position in space with his index finger and pronounces the voice command 'Start' (as seen from Hololens 2).

Object and pose recognition in 3D space

To locate objects in 3D space, the first step is to process the image of the object in 2D. To do this, we must train and then predict a model for object detection and identification, using custom YOLO models with a custom dataset in this case. By using properly aligned RGBD cameras, they can transform a point in 2D to a point in 3D within the camera. This point can be converted to coordinates of the robot or mixed reality glasses through appropriate transformations. In this way, both the robot and the operator can locate the object in the world coordinates.

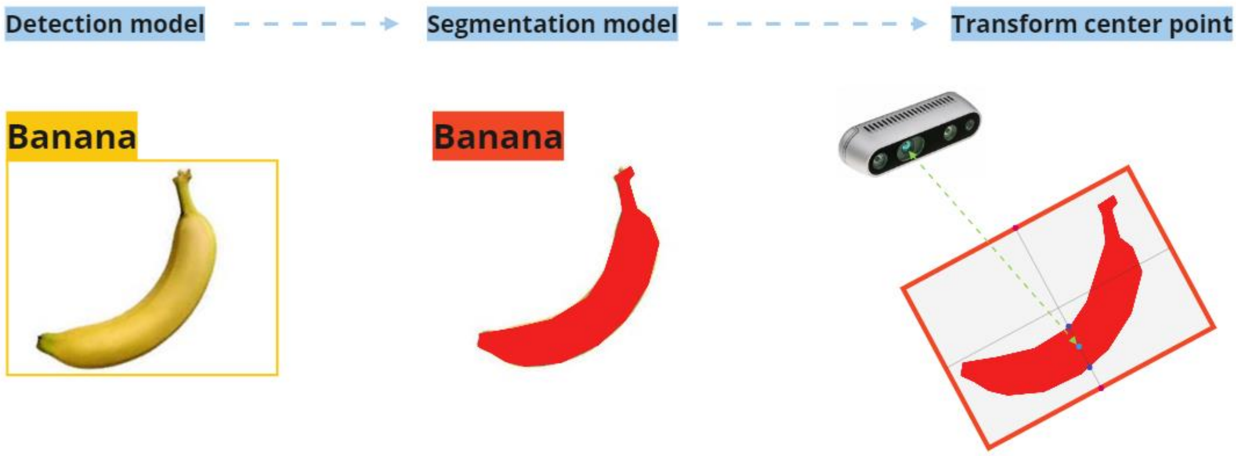

Figure 11: Process of detecting, segmenting, and locating the anchor points of a fruit with Intel RealSense D435.

Control of a robotic cell using natural language

The API key for OpenAI's ChatGPT can be utilized to interface between the human and the software systems (not just the robot). For this purpose, a main set of rules should be predefined for the GPT's LLM model, so it should recognize which conversations correspond with which commands. Then, the outputs of the model should be connected to a main frame that redirects the orders to each device in their own protocols. As an example, if an operator gives an order for the robot to move, the LLM model understands the conversation and returns a standard answer with the parameters needed to define the movement. Afterwards, another program should be the constructor using these parameters and send them to the robot. An analogue approach can be used to control other devices, or to do the inverse and feed the AI with information without active interaction with the operator.

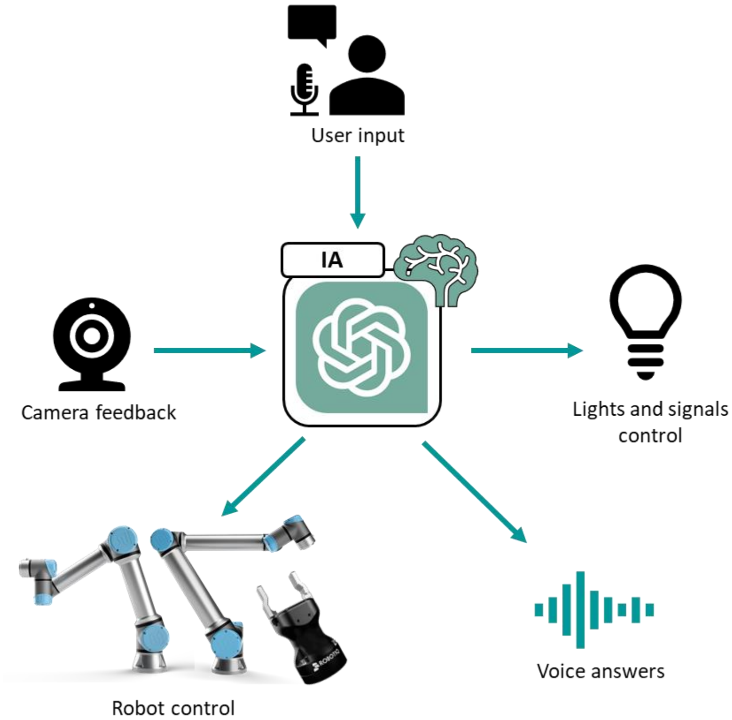

Figure 12: Multimodal system architecture with AI for collaborative robots.

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3.2 TEF 2- Re-programmable Co-bots for Flexible Manufacturing [INT]

3.2.1 TEF Overall Introduction

The TEF 2 presented by INT is the JOiiNT LAB[3], established in 2020 in partnership with Istituto Italiano di Tecnologia (IIT). This laboratory is focused on advanced robotics technologies and aims at strengthening the technology transfer mission, bridging research activities and industrial needs, training high-level professional figures with advanced technical-scientific skills, and enhancing the technological excellence of the area. This joint laboratory is unique in terms of size and strategic importance, making it the ideal base for IIT's projection towards supporting the Lombard and National Industry.
The following image illustrates an overview of the collaborative network behind this initiative, showcasing the diverse range of partners involved. Indeed, JOiiNT Lab involves institutions, research organizations, academic entities, and industrial companies. This coexistence of researchers and engineers from the industrial partners fosters a fertile ground for synergistic interactions, facilitating the exchange of ideas and expertise. As a result, the initiative enhances the competencies of the entities involved and enables effective responses to industrial needs.

Figure 13: Institutional, research, academic and industrial entities involved in the JOiiNT Lab initiative.

[3] https://www.joiintlab.com

Figure 14: JOiiNT Lab: Robotic Intelligence League Bergamo

The technologies and the areas of expertise handled in the JOiiNT Lab are summarized in the following image.

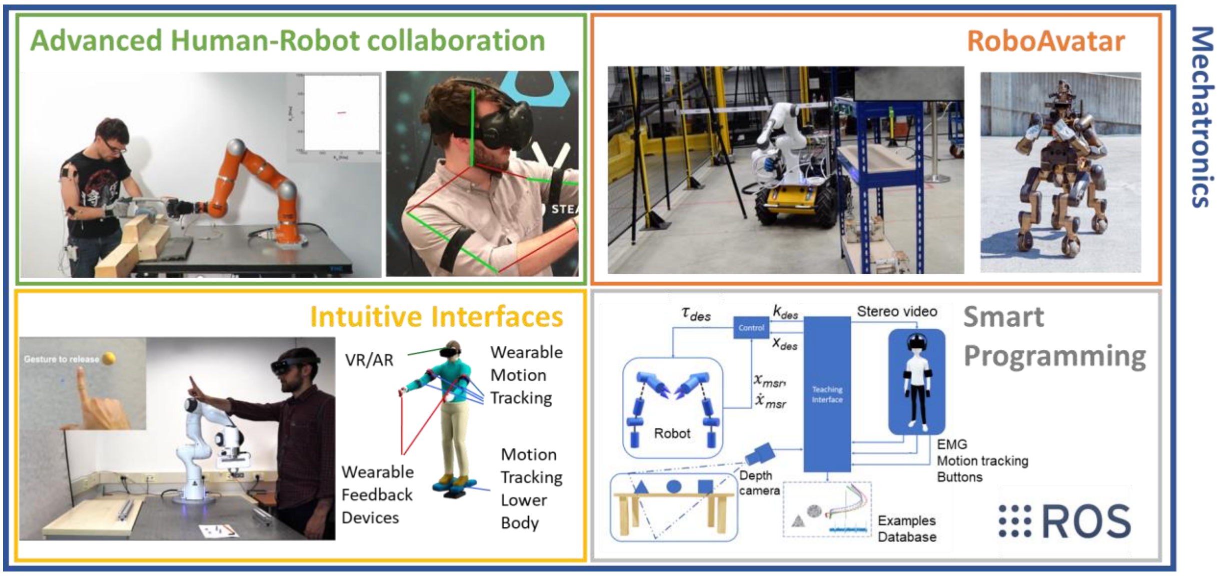

Figure 15: JOiiNT Lab areas of expertise.

Starting from these technologies and competencies, JOiiNT LAB defined 4 use cases that collectively address the industrial challenges presented by the companies:

- Flexible robotic workstation
- Robotic assistant
- Logistic 4.0
- Robot avatar for remote physical activities.

These 4 use cases cover different aspects and challenges commonly faced by industries requiring humans and robots to collaborate and work effectively together.

