REMODEL - Robotic tEchnologies

for the Manipulation of cOmplex

DeformablE Linear objects

Deliverable 6.1 – Development of the Robotic Platform

Version 2021-10-25

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1. SCOPE

The task T6.1 focuses on selecting, installing, and integrating the plethora of hardware devices, tailored to meet the requirements for each individual Use Cases (UC). The general list of devices commonly used across all the UCs include industrial or collaborative robot manipulators, industrial grippers, Vision System with 3D cameras, safety sensors, safety controller, etc. All the afore-mentioned devices have varied working principles, communication protocols, data libraries and repositories, etc. and the individual components are set-up in their dedicated WPs/ tasks. The integration of these devices with each other and the proper establishment of communication between the other devices and systems, is the core purpose of this specific task.

The deliverable aims to summarize in a concise manner, the various hardware devices utilized in individual use cases. The biggest differences between the individual partners of REMODEL are the hardware they use for performing the various objectives of the project; hence this deliverable prioritizes the description of the hardware solutions. The software developed for each component of the project provides generic functionalities, which could be tailored to each use case as required. Furthermore, the approach to integrate the developed hardware and software components are structured to be generic for all the use cases. Hence the REMODEL system architecture, the developed software components and the integration between the various software and hardware-based subsystems is detailed in a single section.

2. HARDWARE DEVELOPMENTS

2.1. Use Case 1 Platform Description

The platform developed by UNIBO for Switchgear cabling (UC1) is shown in Figure 1 and Figure 2. It is composed by a couple of UR5 anthropomorphic robots and equipped with purposely design end effectors, which details are reported in Figure 3, Figure 4 and Figure 5. The platform simulation has been implemented in Gazebo environment, and the MoveIt-based dual-arm controller has been integrated. The platform has been tested through both simulations and experimental tests. Moreover, the MOVE-RT package has been used for simultaneous motion and collision detection of the two arms. The considered switchgear has a dimension of 600×400 mm and is composed by three main sections where the component are mounted on DIN guides (IEC/EN 60715).

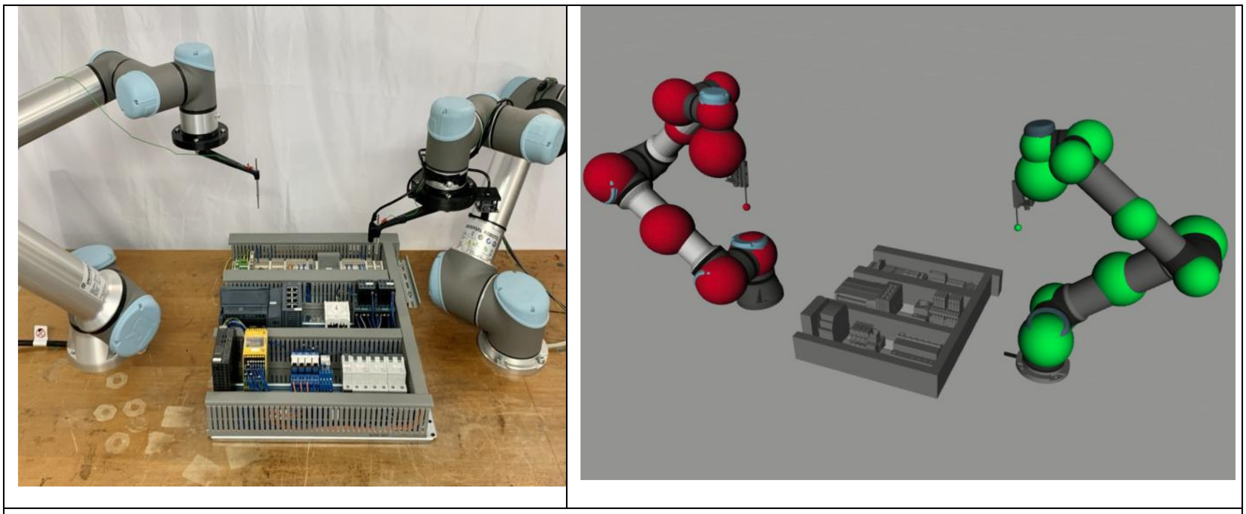


Figure 1: Robotic platform for component detection (left) and collision avidance (right).

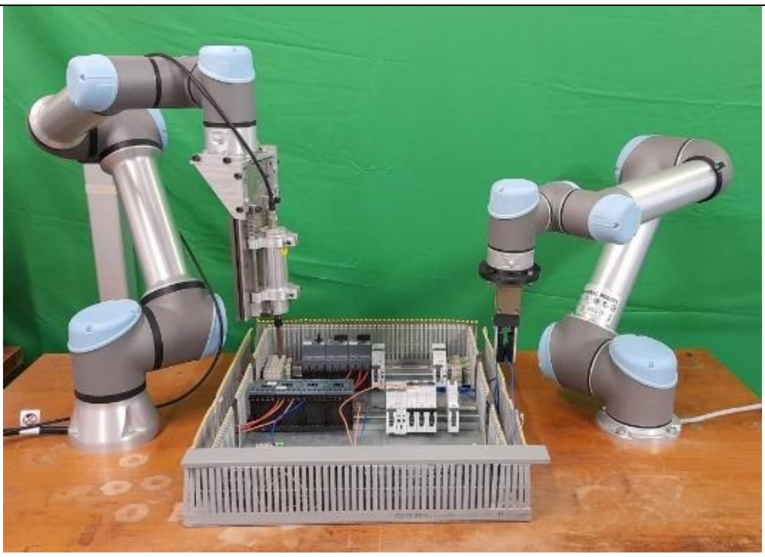
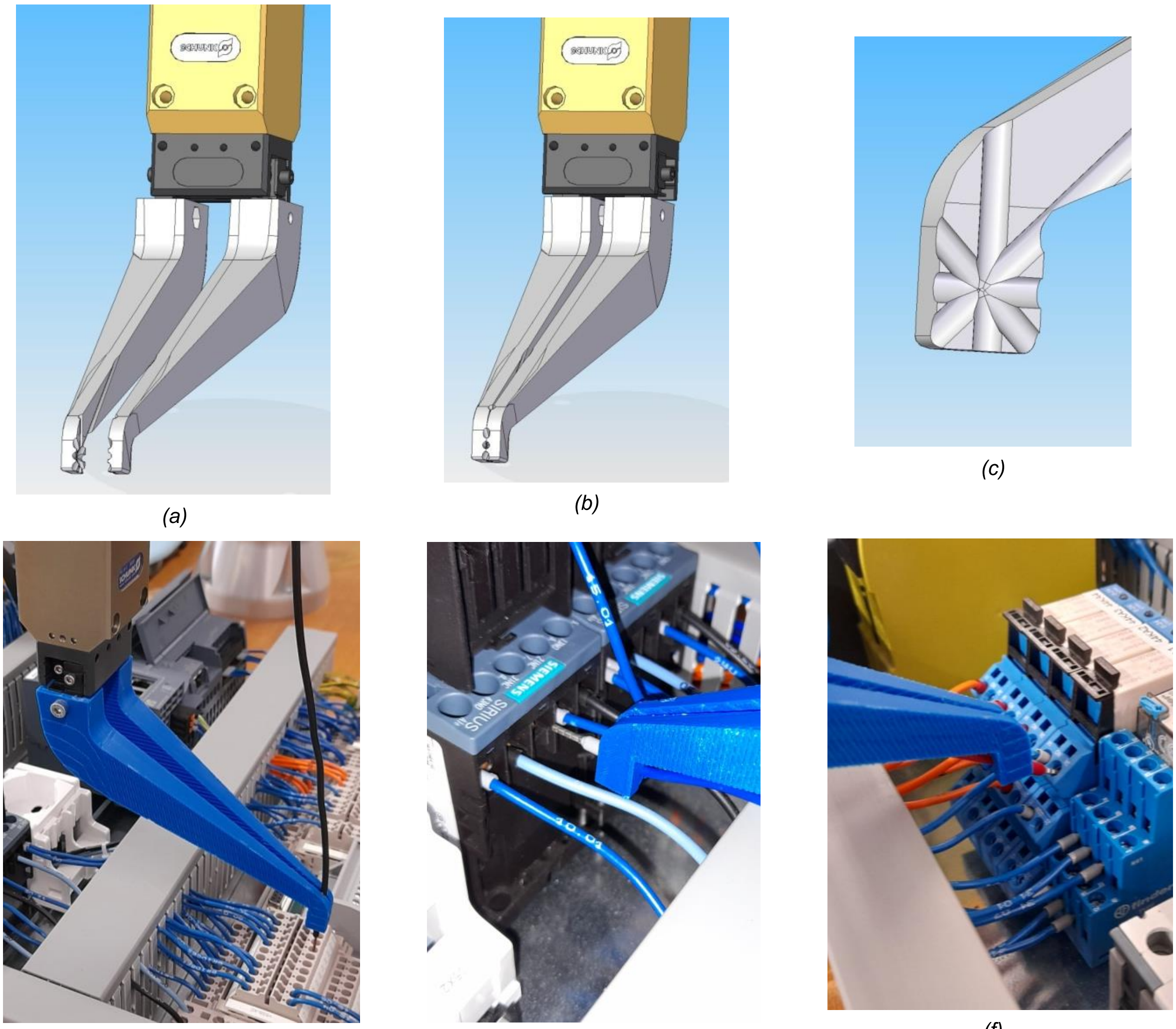


Figure 2: The platform developed by UNIBO for Switchgear cabling (UC1).