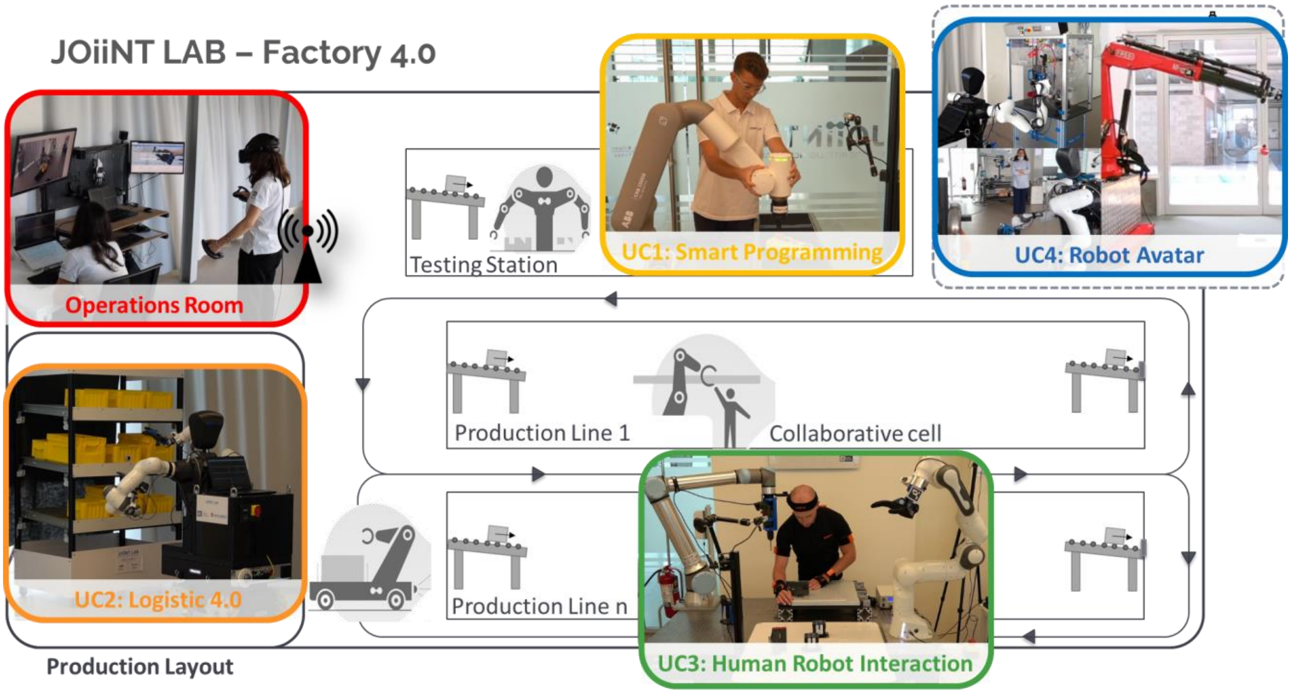

Figure 16: JOiiNT Lab Use Cases (UC) representing the identified industrial challenges.

3.2.2 Hardware Equipment

The JOiiNT Lab relies on various hardware equipment to address the different use cases and industrial challenges posed by the partners.

The available equipment includes but is not limited to:

- Cobots from different brands (ABB, Franka, UR, Doosan):
    - ABB Gofa 5
    - Franka Panda
    - Doosan M0609
    - UR10e
- Mobile robots (Robotnik, Clearpath Robotics)
    - Robotnik XL steel
    - Clearpath husky
- Composed robotic platforms (semi-humanoid platform)
    - FrankONE (custom integration of robots, 2 arms, mobile robot for lower body, custom neck, and head)
    - Frasky (custom integration robot for outdoor activities composed by outdoor mobile base, custom neck, 1 robotic manipulator)
- VR and optic motion capture systems:
    - HTC Vive kit
    - Valve Index kit
    - Oculus Quest 3 kit

- Vicon motion capture system equipped with 12xVero camera for IR tracking and 2x Vue camera for video recording.
- Inertial motion capture:
  - xsens suit
- 2D cameras and 3D cameras (stereo, infrared, structured light)
  - ZED 2
  - Intel RealSense D415
  - Intel RealSense D435
  - Intel RealSense D455
  - ZVID 3D camera
- Gripper (hands, parallel, vacuum) from different brands (qb robotics, OnRobot)
  - qb robotics SoftHand (research and industrial edition)
  - OnRobot RG2
  - OnRobot 2FG7
  - OnRobot VGC10
  - OnRobot VGP20

Below, a partial representation of the adopted hardware and technologies is presented.

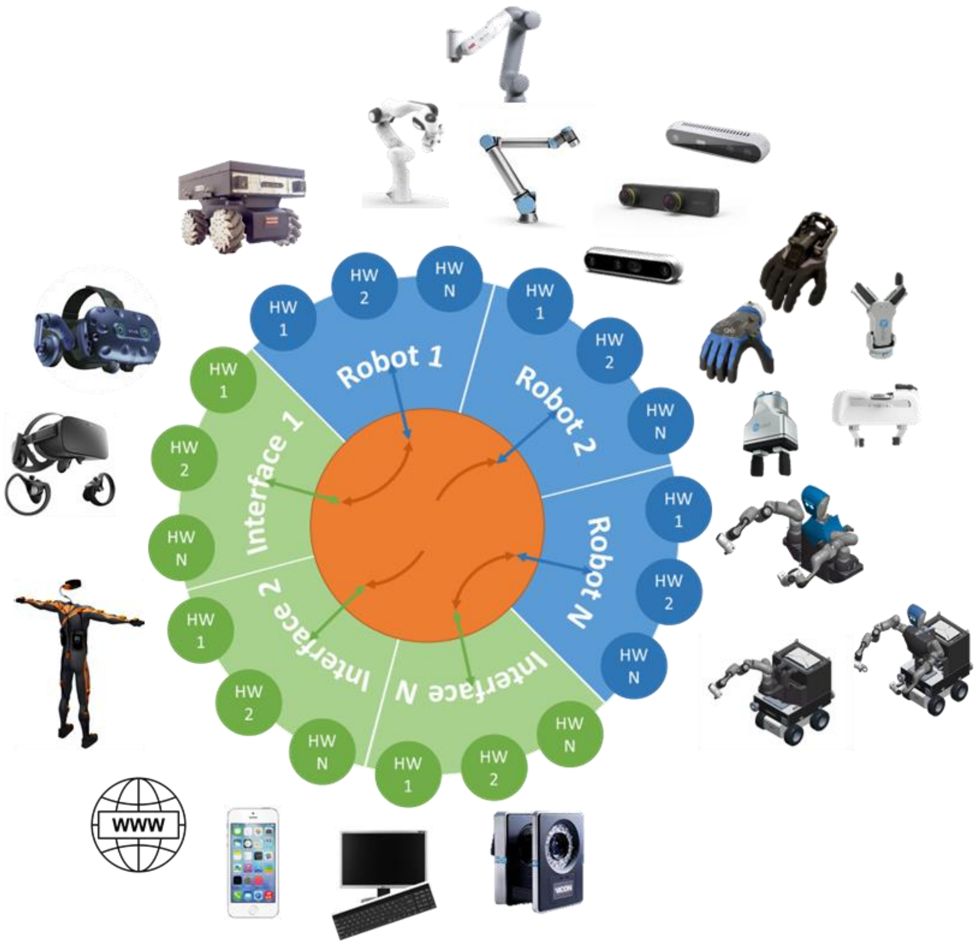

Figure 17: JOiiNT Lab Hardware Equipment.

3.2.3 Software Architecture

All the hardware described in the precedent section is integrated through ROS1 in a modular framework used to implement the different use cases and industrial challenges provided by the industrial partners.

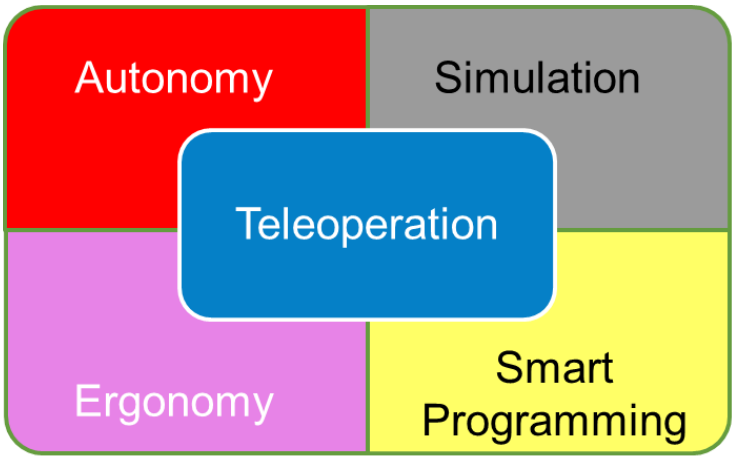

Figure 18: JOiiNT Lab Software Paradigm.

The JOiiNT LAB framework has the following main features:

- Modular ROS-based framework that integrates functionalities coming from different use-cases.
- Teleoperated robot control system leveraging VR technologies.
- Data acquisition and elaboration platform for ergonomics.
- Smart programming tools relying on intuitive interfaces.
- Speed up testing and prototyping for industrial use cases.

Below are the software components adopted in the JOiiNT LAB for developing industrial use cases.