Due to the specific requirements of the switchgear cabling use case, specific very thin fingers have been designed to execute the cable grasping and connection. The Schunk MEG 40 electric gripper has been preliminarily selected for this use case due to its reduced size and opening compatible with the application requirements. A ROS package to control the Schunk MEG 40 gripper has been released at it is available in the REMODEL gitlab repository[1].



(a) (b) (c) (d) (e) (f)

Figure 3. CAD design of the fingers for cable connection in UC1 in open position (a), and in closed position (b), detailed view of the finger pad with grooves for cable holding (c), the finger prototypes inserting a cable in vertical direction (d), horizontal direction (e) and at 45 degrees (f).

Figure 3 reports some CAD drawing of the developed finger prototypes. In particular, Figure 3(a) and Figure 3(b) show the gripper in open and closed configuration respectively. Figure 3(c) shows a detail of the finger pad, in which suitable grooves have been included to hold the wire orientation during the insertion task. These grooves allow to hold the cable in horizontal and vertical position and at ±45 degrees of rotation. These fingers have been used to evaluate the cable insertion on different types of components. In particular, Figure 3(d)

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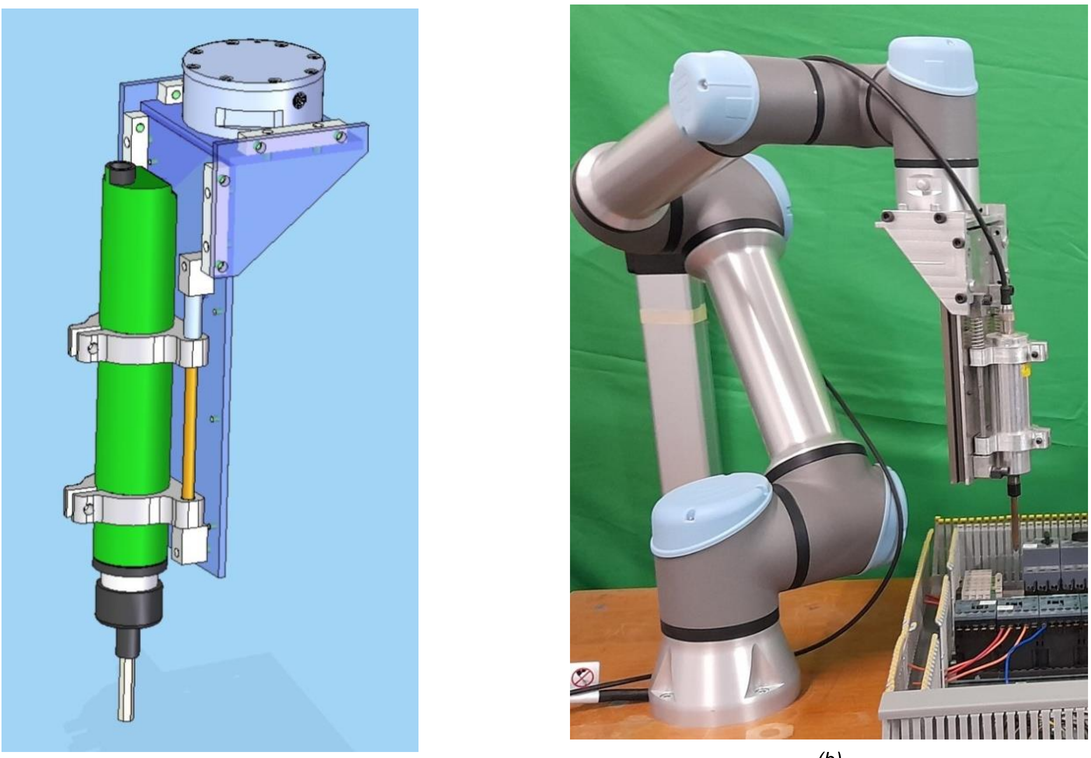
[1] https://dei-gitlab.dei.unibo.it/lar/gripper_meg_40_ec_control_package.

shows the insertion of a cable into a vertical terminal block, while shows the insertion of a cable into a vertical terminal block, while Figure 3(e) shows the insertion on a horizontal screw terminal. Finally, Figure 3(f) show the insertion of a cable in relay blocks at 45 degrees.

The screwdriver tool is composed by an integrated torque/controlled screwdriver with remote PLC control and process data recording capabilities (Kolver PLUTO3CA electric screwdriver + EDU2AE/TOP/E control unit) an by a support for the integration of the screwdriver into the robot. Figure 4(a) reports the CAD model of the tool, while *Figure 4*(b) show its integration with the robotic manipulator in the UC1 robotic platform.


(a)

(b)

Figure 4. CAD model of the screwdriver with robot support (a), picture of the tool mounted on the robot (b).

The screwdriver controller is programmable in terms of rotation speed and maximum torque, and a ROS interface has been developed to in order to select the different program to run depending on the different type of connections to be performed. The software package to control the screwdriver is available at the REMODEL repository2.

A specific tool have been designed to open the elastic clips for the connection on terminal blocks and for the execution of connection check. Figure 5 shows the design details and the prototype of this tool implemented for the system validation.

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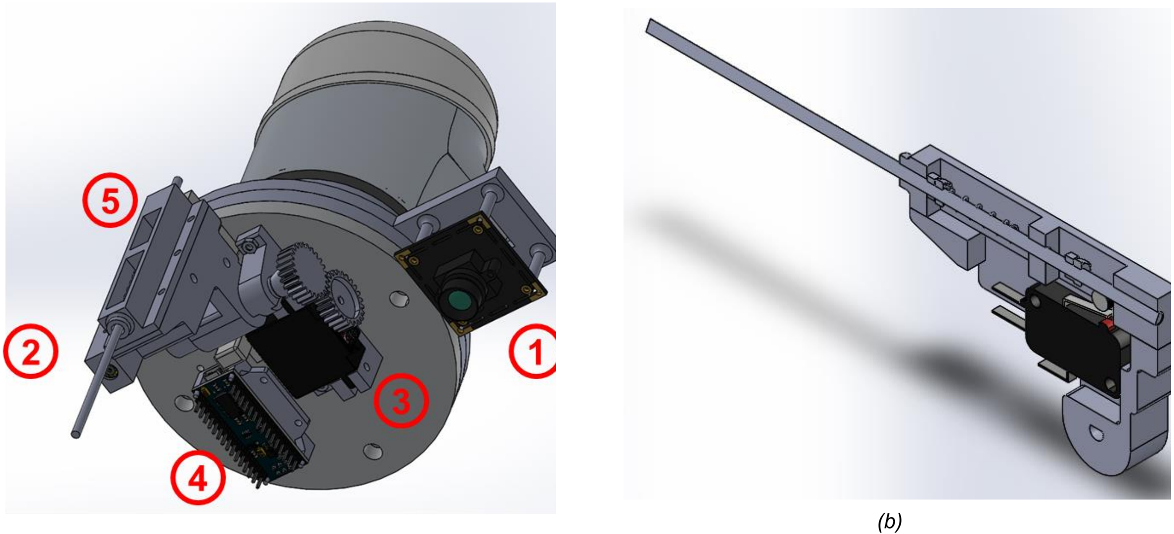
[2] https://dei-gitlab.dei.unibo.it/palli_group/screwdriver_interface

In particular, with reference to Figure 5(a), this tool is composed by:

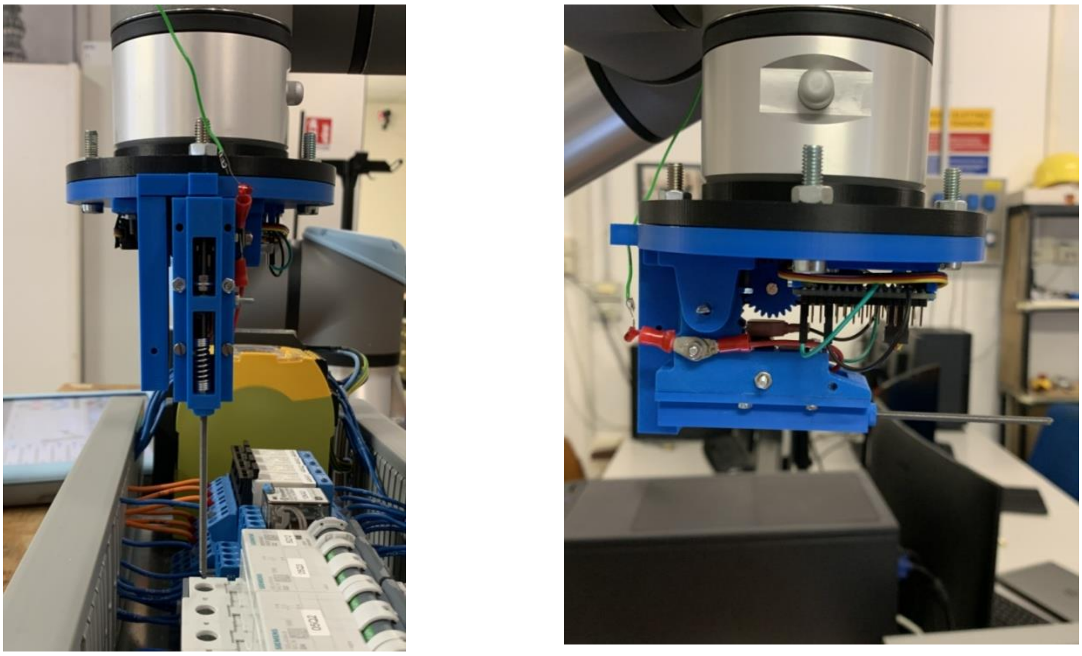
1. 2D USB Camera for component detection;
2. Endoscopic Camera for precise insertion control;
3. Micro-Servo Driver to retract the tool when not needed;
4. An Arduino Nano board to control the tool;
5. A Sliding tester to sense the contact and check the connection.