- Operative system:
  - Windows: used for Unity and C# development.
  - Ubuntu: used as OS for all the robotic platforms in the lab and teleoperation system.
  - Docker: used for containerizing applications, especially AI applications.
- Programming languages and middleware:
  - C++: used for developing high-performance control software.
  - Python: used for scripting and AI related development.
  - ROS1: used for middleware for all the robot and the high-level related application.
- Libraries:
  - OpenCV is used for image elaboration, object recognition, streaming video, GUI development.

- OpenVR interacts with HTC and Valve or systems in ubuntu environment.

- Simulation and digital twin:
  - Gazebo: used to simulate robotics tasks and evaluate robotics control performances
  - Unity VR: GUI development and software interface with Oculus VR hardware

3.2.4 Interoperability aspects/Communication protocols

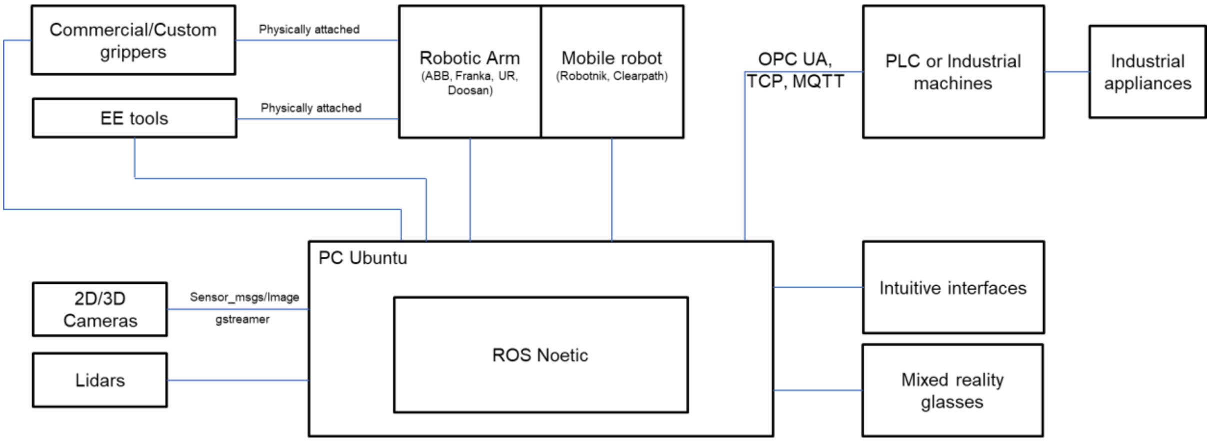

Figure 19: INT TEF: Interoperability and communication protocols.

The industrial partners guide the interoperability requirements and communication protocols adopted in the INT TEF. In particular, integration with industrial machines should be guaranteed. Thus, industrial protocols such as OPCUA and MODBUS TCP are covered, and integration with IoT devices or web servers using MQTT and RESTful API is also included.

3.3 TEF 3 - HRI-enhanced robots to provide support in healthcare [PAL]

3.3.1 TEF Overall Introduction

The TEF 3 facility at PAL Robotics is a specialized hub for testing robotic technology, particularly in healthcare settings. It offers adaptable environments that can simulate various real-life scenarios. PAL Robotics utilizes this space to refine capabilities and test solutions using advanced platforms like Gazebo and TIAGo Pro's digital twin. TEF 3 prioritizes a human-centred design approach to ensure that robotic systems enhance healthcare delivery seamlessly.

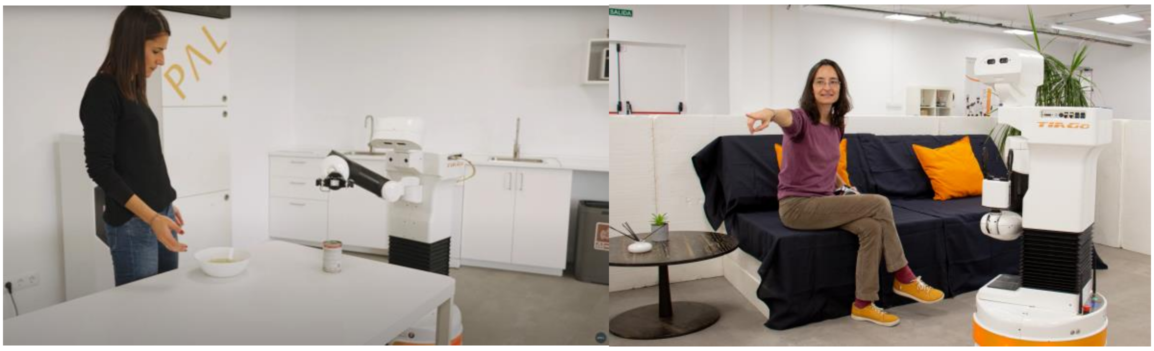

Figure 20: PAL TEF: Testbed examples in PAL.

The primary focus of TEF 3 is to develop a robust HRI framework that enables robots to exhibit clear and understandable behaviors. One key application is to improve fetch and carry tasks within healthcare environments, where robots will assist by transporting specific items to designated locations. This functionality is designed to free up healthcare staff to focus more on patient care rather than routine transport tasks. Interactions with these robotic systems will be facilitated through multimodal social signals such as voice, gestures, and gaze, making the technology intuitive and user-friendly for hospital staff. This initiative aims to transform robots from simple mechanical assistants into intuitive and empathetic partners in patient care.
Additionally, the second focus is on developing an HRI layer that transcends traditional robotic functionalities by understanding and adapting to human conditions, preferences, and environmental interactions.

3.3.2 Hardware Equipment

Our facility includes an electro-mechanical workshop equipped for complete robot assembly, encompassing structural components, actuators, sensors, devices, cabling, and covers. The TIAGo Pro robot, integral to our TEF, is a cornerstone of our hardware capabilities.
TIAGo Pro is designed with advanced navigation, perception, manipulation, and HRI capabilities, specifically tailored for complex environments where human-centric interaction is crucial. This robot features fully torque-controllable arms equipped with brakes at each joint to ensure safety and precision in its movements. The arms are part of a new version of the robotic arm system that includes 7 Degrees of Freedom and Series Elastic Elements for joint torque sensing, supported by a 1kHz EtherCAT bus that ensures high torque bandwidth. Its structural design is optimised with a placement that maximises its workspace, allowing for easy frontal and lateral reach. The TIAGo Pro operates on a custom electronics architecture, including a powerful Intel i7 14th generation CPU, 1TB SSD, and 64 GB of RAM, with an optional NVIDIA Jetson AGX Orin for enhanced processing capabilities.

Figure 21: TIAGo Pro

The autonomy of the robot is also significant, boasting 8-10 hours of battery life with normal or moderate use. Its omnidirectional drive enhances its maneuverability in complex environments, and its end effectors are compatible with ISO 9409-1 standards, supporting a payload of 3kg in each arm. This high degree of mechanical and electronic sophistication makes TIAGo Pro Edition an ideal candidate for tasks requiring advanced manipulation and interaction in settings such as Industry 4.0, Industry 5.0, logistics, and healthcare.

TIAGo Pro excels in environmental monitoring using ambient sensors and semantic mapping, enhancing its navigational and interactive abilities in various settings. The robot also manages tasks such as object transportation and visitor reception, facilitated by integrated features like a touchscreen for interaction and a thermal camera.

3.3.3 Software Architecture

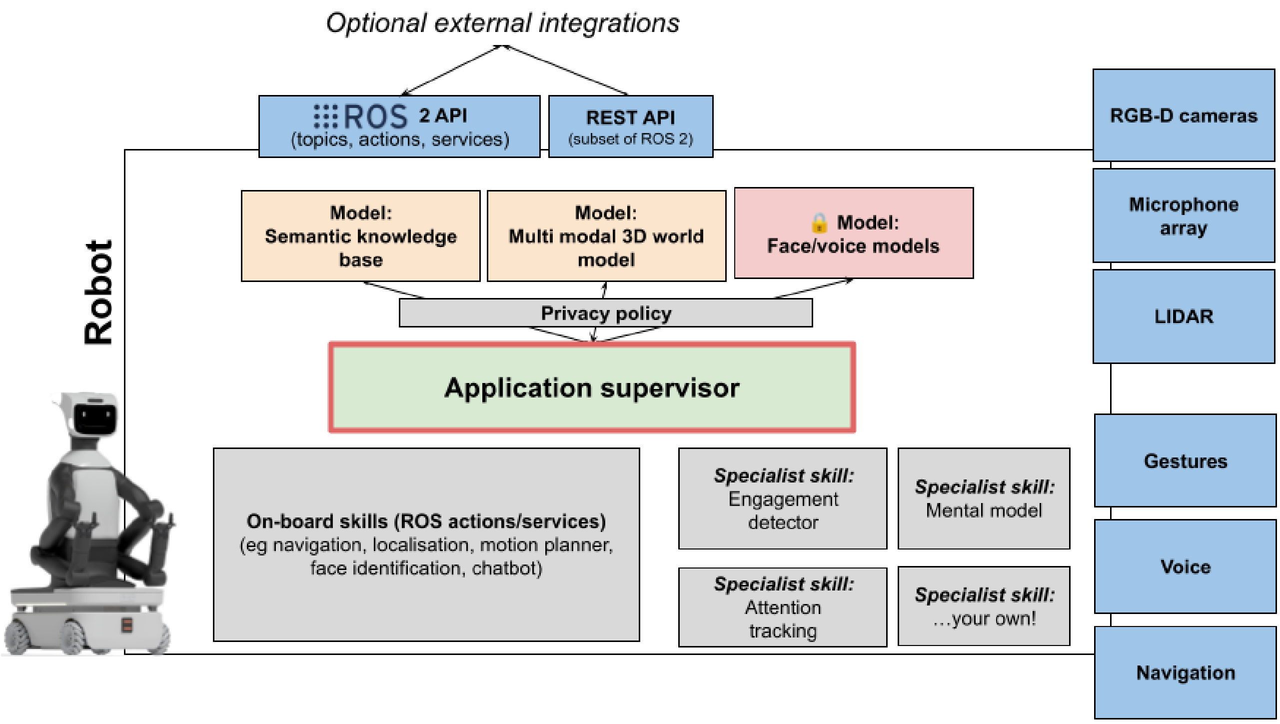

Figure 22: TIAGo PRO Software Architecture.