Figure 5(a) reports also a detail of the mechanism to retract the probe, while Figure 5(b) reports details of the tool suspension and probing mechanism, together with a view of the switch that can be used by the robot to improve the interaction with the terminals. The retractable tool will be combined with the screwdriver in order to be able to operate with both screw and clip terminals with the same tool. A picture of the developed prototype with extended probe can be seen in Figure 5(c), while a picture in which the probe is retracted is reported in Figure 5(d).



(a)

(b)



(c) (d)

Figure 5. CAD design clip opening and testing tool (a), detail of the tool suspension and contact detection mechanism (b), a picture of the developed prototype with extended probe (c) and with retracted probe (d).

The camera mounted on the end effector are used both for component detection and to guide the insertion of the cables, as shown in Figure 6. The 2D camera mounted laterally with respect to the test probe, is used mainly for the initial component localization, this camera module is composed by an average USB camera with a resolution of 640×480 pixel.

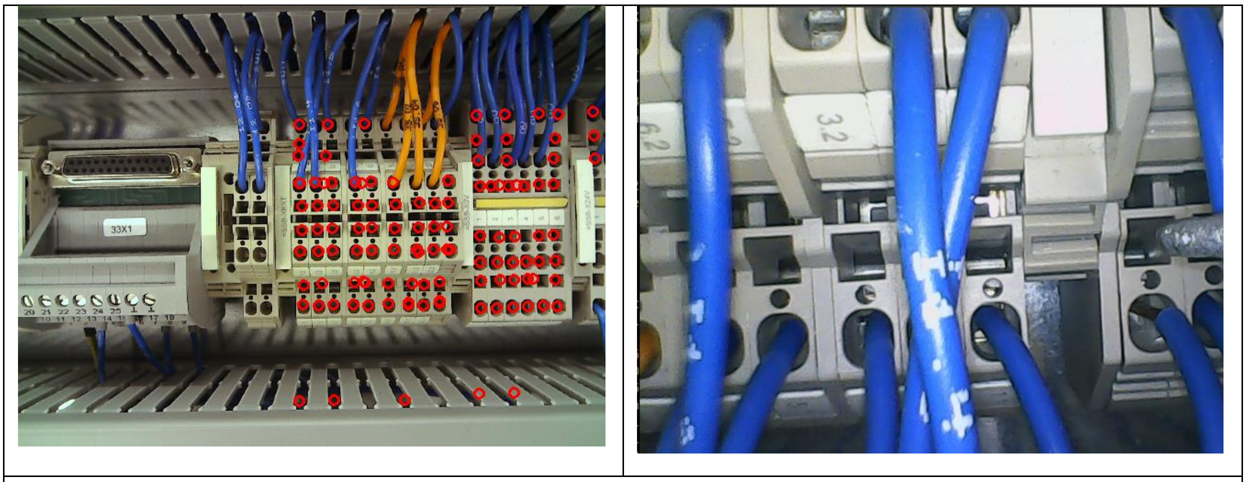


Figure 6: Component detection provided by the USB camera mounted on the tool (right) and closed view provided by the endoscopic camera (left).

The choice of a 2D camera is justified by the fact that they are in general smaller, lighter and cheaper compared to their 3D counterpart, thus the knowledge of the depth offered by 3D camera are not a characteristic used for the component detection since the studied scanning method doesn't rely on distance, which is instead known given the dimension of the database's components. The information coming from the pointcloud map are instead not sufficient precise, and in order to obtain the required precision for the localization, the 3D sensor dimension and cost would be increased.

A second camera can be mounted laterally with respect to the tool, so that is view won't be obstructed by the tool. This camera placed at a different height and optical focus can be used for other application in which the tool is not required to be close to the components, such as switchgear inspection and so on.

Both of the cameras require the knowledge of the intrinsic and extrinsic parameters, so they are calibrated using the same approach, the initial description of the extrinsic parameters were obtained retrieving the information from the CAD files and they been further adjusted by using an eye-in-hand calibration approach based on a chessboard calibration pattern.

The cables prepared by the Komax machine will be collected through a suitably robotic station based on the OMRON Tm5-900 robot with the Robotiq Hand-e gripper, under development by IEMA, as shown in Figure 7. In this robot station, the cables collected in suitable warehouses will be grasped, routed and connected for the robotized switchgear cabling. The warehouse has been designed for different solutions: single wall, multiple wall with rotation and polygonal warehouse. Analysis of the possible collection system has been performed on the basis of usability both for robot and operators and easy transportability.

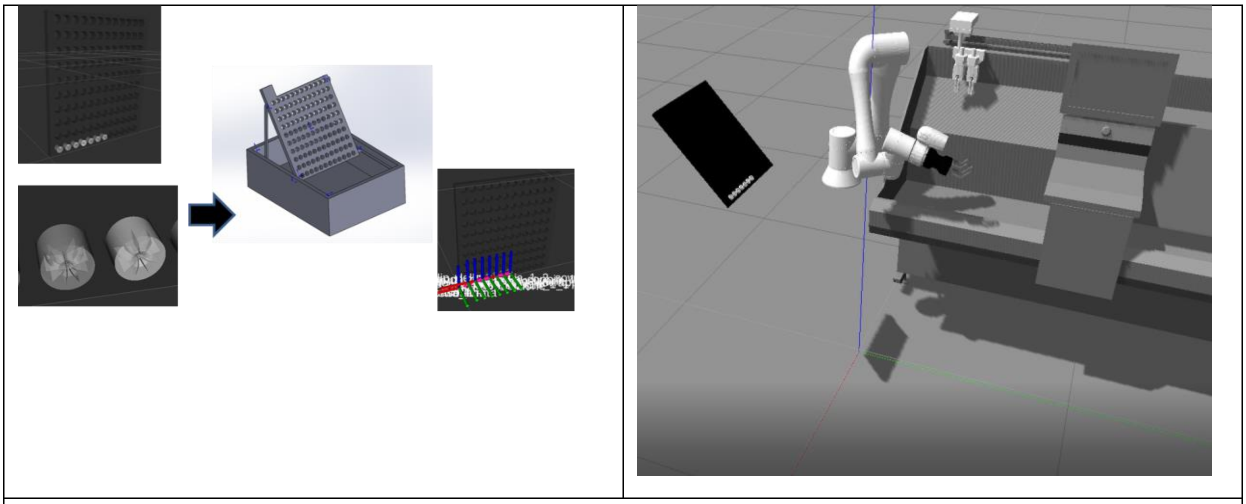
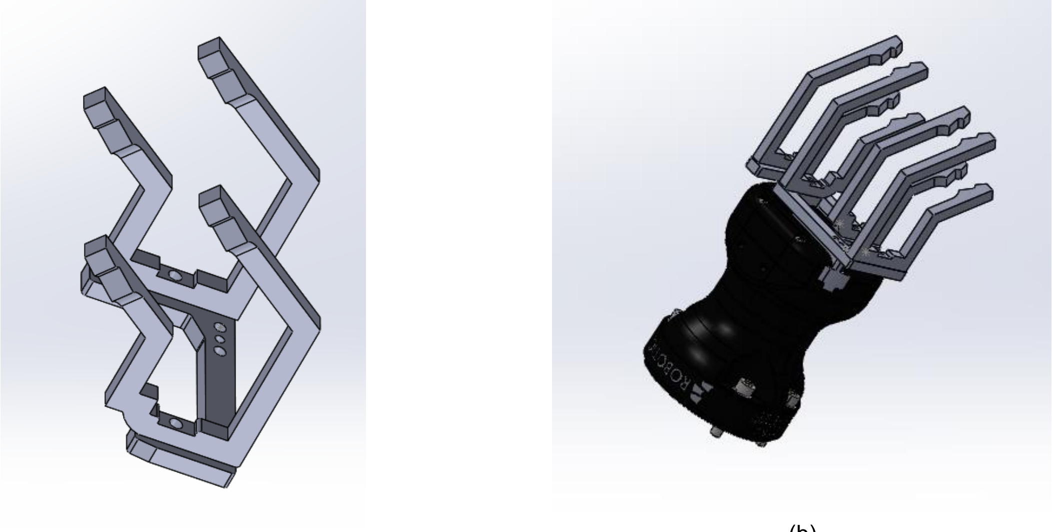


Figure 7: Design of the cable warehous (left) and robot placement for the extraction of cables from the Komax machine (right).