The TIAGo Pro Edition is equipped with a sophisticated software suite designed to enhance Human-Robot Interaction (HRI) and improve its adaptability and usability across various industries. The robot operates on Ubuntu LTS with a Real-Time Operating System, providing a stable and responsive platform for its applications. It features the advanced ROS4HRI ROS specification, which includes capabilities such as 2D/3D real-time skeleton tracking, 6D head pose estimation, automatic facial landmark extraction, gaze tracking, and face identification, all designed to foster intuitive interactions between humans and the robot. Speech and language processing are significantly enhanced with fully offline speech recognition available in over 20 languages, a versatile new chatbot engine, and "chit chat" chatbots. Additionally, the TIAGo Pro offers voice synthesis with markup support for synchronised text, gestures, and facial expressions, along with automatic subtitling to enhance accessibility. A configurable wake-up word detection system, which does not require pre-training, further optimises its interaction capabilities. The robot also incorporates a novel algorithm for probabilistic data fusion, enabling real-time, accurate matching of faces, skeletons, and people. This comprehensive suite of software features supports the robot's ability to learn from demonstration, allowing it to adapt to new tasks and collaborate effectively in environments such as Industry 4.0, Industry 5.0, logistics, and healthcare sectors.

3.3.4 Interoperability aspects/Communication protocols

ROS2: The backbone of TIAGo Pro's software architecture is ROS2 (based on ROS2 Humble), providing a robust and flexible framework for robot programming. The robot exposes an extensive API[4] enhanced with the ROS4HRI ROS specification, it facilitates advanced human-robot interaction capabilities, including real-time human model representation. This system enhances TIAGo's perceptual and interactive abilities significantly.

Networking and Connectivity: The robot is equipped with connectivity technologies including Wi-Fi 6 (802.11ax) and Bluetooth Smart 4.0, ensuring reliable and fast wireless communication. This connectivity enables interactions with networked sensors and other IoT devices, allowing the robot to operate efficiently in smart environments.

Standardized Interfaces and Modularity: The use of standardized interfaces like ISO 9409-1 for end effectors ensures easy integration with various tools and attachments, enhancing the robot's versatility. The modularity extends to software components, which can be easily updated or replaced as needed to adapt to new tasks or environments.

Real-Time Operating System: Running on Ubuntu LTS with RT Preempt ensures that TIAGo Pro can handle time-critical operations requiring precise timing and synchronization. This feature is particularly crucial in environments where timing and reliability are paramount, such as in Industry 4.0 and healthcare.

Integrated Environmental Sensing: With front and back LIDAR systems providing a 360-degree field of view and additional sensors like RGB-D cameras, TIAGo Pro excels in environmental monitoring and navigation. These capabilities are foundational for the robot's ability to understand and adapt to its surroundings, enhancing both navigation and interaction.

3.4 TEF 4 - Human centric Zero-Defect Manufacturing [POLIMI]

3.4.1 TEF Overall Introduction

The POLIMI Industry 4.0 is a laboratory fully equipped with industrial assets in order to create a realistic environment for testing research findings and developing customized solutions based on cutting-edge equipment and technological solutions.
POLIMI will exploit Industry 4.0 Lab infrastructure as a testbed for innovative solutions benefiting from the modular and flexible facilities and tools gathered in this laboratory. This

[4] https://docs.pal-robotics.com/sdk/23.12/

lab also being part of a public university, acts like a didactic factory in order to train students with real-like circumstance.
Within ARISE project, POLIMI Industry 4.0 Lab acts as a Testing and Experimentation Facility (TEF) addressing "Human centric zero-defect manufacturing" framework. Within this TEF, two challenges will be investigated following a relevant application case for each challenge which enables potential stakeholders to see an instance of addressing technical challenges inside a testbed. The first challenge of POLIMI TEF deals with "HRI for improving efficiency of workers in high-precision flexible tasks", in manufacturing environments, technicians handle high-precision tasks with diverse processes, such as manual reworking of defective intermediate goods, often entrusted to expert technicians equipped with a variety of tools, though the time-consuming selection and setup process detracts from value-adding activities; therefore, the proposed solution aims to predict and arrange the necessary tools and workspace for each technician based on production line data, optimizing efficiency and accommodating individual preferences.
The second POLIMI TEF challenge is related to "HRI for improving ergonomics in high-precision tasks" by which the system under consideration should allow a collaborative robot to pick up goods to be reworked from their carrier and place them in a fixed location based on the technician's physical characteristics (e.g., height) to enhance human operator ergonomics during performing the task.

3.4.2 Hardware Equipment

The core of the Lab is constituted by the fully automated assembly and manufacturing line (Figure 23) with a robotic cell with a high precision 7 axis articulated robot. An AGV and a cobot, controlled by open and independent informative systems, complete the industrial-like scenario with several vertical-integration solutions.

Figure 23: Industry 4.0 Lab Manufacturing Line.

The high flexibility of the system and the modularity of the configuration allows POLIMI to test and replicate virtually any variety of manufacturing/assembly system for discrete manufacturing. The configuration of the system can be quickly very quickly and reshaped with ad hoc modelling and simulation tools.
Each workstation is controlled by an individual logic and services can be instantiated on each component/phase both for operational and for energy (electricity and air) consumption.

Other hardware equipment in the laboratory can be listed as follows:

Universal Robots e-series (UR5e) Collaborative Robot
Considering the flexibility and functionality for educational purposes, Universal Robots e-series has been installed at Industry 4.0 Lab of POLIMI. The UR5e robot, with a 5 kg payload and an 850 mm reach radius, the medium-sized member of the Universal Robots family is perfect for automating low weight processing tasks. The UR5e strikes the optimal balance between size and power and is quick and simple to set up. The UR5e robot has 6 degrees of freedom and can be used in several applications.

Figure 24: POLIMI Lab 4.0 UR5e robot.

Franka Emika Panda Collaborative Robot
The Franka Emika Panda robot is a 7-axis robot arm, it offers a 3 kg payload and 850 mm of reach. The repeatability of the Franka Emika Panda robot is 0.1 mm, and the robot's weight is approximately 18 kg.

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Figure 25: Franka Emika Robot.

Intel RealSense D435i depth camera

The Intel® RealSense™ depth camera D435 is a stereo solution, offering quality depth for a variety of applications. Its wide field of view is perfect for applications such as robotics or augmented and virtual reality, where seeing as much of the scene as possible is vitally important. With a range up to 10m, this small form factor camera can be integrated into any solution with ease and comes complete with Intel RealSense SDK 2.0 and cross-platform support[5].

Jobot AGV

Jobot® is the mobile robot designed and produced by Eutronica to support and facilitate human work; it is a compact and efficient transport system that moves within programmed routes carrying out simple missions from loading and unloading stations to work centres.

Figure 26: Jobot AGV.

[5] https://www.intelrealsense.com/depth-camera-d435/

Robotiq Wrist Camera
The Robotiq Wrist Camera is the only vision system designed to perform industrial applications on the UR teach pendant. Use the Robotiq URCap to quickly teach new parts and detect features for repeatable picking, even if you are a beginner. Advanced users can also fine-tune their program with the expert mode. The camera's form factor makes it the only one that seamlessly integrates with Universal Robots[6].

Robotiq Hand-E gripper
Hand-E's high accuracy and 50 mm parallel stroke make it perfect for precision assembly tasks, while its sealed design ensures reliability in the toughest manufacturing conditions. Hand-E's design adheres to ISO/TS 15066 standard best practices, with maximum force, rounded edges, self-locking functionalities, and other features making it the gripper for collaborative robots[7].

Robotiq 2F-85 gripper
The Robotiq 2F-85 adaptive gripper is easy to integrate and use in all automation cells in the factory. It handles parts of various sizes and shapes and is ideal for pick and place, machine tending, assembly, and quality testing. With a grip stroke up to 85 mm and its multiple adaptable grip configurations (internal, external, parallel, and encompassing) this gripper can accomplish a wide range of different tasks. This gripper allows a very high gripping force of 235 N that secures a firm grip of payloads up to 5 kg.

Robotiq Vacuum gripper
Robotiq Vacuum Grippers can handle a wide range of applications and are ideal for picking up uneven and even workpieces made of different materials, such as cardboard, glass, sheet metal (dry) and plastic. Because of the customizable bracket and unique air nodes.[8]

Moreover, the Lab is well equipped with hardware for desoldering printed circuited board (PCB) components, namely RMSE Complete Rework System from JBC, which is quickest and safest solution for soldering and rework using hot air. RMSE consists of JTSE hot air station controlling the temperature and airflow profiles, JTT Heater Hose Set, ESHT Magazine for Protectors & Extractors.

Figure 27: RMSE Complete Rework System.

[6] https://www.universal-robots.com/fi/plus/products/robotiq/robotiq-wrist-camera/
[7] https://robotiq.com/products/hand-e-adaptive-robot-gripper
[8] https://robotiq.com/products/vacuum-grippers

3.4.3 Software Architecture

Assembly line: The Manufacturing Executing System (MES) enables defining type and quantities of the products to be assembled by the assembly line. These items could be inserted by the user on MES interface manually by inserting the required pre-defined fields on the MES panel. After setting the types and quantities of products, at the "Manual Station" the pallet will be placed by an operator manually so that the assembly process starts as described earlier. During the process of part at each station, there are several sensors recording operational, energy, MES and RFID signals of the parts and stations. The architecture of the line is shown in Figure 28. The system is designed for transporting work pieces on carriers, which are equipped with RFID-tag. The production process coming from MES is saved on the RFID-tag.

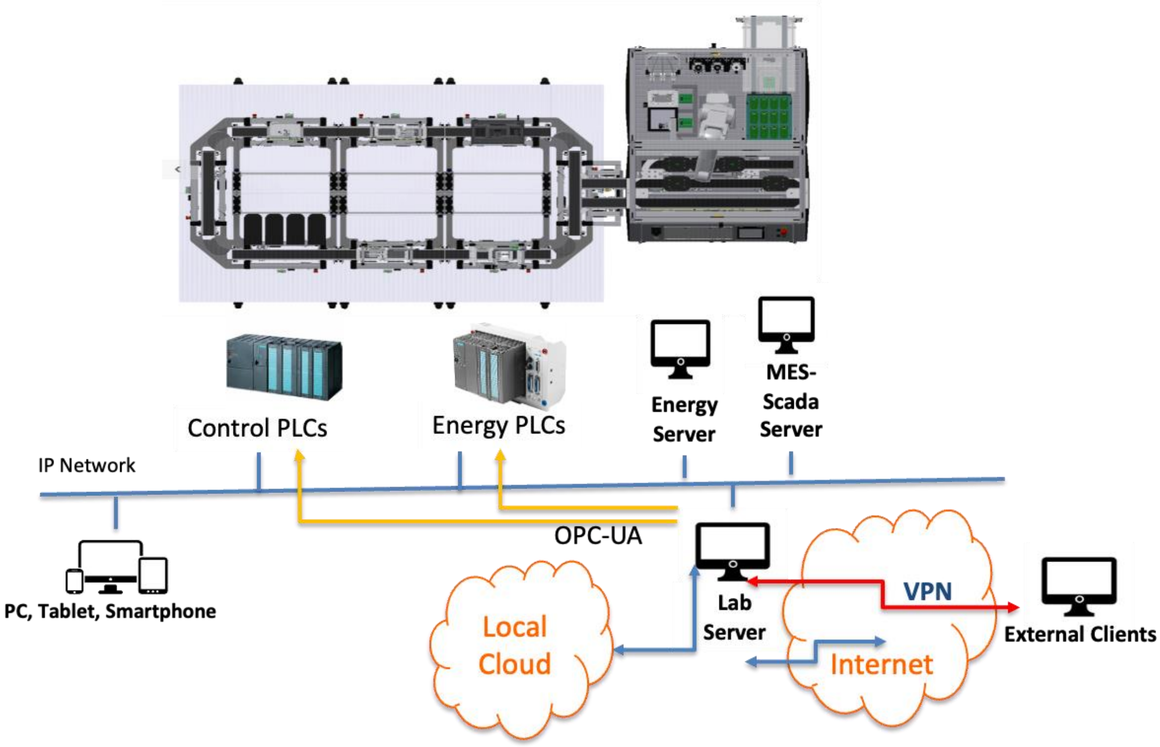

Figure 28: General architecture of the assembly line.

UR5e robot: the Universal Robot ROS Driver[9] has been leveraged for operating UR5e robot which an overview of the driver architecture has been depicted in Figure 29.

[9] https://github.com/UniversalRobots/Universal_Robots_ROS_Driver/tree/master

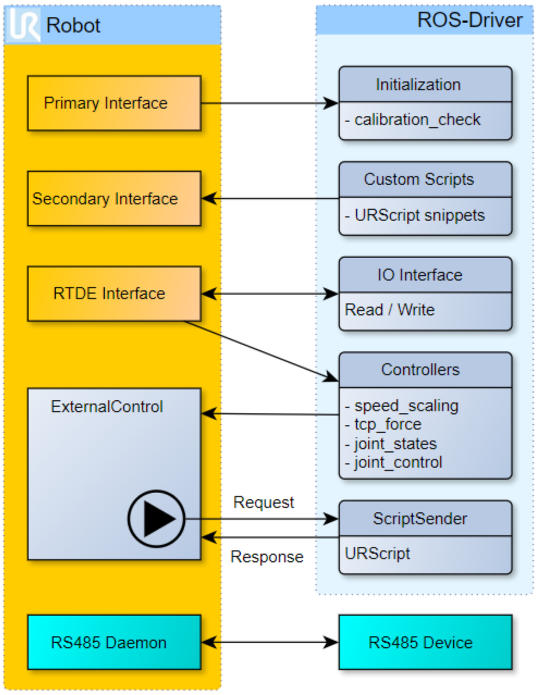

Figure 29: Overview of UR_ROS driver's architecture[10].

Intel RealSense D435i Camera: Intel® RealSense™ SDK 2.0 is a cross-platform library for Intel® RealSense™ depth cameras (D400 & L500 series and the SR300)[11]. In addition, in order to use ROS for communication to the camera ROS Wrapper[12] has been installed.

Franka Emika Panda Robot: the franka_ros[13] driver has been employed for communication with the robot.

[10] https://github.com/UniversalRobots/Universal_Robots_ROS_Driver/tree/master/ur_robot_driver

[11] https://github.com/IntelRealSense/librealsense
[12] https://github.com/IntelRealSense/realsense-ros
[13] https://frankaemika.github.io/docs/franka_ros.html

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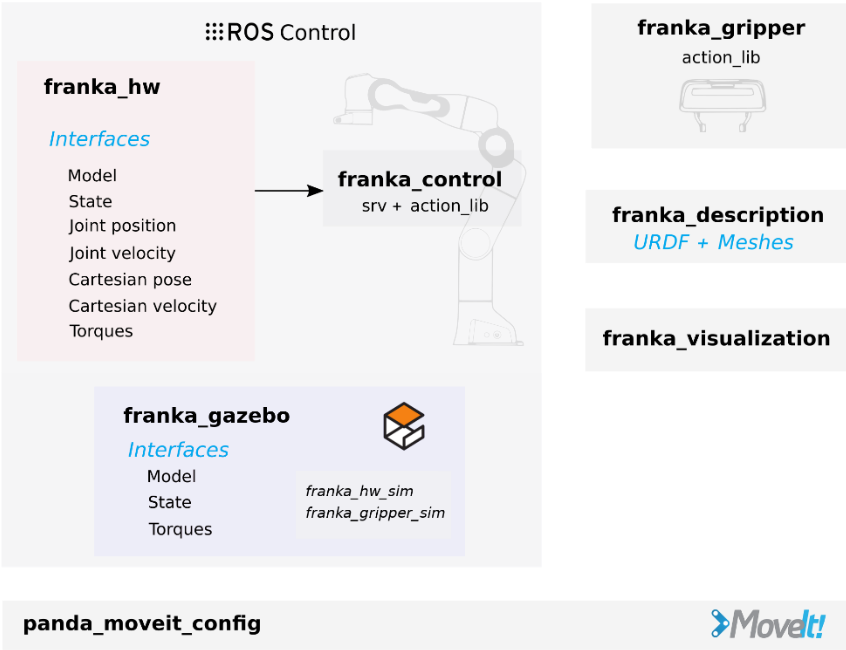

Figure 30: Franka_ROS Overview5.

3.4.4 Interoperability aspects/Communication protocols

As described in previous section, for each asset there is a specific communication protocol which enables sending/receiving data from it. From interoperability point of view, the Asset Administration Shell (AAS) technology have been exploited in order to represent each asset at POLIMI TEF based on a Common Information Model (CIM) facilitating the exchange of asset with other stakeholders. The purpose of developing AAS packages for assets is to enable self-explainability of the assets for potential exploitation with regard to data pipelines.