Figure 8 shows the design of the so called crocked fingers that have particularly conceived to deal with the grasping of the cables directly from the Komax machine. The shape of these fingers will couple with the ones used in the Komax machine for the final cable preparation stage. The crooked fingers will approach Komax grasping point from bottom have been designed to be integrated into Robotiq Hand-e gripper. The collected cables are then arranged on a suitable warehouse than can be then moved to the assembly station for both manual and automatic assembly. Suitable clips to be integrated inside the warehouse for cable collections have been designed and mechanically simulated (via FEM) to evaluate its functionality with cables ranging from 0.5mm to 6mm. In T6.2, the design of tactile sensors for the crocked fingers has started.



(a) (b)

Figure 8. CAD design of the fingers for cable production management (a), detailed view of the integration in the hand-e gripper (b).

Mechanical connectors have been developed in order to integrate the sensorized fingers in the Panda gripper used in this use case (see Figure 9). Details about sensor characteristics are reported in Deliverable 6.2. By the end of the project, the use of the sensorized fingers or other custom solutions will be evaluated.

Figure 9 Sensorized fingers integrated in PANDA gripper

2.2. Use Case 2.1 Platform Description

The main hardware piece of the wire harness manufacturing use case of ELIMCO (UC 2.1) is a dual-arm robotic set-up of two Kuka LBR iiwa robots. Specifically, two Kuka LBR iiwa R800 have been selected, robots with a reach of 800mm and a payload of 7kg. Moreover, these robots include torque sensors in each joint and offer force-driven capabilities.

The current layout includes two Kuka LBR iiwa placed side-by-side at a distance of 500mm to allow the dual-arm manipulation of wire harnesses (see Figure 10). The robots are installed in front of a workbench used for the assembly and inspection of wire harnesses. Both robots are equipped with Schunk SWK automatic tool changers with pneumatics and electric power

(24V) to allow a fast tool exchange and a simple placement of different types of grippers and sensors.

Figure 10. Kuka LBR iiwa robots for ELIMCO use case.

The original layout of ELIMCO has been slightly modified from the initial design presented on deliverable D2.4. The preliminary idea was to use a wooden workbench (as the ones used nowadays at ELIMCO, see Figure 11) although it was decided to move towards a perforated workbench with a known hole pattern (Figure 12). The main purpose of this modification is the definition of a new workbench paradigm that will allow the future hybrid assembly of wire harnesses between robots and humans at ELIMCO. The hole patterns allow maintaining the actual manufacturing procedures, besides facilitating the automation and introduction of robots.

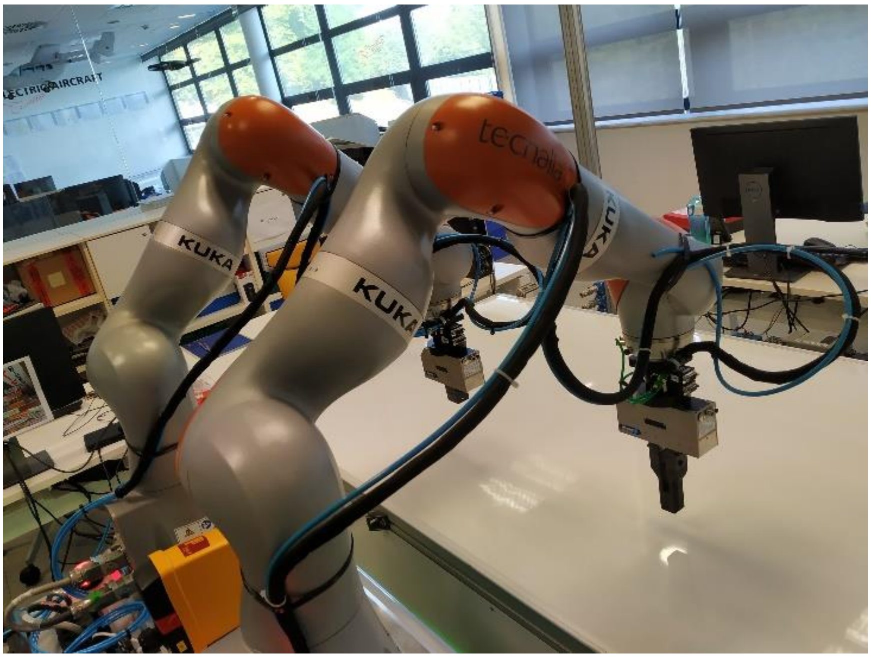


Figure 11. Original workbench for ELIMCO use case.

Figure 12. New perforated workbench for ELIMCO use case.

Finally, the robotic system is completed with Schunk WSG50 grippers for the grasping and manipulation of different elements used during the manufacturing of wire harnesses, as well as the preparation of the workbench for the hybrid robot-human manufacturing of the parts.

Grippers - fingers

Two Schunk WSG50 parallel grippers have been selected (see Figure 13) for the wire-harness manufacturing use case of ELIMCO. This electrical gripping system with integrated control and power electronics offers high precision with force sensing capabilities for manipulating delicate elements such as cables, connectors, and pins.

Figure 13. Schunk WSG50 grippers installed on robots for ELIMCO use case.

Additionally, specific fingers have been designed and installed. These fingers, Figure 14, allow the manipulation of cables and a suitable grasping of the pins used to create the guides on the workbench for the different sections of the wire harness. These fingers allow the manipulation of both types of elements, representing the core elements of the hybrid manufacturing process.

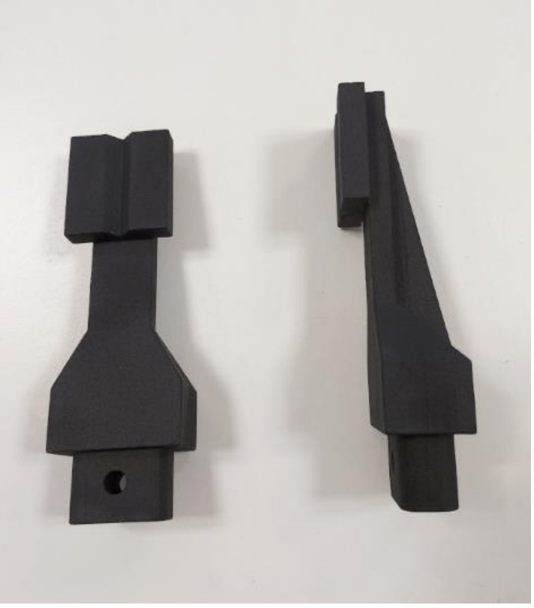


Figure 14. Fingers for Schunk WSG50 gripper in ELIMCO use case.

Suitable mechanical connectors have been developed to integrate the sensorized fingers in the Schunk WSG-50 gripper used in this use case (see Figure 15). Details about sensor characteristics are reported in Deliverable 6.2. By the end of the project, the use of the sensorized fingers or other custom solutions will be evaluated.

Figure 15 Sensorized fingers integrated in WSG-50 gripper

Vision system

A Photoneo MotionCam-3D vision system has been selected as it is the world's highest-resolution and highest-accuracy area 3D camera for dynamic scenes. This laser-based 3D camera generates accurate point clouds without compromising quality loss caused by vibrations, ambient light, or motion blur.

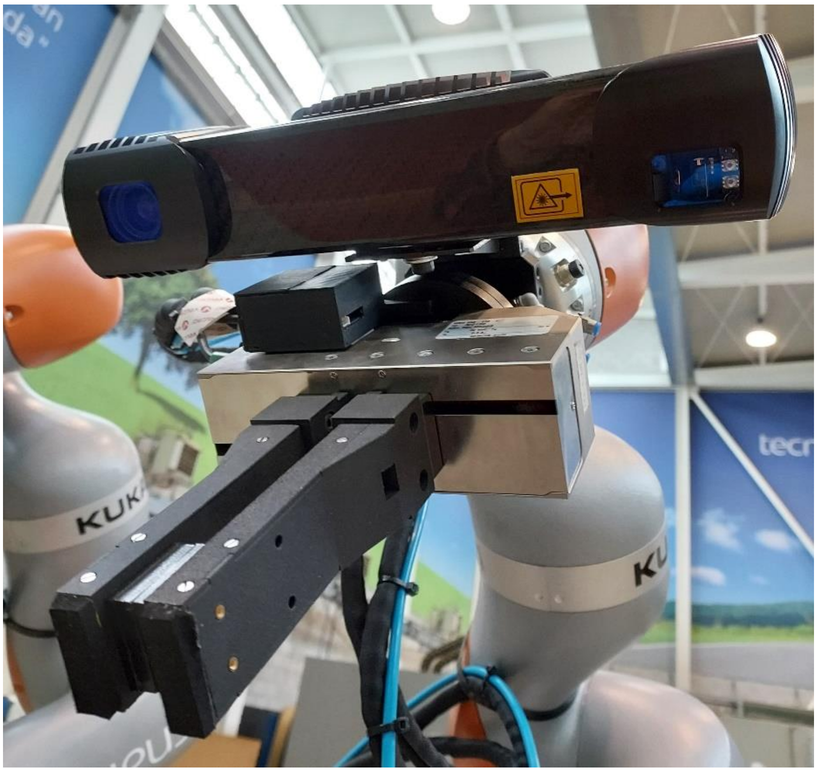


Figure 16. Photoneo MotionCam-3D camera mounted on robot in ELIMCO use case

The camera has been mounted on the flange of one of the robots in an eye-in-hand configuration, see Figure 16. It allows moving the vision system around the workbench and making it possible to detect parts in all the robot's workspace or even reconstruct the whole work environment.