4. Integration of ARISE Framework into TEF's Challenges

4.1 TEF 1 [CARTIF]

4.1.1 Analysis of potential exploitation of enablers

Evaluating the opportunities and strategies for leveraging key factors that facilitate the success and adoption of a particular ARISE technology, it is necessary to consider the diverse experiments that will be carried out on CAR TEF as efficient picking and disassembly of products, ensure worker safety, maximize efficiency, and minimize errors in the process. However, different improvements are needed to effectively achieve industrial applications through the proposed technologies. The main expected contribution of ARISE middleware to address the proposed challenges and maximize the impact within the CAR's industrial network can be summarized as follows:

-**Standardization**: Transitioning from in-house solutions to standardized HRI tools accelerates industrial applicability and fosters innovation within TEF1. Standardization ensures interoperability and reliability, crucial for seamless integration and advancement within an open innovation ecosystem.

-**Interoperability**: ARISE promotes interoperability between different hardware and software components, enabling seamless integration and communication within robotic systems. This interoperability reduces compatibility issues and facilitates the exchange of data and commands, enhancing the overall efficiency and functionality of TEF1's solutions. This will also prepare TEF1 to integrate new hardware more quickly than it could otherwise.

-**Modularity**: ARISE offers reusable and composable modules for Industrial HRI, built on a flexible, modular, and standardized framework. This approach streamlines the integration of hardware and software components into robotic systems, facilitating rapid development cycles, simplified system configuration, and enhanced interoperability.

-**Scalability**: ARISE technologies support scalability, allowing TEF1 to adapt and expand its capabilities as the scope of its use cases evolves. This scalability ensures that the solutions developed within the TEF1 can meet the growing demands of industrial applications while maintaining performance and efficiency.

ARISE brings forward a significant advancement with the All-in-one middleware, which combines ROS2, Vulcanexus and FIWARE. This integration not only strengthens the safety, robustness, and scalability of the current solutions within TEF1 but also anticipates notable enhancements in performance optimization and reduced latency. Also, ROS4HRI framework will enable to precisely estimate the human body features shortly and with deploying the developed middleware, the cobot will respond to the operator's voice command promptly for further adjustment via a more intuitive interface. These improvements are particularly advantageous for real-time applications, ensuring smoother and more efficient operation in dynamic industrial environments.

4.1.2 Redefinition/Remapping of involved Hardware/Software

Incorporating ARISE technologies and tools within CAR's TEF1 journey necessitates a redefinition and remapping of the involved hardware and software components. The integration of ARISE middleware, encompassing ROS2, Vulcanexus, and FIWARE, serves as a pivotal advancement in strengthening the safety, robustness, and scalability of existing solutions within TEF1.

- **Upgrading ROS1 to ROS2**: Enhancing the system by transitioning to ROS2 using the Vulcanexus open-source software stack will result in an upgrade in technological infrastructure for the use cases.
- **FIWARE Integration**: Integrating the system with industrial company hardware and software via FIWARE facilitates data exchange with external systems, such as sending ROS2 data from the robot to the company dashboard and vice versa, enriching the interaction between the TEF and external stakeholders without compromising the performance of the HRI application.
- **Incorporating ROS4HRI**: Introducing new intuitive interfaces and user-friendly technologies leveraging ROS4HRI, the 3D camera to estimate the operator's physical ergonomics index, will enhance technology acceptability among operators, fostering smoother interactions and improved usability. Existing integrations will need to be transformed into ROS4HRI.

Notably, this integration will anticipate significant enhancements in performance optimization and reduced latency, crucial for real-time applications in dynamic industrial environments. Additionally, the introduction of the ROS4HRI framework enables precise estimation of human body features, facilitating prompt response to operator voice commands and adjustment via a more intuitive interface. Through these upgrades, CAR TEF is poised to enhance its capabilities in addressing diverse use cases not only the ones proposed to demonstrate the adherence to project's challenges, ensuring smoother operation and greater efficiency across industrial processes.

4.1.3 Implementation plan

Below is an outline detailing the initial setup plan for the CAR TEF and its associated use cases, to be implemented by Month 9 of the project timeline. This plan encompasses various key activities aimed at identifying hardware and software requirements, upgrading software packages, integrating necessary frameworks, developing monitoring systems, enhancing motion planning, and training operators. The systematic execution of these steps is crucial for the successful deployment and experimentation within the TEF environment, enabling effective testing and validation of human-robot interaction (HRI) solutions.

Step number	Description of activities
1	Identify the hardware and software required for the CAR TEF and use cases
2	Upgrade current software packages of each hardware involved in the use cases (robot, camera, glasses etc.) and software from ROS1 to ROS2
3	Introduce FIWARE to enable sharing context data (Orion Context Broker)
4	Integration of Vulcanexus tools and eProsima's Fast DDS
5	Develop the motion tracking system and the intuitive interface (e.g., Grafana) for monitoring the system
6	Upgrade of the motion planning of robots
7	Extraction of physical features of the operator via image processing (camera, glasses)
8	Introduce ROS4HRI for operator data collection and body tracking
9	Integration of outcomes from previous steps to achieve HRI/HRC
10	Training of operators to align with the developed solution within the HRI framework

Table 2: CARTIF description of activities.

4.1.4 Expected Results

The expected results section outlines the anticipated outcomes and achievements of the ARISE project. It provides a comprehensive overview of the advancements and innovations expected to emerge from the project's activities, through the ARISE middleware, and improved experimental design support. These expected results form the basis for measuring the project's success and impact on the field of human-robot interaction in industrial settings.

Item Number	Expected Result Description
1	[Short-term] Introduce new hardware and software that will be used in the use cases
2	[Short-term] Assessment of the opportunities related to the ARISE framework
3	[Short-term] Create off-the-shelf applications of the TEF using the ARISE framework
3	[Short-term] Re-mapping of the proposed use cases with the developed ARISE enablers
4	[Long-term] Obtain an Agile Simulation and Testing Environment with the ARISE technology
5	[Long-term] Advanced Robotics Capabilities through the ARISE middleware as 3D object recognition

Table 3: CARTIF expected results.

4.2 TEF 2 [INT]

4.2.1 Analysis of potential exploitation of enablers

Currently, the use cases investigated in the INT TEF represent proof of concepts of different robotics technologies aiming to demonstrate the effectiveness of an HRI solution in a manufacturing facility where the product's high variability and the production's high flexibility impose human involvement, especially considering demanding tasks where physical ergonomics and safety are at risk. However, different improvements are needed to effectively achieve the industrial application of the proposed technologies. The main expected contribution of ARISE to address the proposed challenges and maximise the impact within the INT industrial network can be summarised as follows:

Technologies improvement: The current INT TEF use cases present different technology challenges which hinder effective industrial exploitation. The All-in-One ARISE middleware - integrating ROS2, Vulcanexus, and FIWARE - will enable the TEF to improve the proposed solutions' safety, robustness, and scalability. For instance, significant advantages are expected concerning performance optimisation and reduced latency for time-sensitive applications.

Standardisation: While INT TEF currently relies on different in-house solutions, ARISE will support INT towards applying standardised HRI tools, boosting industrial applicability and further innovation. Indeed, standardisation plays a crucial role in ensuring the proposed solution's interoperability and reliability. Moreover, a standard and common framework is essential to promote development in an open innovation ecosystem.

Modularity and Extensibility: Providing access to reusable and composable modules for Industrial HRI built upon a flexible, modular, and standardised framework will facilitate the integration of hardware and software components into robotic systems, thus contributing to faster development cycles, more straightforward system configuration, and greater interoperability.

4.2.2 Redefinition/Remapping of involved Hardware/Software

Among the ARISE technologies and tools, the following redefinition and remapping of involved hardware and software will be implemented:

- Upgrading the system to ROS2 using Vulcanexus open-source software stack: this upgrade leads to improvement in terms of technologies used in the use case and to enhancement of the INT TEF competencies.
- Integrate the system with industrial company hardware and software (IoT and business intelligence) through FIWARE: currently, the use cases do not exchange data with external systems. For example, the INT TEF aims to send ROS2 data from the

robot to the company dashboard and, conversely, send some company info (e.g., product code) to the robot.

- Introducing new intuitive interfaces and more user-friendly technologies exploiting ROS4HRI: for instance, the Xsens suit currently used to estimate the operator's physical ergonomy index could be replaced by a 3D camera, enhancing the technology acceptability by the operators.

4.2.3 Implementation plan

Step number	Description of activities
1	Setup the hardware and software for the INT TEF use case
2	Upgrade current software packages of each hardware involved in the use case (robot, camera, etc.) and software from ROS1 to ROS2 (Vulcanexus)
3	Develop the motion tracking system and the intuitive interface (e.g., pen or glove) for programming the pose goal for the robot
4	Motion planning of robotic arms
5	Introduce FIWARE to enable sharing context data
6	Introduce ROS4HRI for operator data collection and body tracking
8	Extraction of physical features of the operator via image processing
9	Determination of ergonomics and comfort zone of operators according to the extracted physical features
11	Integration of outcomes from previous steps to achieve HRI/HRC
12	Test the use case with different operators to evaluate the HRI solution

Table 4: INT description of activities.

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4.2.4 Expected Results

Item Number	Expected Result Description
1	Introduce new hardware and software that will be used in the use case
2	Development of the current use case relying on the ARISE framework to evaluate the potential improvements of the prototypal solution
3	Assessment of the opportunities related to the ARISE framework
4	Re-mapping of the proposed use cases with the developed ARISE enablers tailored to enhance technical and HRI aspects
5	Development of a second version of the proposed use case benefiting from the developed ARISE enablers

Table 5: INT expected results.

4.3 TEF 3 [PAL]

4.3.1 Analysis of potential exploitation of enablers

TEF 3 [PAL] concentrates on two pivotal enhancements in healthcare robotics: advanced multimodal HRI for enhanced functionality (Challenge 5) and automation of fetch & carry tasks (Challenge 6).

Challenge 5 aims to improve how robots and humans collaborate on functional tasks by utilising a combination of communication methods—verbal, gestures, and visual cues. The application example looks into using an interactive social robot-like PAL TIAGo Pro to help with non-critical healthcare tasks, like physical exercising (e.g. stretching).

As such, we expect ARISE to enable better **multi-modal communication capabilities**, with real-world **evidence of their effectiveness**.

A key aspect of TEF3 is its human-centred approach: we want the technology developed in ARISE to be designed for and with end-users, and we expect ARISE to enable a **human-centred design mindset** supported by adequate tools and robot capabilities. This might involve for instance new technology (or technology integration) to **recognise, represent, store and reason about individual user preferences, limitations, and desires**, providing a personalised and engaging care experience.

In addition, the ARISE SSH framework will enable a better, more **systematic understanding of the SSH-related challenges arising from human-robot social interactions**, paving the way for the effective implementation of principles and mechanisms pertaining to safe, ethical and privacy-preserving algorithms on the TEF robots.

Challenge 6 addresses the development and implementation of robotic systems designed to autonomously perform fetch and carry tasks within healthcare settings. By automating these routine tasks, the aim is to free up medical staff to focus on direct patient care and other critical responsibilities, enhancing overall efficiency and care quality in hospitals.

Here, we expect ARISE to enable the development of **better 'off-the-shelf' skills for robots interacting with humans**, including social navigation and multi-modal communication.

These improved skills will build on ARISE key technologies (like ROS4HRI) and will be integrated into the ARISE All-In-One middleware.

4.3.2 Redefinition/Remapping of involved Hardware/Software

The TEF3 is focused on software developments integrated on the PAL TIAGo Pro platform. As such, it will involve remapping the key ARISE technologies to this platform:

- Introducing /presenting from ROS 2 Humble to the latest release of Vulcanexus. While we do not anticipate major changes, some adaptations will be required, for instance regarding the networking stack of the robot.

Besides, PAL offers an extensive set of APIs on top of ROS 2; these API will need to be reviewed, adapted, and tested to align with the ARISE technology stack.

- The TEF 3 relies heavily on ROS4HRI. While ROS4HRI is already integrated in the TIAGo Pro platform, we will keep track of the progress of the standard and new ROS4HRI components that might be developed in the ARISE project to upgrade our stack accordingly.

- The robot API and documentation will need update to reflect the ARISE All-In-One Middleware standards and conventions

- The TEF use-cases will be aligned with the SSH framework, also ensuring the actual operationalisation of the SSH framework in terms of APIs, data processing and safeguarding mechanisms on the robot.

4.3.3 Implementation plan

Below is an outline detailing the initial setup plan for the PAL TEF and its associated use cases, to be implemented by Month 9 of the project timeline. This plan encompasses various key activities aimed at identifying hardware and software requirements, upgrading software packages, integrating necessary frameworks, developing monitoring systems, enhancing motion planning, and training operators. The systematic execution of these steps is crucial for the successful deployment and experimentation within the TEF environment, enabling effective testing and validation of human-robot interaction (HRI) solutions.

Step number	Description of activities
1	Identify the hardware and software required for the PAL TEF and use cases
2	Upgrade current software packages of each hardware involved in the use cases (robot control, camera, etc.) and software from ROS1 to ROS2
	Identify in the ARISE SSH framework the main principles and mechanisms that can be implemented on the TEF platform
3	Assessment of Vulcanexus requirements with respect to ROS 2 Humble

4	Upgrade to latest eProsima's Fast DDS
5	Integration of ROS4HRI on the TEF robot platform
6	Documentation of the TEF APIs

Table 6: PAL description of activities.

4.3.4 Expected Results

The expected results section outlines the anticipated outcomes and achievements of the ARISE project. It provides a comprehensive overview of the advancements and innovations expected to emerge from the project's activities, through the ARISE middleware, and improved experimental design support. These expected results form the basis for measuring the project's success and impact on the field of human-robot interaction in industrial settings.

Item Number	Expected Result Description
1	Alignment of the proposed use cases (Challenges 5 and 6) with the developed ARISE enablers
2	An implementation of the SSH framework in terms of APIs, data processing and safeguarding mechanisms on the robot
3	Exploration of new robot HRI-enabled skills, like social navigation

Table 7: PAL expected results.

4.4 TEF 4 [POLIMI]

4.4.1 Analysis of potential exploitation of enablers

The preparation of working space where the defective printed circuit boards (PCBs) need to be reworked is a time-consuming process for operators. The solution to reduce the set-up time of reworking is to utilize the cobot to prepare the workspace in advance, i.e., to select the functional component and tools and to place them in the space that will be used by an operator before the arrival of PCBs and the operator. The control station recognizes the defective PCBs and sends the required information for selecting suitable tools and functional components to be replaced to the refabrication station. In the meantime, an automated guided vehicle (AGV), transports the defective PCBs to the refabrication station where the cobot prepares the required setting by arrival of defective PCBs.

According to the current architecture used in the use case, it is advantageous to further reduce the overall setup time by shortening the time required for data transmission from one station to another one, image processing to identify suitable tools and functional components from the available pool, robot movement, and pick and place action. In other words, to further reduce the setup time and improve efficiency, it is necessary to move toward a more agile solution (cobot).

In the second use case, the cobot improves the operator's ergonomics and comfort during a manual high-precision task in which the operator works on a fixed frame for a prolonged period. The cobot should place and hold the workpiece in the appropriate position and orientation according to the operators' physical features including their height and neck length. Through computer vision, those physical features should be estimated. In addition, the operator should be able to adjust the orientation further by speech command for easier interaction with the cobot.

ROS4HRI framework will enable us to precisely estimate the human body features shortly and with deploying the developed middleware, the cobot will respond to the operator's voice command promptly for further adjustment via a more intuitive interface.

4.4.2 Redefinition/Remapping of involved Hardware/Software

Given the limitations imposed by ROS1, moving towards applying the ROS2 for communication with two collaborative robots as well as the Intel RealSense camera seems necessary especially to address the proposed challenges.
Universal Robot UR5e: the Universal Robots ROS2 Driver[14] will be exploited to fill the ROS1 gaps and security issues.
Franka Emika Panda Robot: the franka_ros2 driver[15] will be benefited after remapping of the software requirements.
Intel D435i camera: the Intel RealSense ROS2 Wrapper allows you to use Intel RealSense Depth Cameras with ROS2[16].

[14] https://github.com/UniversalRobots/Universal_Robots_ROS2_Driver/tree/main

[15] https://support.franka.de/docs/franka_ros2.html

[16] https://dev.intelrealsense.com/docs/ros2-wrapper

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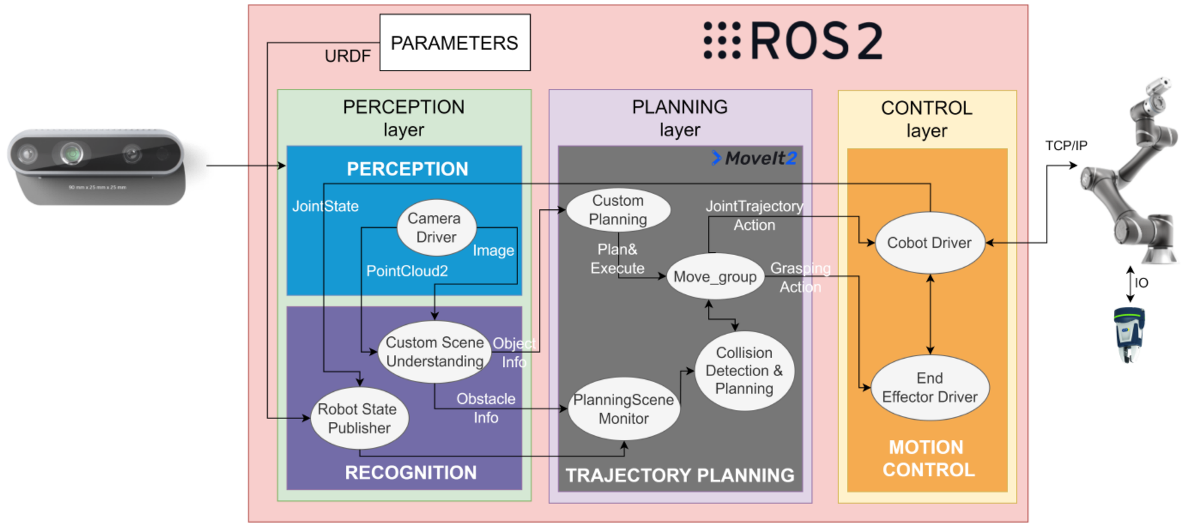

Figure 31: Redefined software architecture for Cobots and Intel D435i.