Safety devices

After analyzing the features of ELIMCO's use case, the implementation of a collaborative environment is the most suitable approach from the safety point of view. Specifically, the implementation follows the standard ISO/TS 15066:2016 for collaborative robotics, which allows the creation of a cooperative environment where humans and robots can share the workspace.

Figure 17. Sick FLEXI soft safety PLC, Sick MicroScan3 safety laser scanner and three colour signal lamp

To implement a general-purpose and reconfigurable solution, the proposed approach includes a Sick safety PLC connected to two safety laser scanners and a visual sign (see Figure 17). The selected components are listed below:

- Sick FLEXI soft safety PLC with the following modules
    - Central unit - FX3-CPU000000
    - EFI-pro communication module - FX3-GEPR00000
    - Modbus TCP module - FX0-GMOD00000
    - Two IO modules - FX3-XTIO84002
- Two Sick MicroScan3 safety laser scanners
- Three colour signal lamp

The main idea of the approach is to use the capabilities of the MicroScan3 lasers to define different safety areas around the robotic cell, as shown in Figure. 18. When the safety zones are violated, the laser scanners will activate different digital outputs that will be received by the safety PLC. This safety PLC will manage the different safety signals to perform the high-level safety management, activating the emergency stop of the robots when necessary.

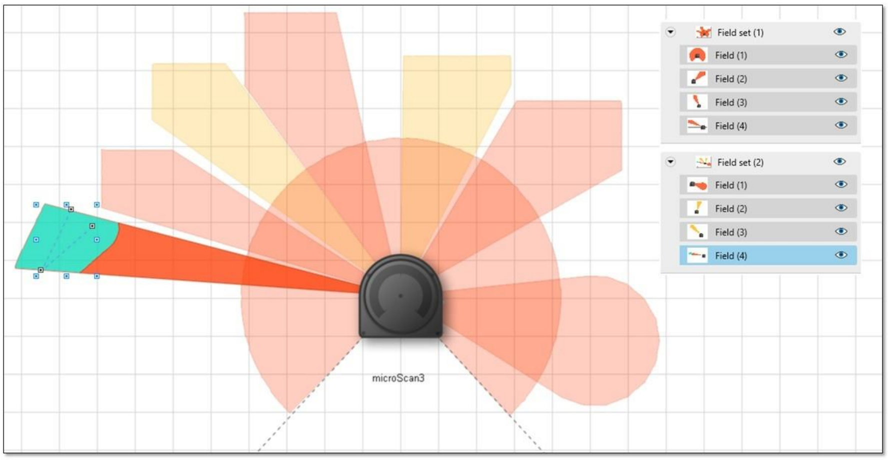


Figure 18. Configuration of safety zones in Sick MicroScan3 sensor

2.3. Use Case 2.2 Platform Description

The manipulator used to perform tests for the wire harness assembly use case (UC2.2) is the Yaskawa SDA10F. See Figure 19 for the manipulator. The manipulator is a dual-arm industrial robot with a payload of 10kg on each arm. The robot is installed in a fully isolated cell, following the IEC safety standards specified for industrial robot work environments. The current implementation of the assembly solution does not follow a collaborative approach for the harness assembly. The cell layout consists of the robot manipulator, the Automatic Tool Changer (ATC) station, the ELVEZ assembly Platform and the comb structure for holding the initial wire harnesses. See Figure 20 for the full cell layout.

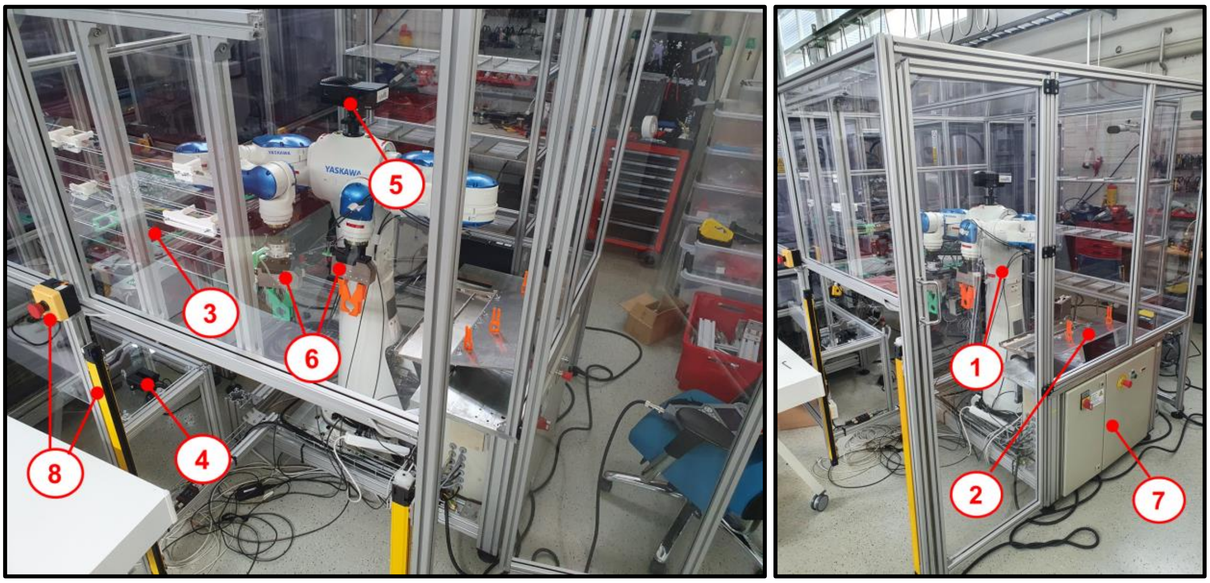


Figure 19. Full robotic cell layout. 1: robotic manipulator, 2: ELVEZ assembly layout, 3: comb structure, 4: ATC station, 5: camera, 6: grippers and fingers, 7: electric cabinet (safety PLC inside and cell power supply inside), 8: safety devices.

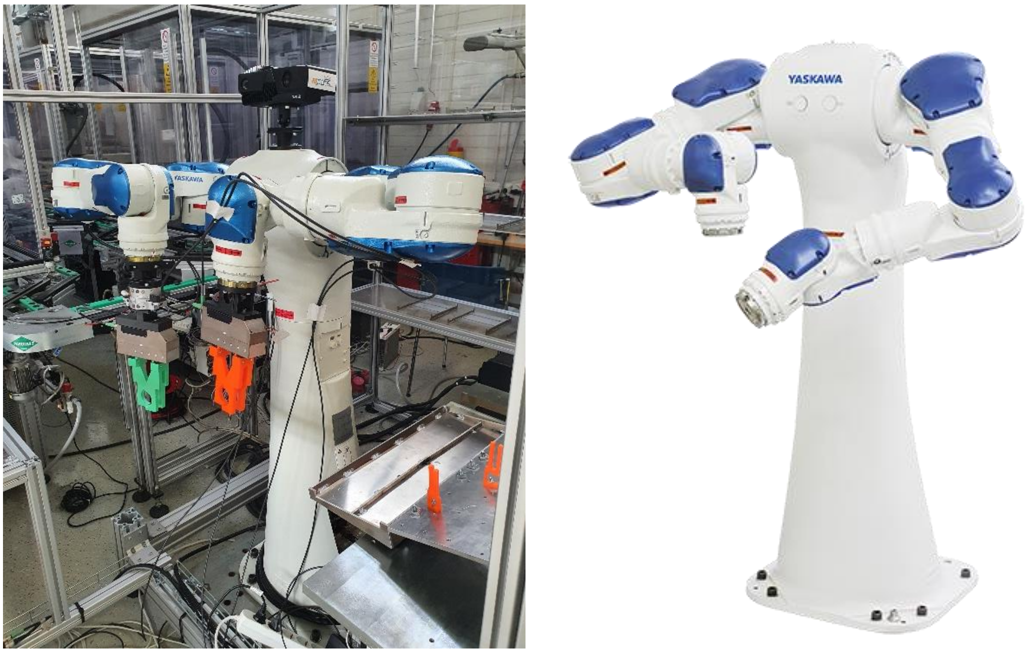


Figure 20. Robotic manipulator. Yaskawa SDA10F.

The ELVEZ assembly layout has been modified from the original design (which was human centric), to an updated version which works more efficiently for a fully robotized setup. The modifications made to the jig involve the removal of the 15degree inclination (from the original human centric layout) to accommodate easier trajectory calculations for the robot. The jigs are updated to consist of a combination of guides with auxiliary columns which acts as a storage buffer, while performing required cable-group separation during the routing process. One of the robot arms will be used to hold the cables (using the end of arm tool) in tension while performing the taping operation See Figure 21 for the ELVEZ assembly layout.