Currently, the architecture for data acquisition at POLIMI Industry 4.0 Lab known as SHIELD (indeed, SHIELD Has Integrated Existing Laboratory Data) has been presented in Figure 10. For the middleware module, Apache Kafka has been used. Kafka is a middleware designed for data streams, aiming for a low latency high speed platform. Among all its features, Kafka embodies some specificity that are considered in the choice, since it is natively distributed (allowing to have multiple nodes running the middleware, granting scalability and the possibility to work on multiple hardware simultaneously), it is topic-based and grants an internal data storage capability (allowing the middleware to work as a buffer). For the modules development two languages have been selected, based on the required characteristics. For the modules that require flexibility and great data manipulation capability Python3 has been used. These modules are the Orchestrator and the User's module. Considering the ARISE application use cases and current middleware (Kafka), the speed of data transmission and processing from the control station to the reworking one, has not yet been satisfactory for a real time data exchange for the HRI. Hence, we would like to upgrade Kafka with the ARISE middleware.

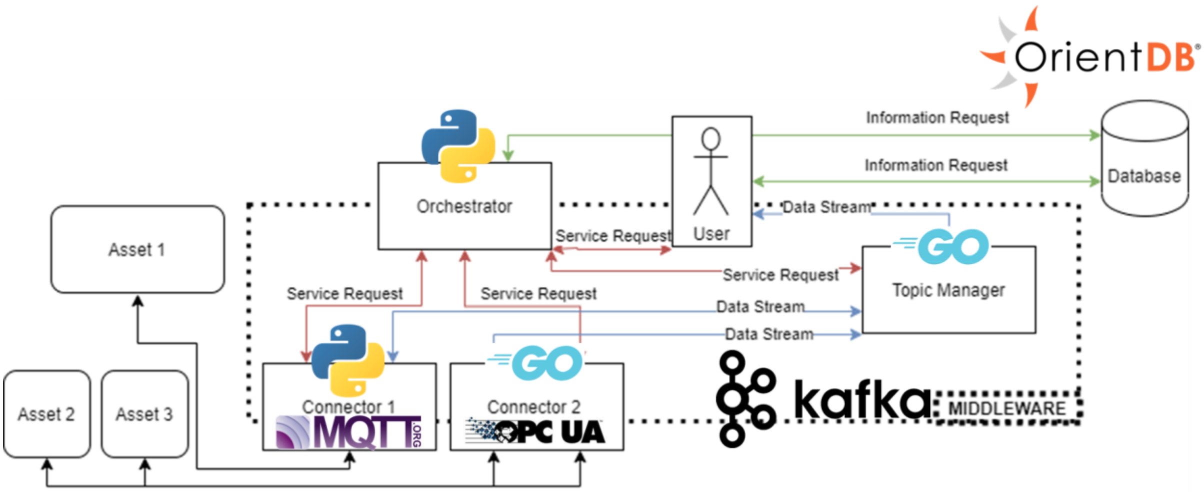

Figure 32: SHIELD Architecture.

The robot operating system used in the experiment was ROS1 Noetic which has limitations including limited real-time processing support, a central master for all communication, and struggle in large-scale and distributed system. Upgrading the ROS1 to the Vulcanexus, which enjoys the eProsima's fast DDS within ROS2 enabling us to improve data delivery with low latency.
ROS4HRI will allow us to obtain the physical characteristics of operators, identify speech commands, and interact with the robot more intuitively.

4.4.3 Implementation plan

The general roadmap of the implementation at POLIMI TEF has been depicted while the technical activities related to proposed use cases have been listed briefly on the table.

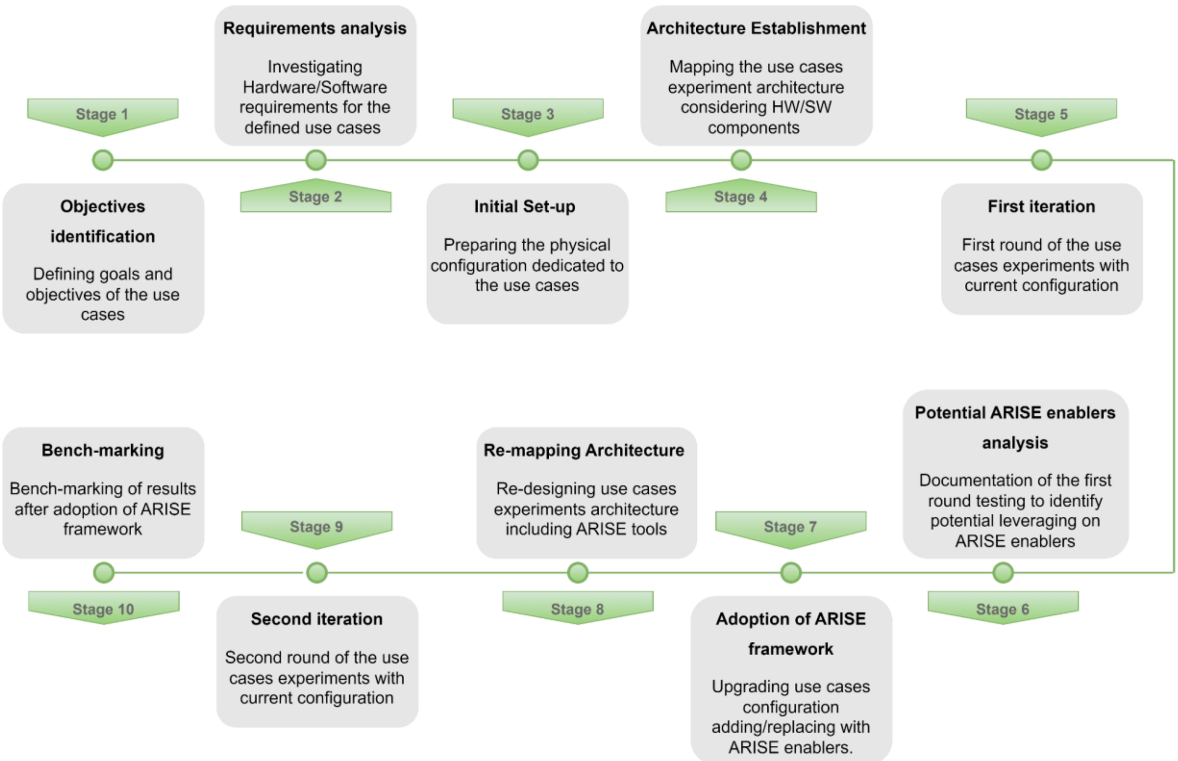

Figure 33: POLIMI Implementation Flowchart.

Step Number	Description of activities
1	Upgrade of existing software packages of each hardware (robot, camera, etc.) from ROS1 to ROS2
2	Acquiring the shop floor map required for navigation and localization of AGV

3	Preparation of a database of available tools and PCB components, i.e., determining which type of tools are suitable for (de)soldering of a specific component
4	Object detection of tools and PCB components via image processing
5	Localization of detected objects with respect to the robot's base reference.
6	Motion planning of robotic arms
8	Extraction of physical features of the operator via image processing
9	Determination of ergonomics and comfort zone of operators according to the extracted physical features
10	Speech analysis of the operator to extract the operator's command to the robot
11	Integration of outcomes of previous steps to achieve HRI/HRC
12	Training of operators to align with the developed solution within the HRI framework
13	Integration of ARISE enablers into proposed use cases

Table 8: POLIMI description of activities.

4.4.4 Expected Results

Item Number	Expected Result Description
1	Set-up of the proposed use cases including hardware and software requirements in order to address POLIMI TEF challenges.
2	First iteration of the use cases to figure out the technical bottlenecks and potential improvements.
3	Assessment of the opportunities offered by ARISE framework.
4	Re-mapping of the proposed use cases with developed ARISE enablers tailored to enhance technical aspects and solve bottlenecks.
5	Second iteration of the proposed use case benefiting from ARISE enablers developed.

Table 9: POLIMI expected results.

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5. Conclusion

To summarize, the ARISE project has made substantial progress in establishing and using testing and experimentation facilities (TEFs) to demonstrate the potential of human-centric, AI-powered, and robotics-based automation solutions for industrial human-robot interaction (HRI). The TEFs, provided by four partners, are intended to demonstrate how ARISE project technologies may solve business problems through human-centric, AI-powered, and robotics-based automated solutions. The TEFs experienced a systematic and iterative procedure, which included selecting industrial issues, designing experimental setups, and analysing ARISE project tools. The results, lessons learned, and produced comments are critical for evolving and better preparing the hosted TEFs to effectively support external experiments in the project's subsequent phases. The ARISE project generated two essential offerings: the ARISE SSH Framework, which guarantees the safety of industrial HRI projects and takes a broad range of ethics-related issues into account throughout the technologies' lifecycle, and the ARISE All-in-One Middleware, which combines various tools and utilities to assist solution providers in reducing costs and efforts in designing and implementing complex industrial HRI projects. The TEFs are outfitted with a wide range of hardware and software elements, such as grippers, cameras, robots, center tables, grippers, and mixed-reality glasses, to enable human-robot interactions and collaborations.