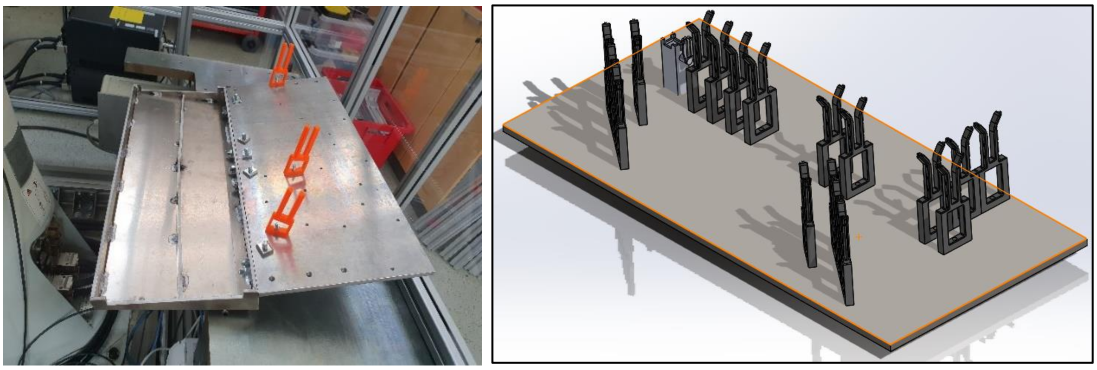


Figure 21. ELVEZ assembly layout. Left: simplified physical layout for simulations, right: 3D model of the final layout that will be implemented.

The ATC station is the region inside the work cell which has the provision for the robot to switch between the WSG50 gripper and the spot taping gun provided by ELVEZ (used in their facilities). See Figure 22 for the ATC station and Figure 23 for the Spot taping gun. Additionally, comb structures are used to hold the individual cable harness sets individually to provide fixed target points, for the robot to pick up the cables at the desired spots. This concession for providing these identifiable target points is to overcome the shortcomings of the 3D camera to identify the individual wires in the harness from the fixed distance and the moderate number of variations in the background setting for the cables. See Figure 24 for the comb.

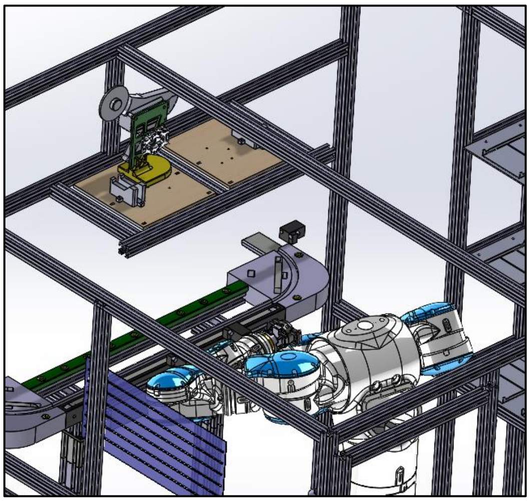


Figure 22. ATC station. Its location inside the cell.

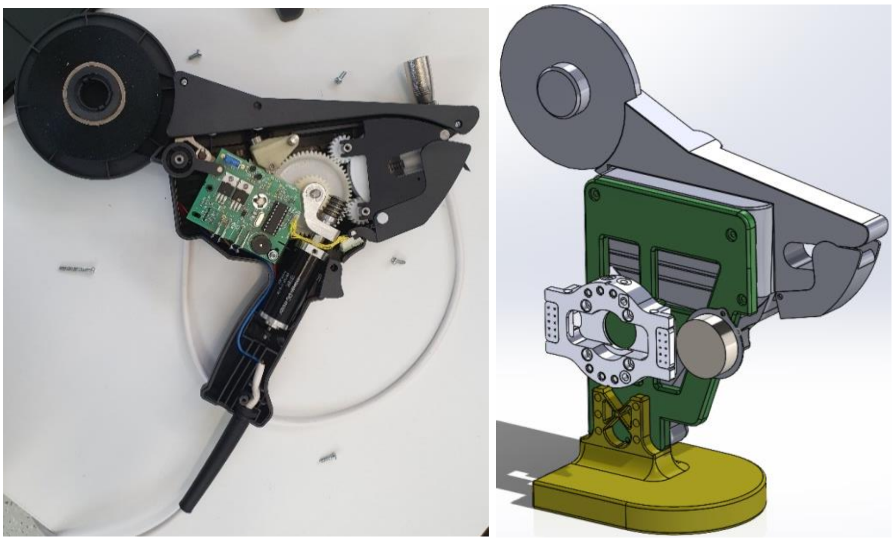


Figure 23. Internal mechanisms of the ELVEZ spot taping gun during its analysis and the finalized adapter to mount the gun and attach to the tool changing module

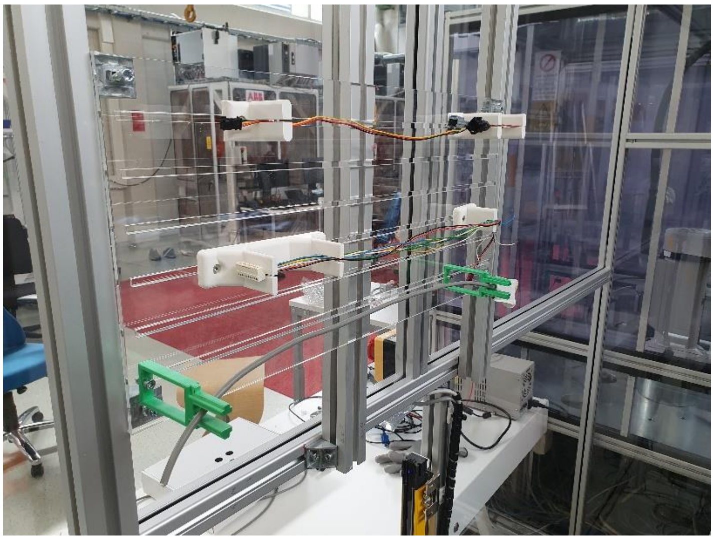


Figure 24. Comb structure. Its location inside the cell is shown in Figure 19

The positioning of these subsystems inside the robotic cell was determined by using MotoSim, to determine the ease with which the robot could access these locations with as many link configurations as possible.

Grippers - fingers

Two WSG50 parallel grippers from Weiss robotics are mounted on both the arms of the Yaskawa SDA10F. The gripper was primarily selected to support the tactile sensing fingers. See Figure 25 for the gripper. The grippers have high precision and good speed control sensitivity, and they are retained for these traits while using our own fingers, specially updated to handle the cable groups. The fingers serve a dual purpose depending on the grasp distance of the gripper- they can be used to grasp connector heads and cables; and they could also be useful in sliding across the length of the cable groups. See Figure 25 for the Fingers.

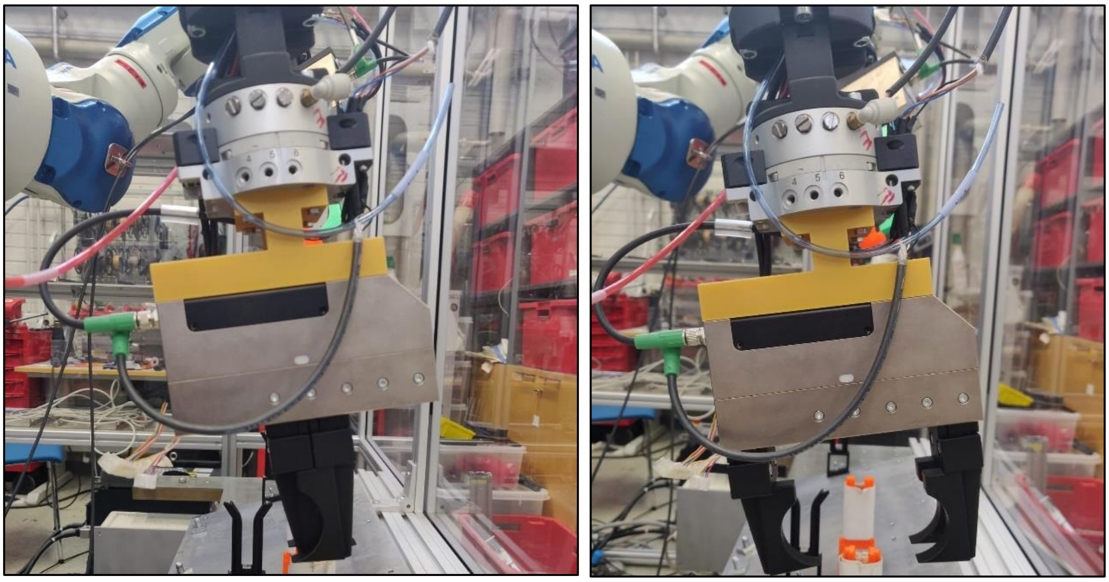


Figure 25. Robot grippers and cable guiding fingers. The ATC can be seen in both the images

Camera

The camera determined **to** be the most suitable for this use case is the Zivid One, the 3D colour camera works on the structured light technology and has very high point precision and dimensional accuracy. See Figure 26 for the camera. The camera is mounted on the torso of the robot and it is capable of detecting the cables position, orientation, entanglement status. This is especially useful while trying to manipulate a single wire element of a grasped cable while performing the required cable routing operation.

Figure 26. Zivid One camera mounted in the robot

PLC Controller - safety devices

The safety of the robotic cell is compliant with the IEC standards for industrial robots. The safety PLC used is an Omron CSG320 with provisions for Digital and Analog input and outputs. The safety logic is and created and exported to the PLC by using the proprietary software Sysmac studio, which was developed by the manufacturer. After the logic for the system safety is updated into the PLC, the requirement for Sysmac studio is eliminated in this implementation. See Figure 27 for the safety PLC.

The safety devices which are currently used in this UC, to detect any cell intrusion or safety compromise are safety curtains from Omron, Door switches and E.stops. The light curtain is primarily used to prevent any other entity except a mobile robot (unrelated to REMODEL) to enter the robotic cell. The door switches are used to prevent a human from entering the cell while the robot is online and is performing any operations. And the Emergency stops are used for stopping all activities inside the cell by an external observer, to prevent accidents or as a safety precaution while entering the cell. See Figure 28 for safety devices. The robot is also connected to the safety PLC, wherein it could generate a signal to signify if the safety of the system has been compromised due to collision.

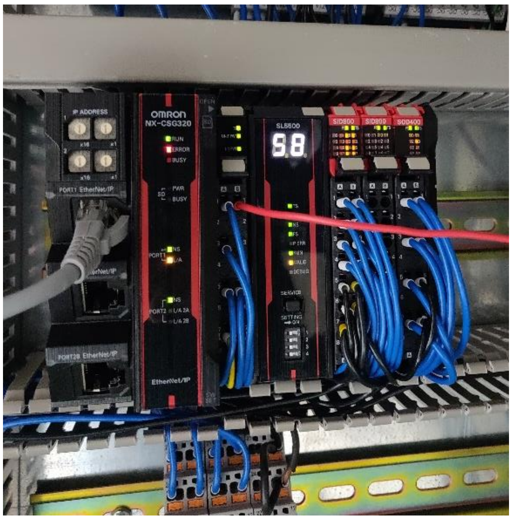


Figure 27. Safety PLC. Its location is shown in **Error! Reference source not found.**7.

Figure 28. Safety devices: Emergency stop buttons, light curtains, and a door switch.

2.4. Use Case 3 Platform Description

The robotic platform for this use case consists of the cockpit palette, the cockpit wiring harness, two manipulators with grippers, accompanied by the vision-based perception system, and safety devices. The development of this system was divided into 2 stages. The first one, realized on the PUT side, was related to the TRL4, while the second one will be created in the VWP factory in the cooperation between PUT and VWP. In general, both platforms share a common structure, but they differ in terms of the used hardware and the physical dimensions of the system. The overview of the platforms is presented in Figure 29 and Figure 30. Moreover, in the second stage of the use case, the check of the electrical connections in the already mounted cockpit has to be made with the use of the ECOS system (see Figure. 31).

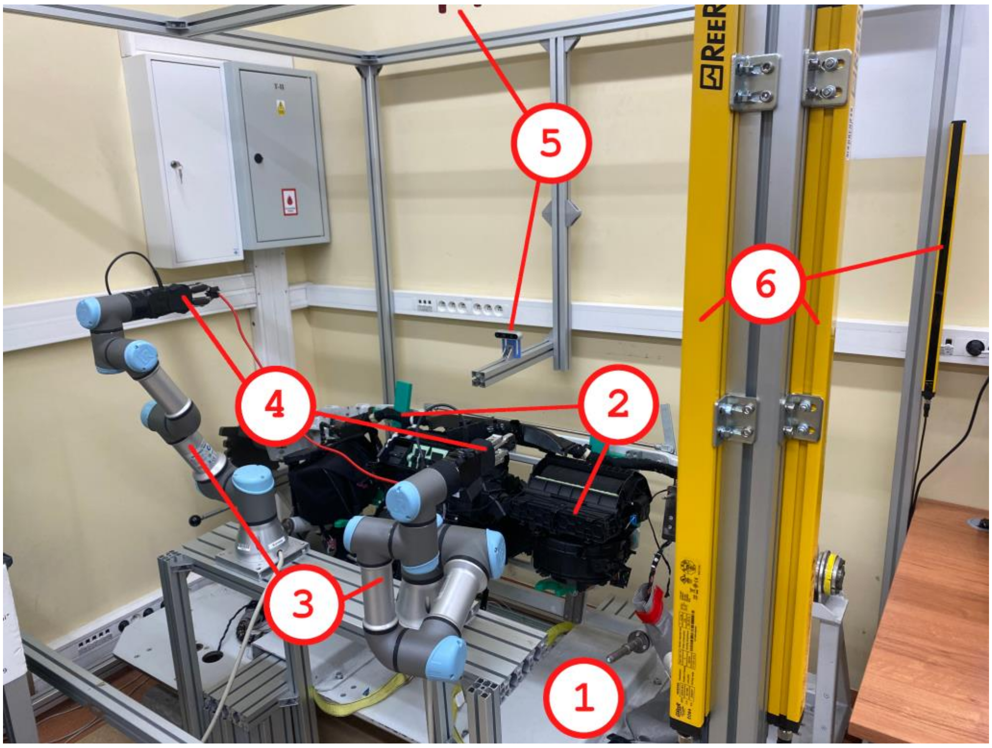


Figure 29. Overview of the robotic cell layout at PUT: 1. cockpit palette,
2. wiring harness, 3. UR3 manipulators, 4. RG2 grippers,
5. Intel Realsense D435 cameras, 6. safety laser curtains

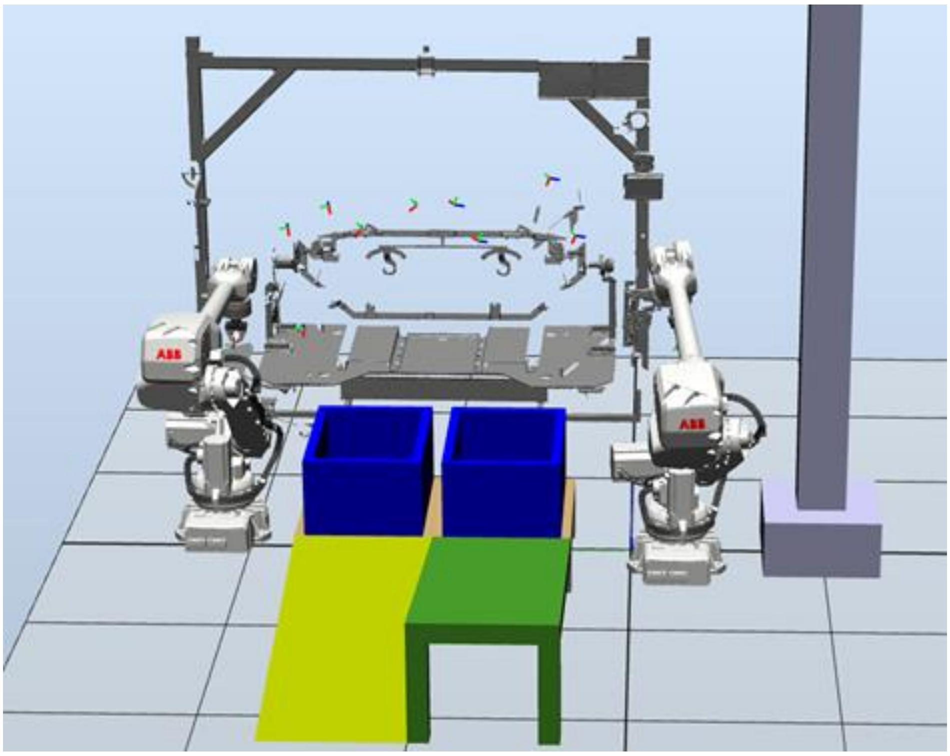


Figure 30. Simulation of the proposed ABB robots, boxes, and cockpit palette in ABB Robot Studio (due to free-of-charge license)

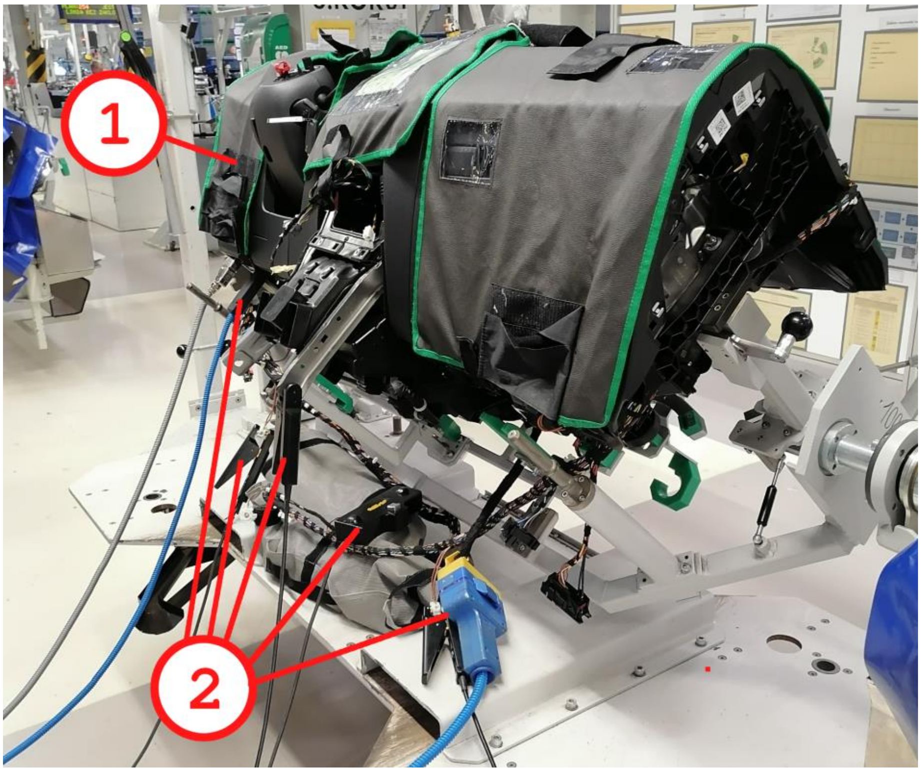


Figure 31. Already mounted cockpit (1) with the ECOS system probes plugged in (2).

Cockpit palette, wiring harness, and ECOS probes

The cockpit palette and wiring harness are the main components of the task that the proposed robotic system is meant to solve. The cockpit palette, presented in Figure. 32, is used to organize the locations of the wiring harness segments in the cockpit. The wiring harness, shown in the transportation box in Figure. 33, consists of multiple branches which vary in terms of length, thickness, and electrical connectors mounted at their ends, packed in the bags, or hanging loose. In both setups, the full-sized palette and harness were used. In Figure. 34 the ECOS probes on the handler are presented.

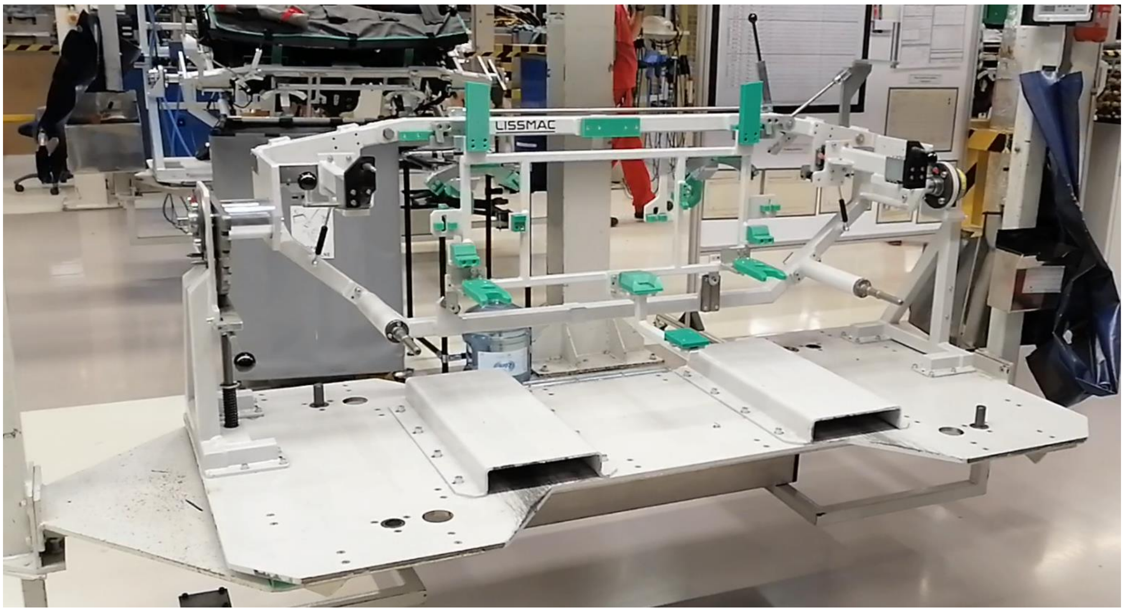


Figure 32. Cockpit palette at the beginning of the assembly sequence

Figure 33. Wiring harness in the transportation box

Figure 34. ECOS probes on the handler

Manipulators

To manipulate the wiring harness considered in this use case, two robotics arms are used. In the case of the TRL4, the UR3 manipulators were used to manipulate low-weight branches located in the middle of the palette. However, for the TRL5 and 6, full-sized robots able to carry and manipulate the whole harness are required, therefore robots of one of the following types will be used: ABB IRB 4600 or Kuka - KR 50 R2500 or Fanuc - M710iC/45M. Each of them has approx. 40 kg payload in total as also a 20 kg armload and a range of 2.55 m.

For the development of TRL4 we used standard RG2 grippers designed to use with UR3 manipulators. However, they are not designed to work with cables, as their relatively small gripping force does not allow them to firmly grip the thick branches, thus for later experiments in the laboratory we 3D printed strong grippers that do not have this drawback.

Suitable mechanical connectors have been developed to integrate the sensorized fingers in the OnRobot RG2 gripper used in this use case (see Figure 35). Details about sensor characteristics are reported in Deliverable 6.2. By the end of the project, the use of the sensorized fingers or other custom solutions will be evaluated.

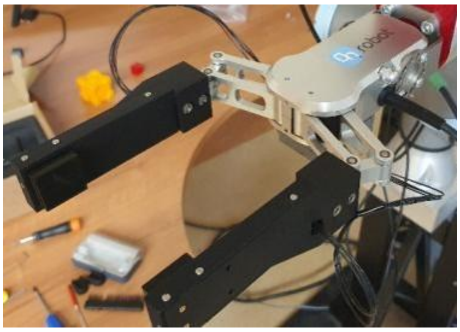


Figure 35 Sensorized fingers integrated in RG2 gripper

For the next stages, we will install our own designed industrial grippers with one degree of freedom on both robots, so that they can easily exchange tasks with each other. Those grippers, due to the high stroke, will be able to handle objects of different sizes, starting from single thin cables and ending on big bags of cables.

Vision-based perception system

The vision-based perception system used to demonstrate the TRL4 abilities consisted of 3 Realsense D435 cameras, one mounted on the top of the robotic cell and two on the sides of the cage frame. While those cameras are enough to support the system with the visual feedback and information about the specific parts of the harness, like connectors, their abilities to reconstruct the depth map of the scene are not sufficient. Due to that, for the TRL5 and 6 we will use more accurate Kinect Azure RGBD cameras mounted on the manipulators, to actively recognize parts of the harness crucial for the manipulation procedure, based on its shape and color. Moreover, we will support them with the Photoneo MotionCam 3D L, which is a high-end depth camera that characterizes with a very high framerate, required by the time limitations and the dynamics of the wiring harness, and high depth accuracy. This camera mounted on the top of a cell will be able to support the robotic system with information about accurate positions and orientation of the wiring harness branches.

Safety devices

To ensure the safety of the robotic cell in the laboratory at Poznan University of Technology, we decided to use cooperative robots, but we also equipped the cell with 2 pairs of laser curtains, that switch off the whole system if anything intrudes the workspace, and the safety button.

In the case of the VW factory, for the duration of the project / demo, white-red barriers will be placed at the appropriate distance. Also, at least two emergency-stop buttons will be available, one will be mounted on the cabinet control and the second one on the teach pendant. Furthermore, the basic and expert profiles will be added to the robot's panel, thanks to which any random or unauthorized person would not be able to activate any process, what is more, not even able to turn on any motors. In the future, for the TRLs above the scope of the project, the system will be equipped with light curtains and safety scanners which would be managed by PLC.

2.5. Use Case 4 Platform Description

Figure 36 shows the design of the robotic station for medical hose manipulation (UC4) and its integration in the extrusion line and with the surface preparation toll and the microscope for surface inspection.

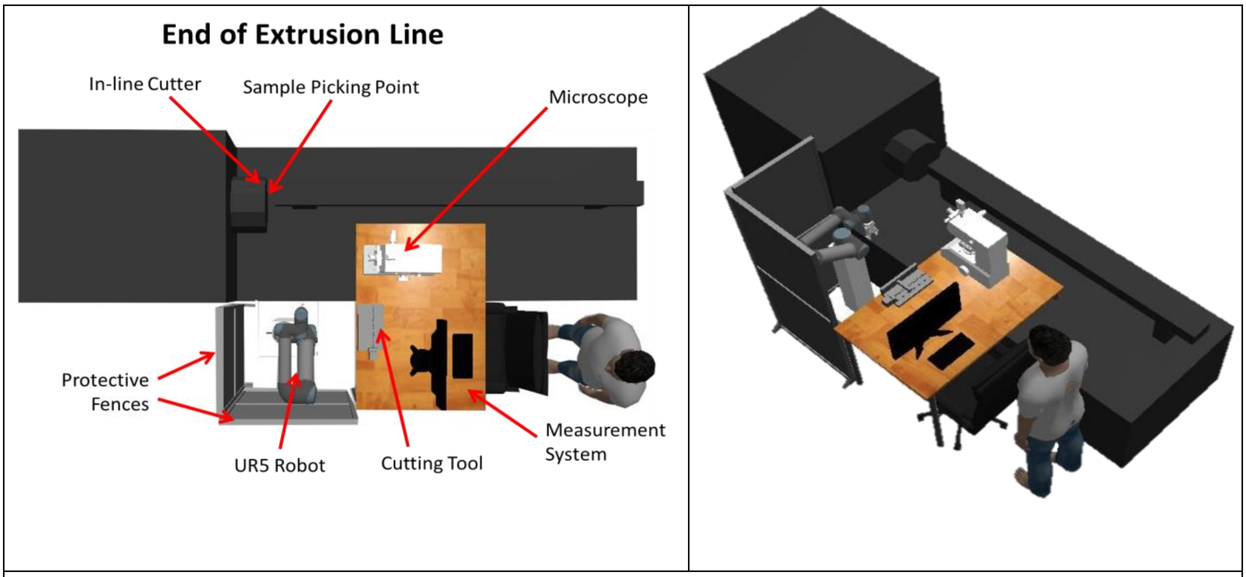


Figure 36: UC4 Robot Station Design.

In Figure 37 the platform developed by ENKI for UC4 is shown. The robotic platform is composed by UR5 anthropomorphic robots and Robotiq Hand-e gripper. This platform has been tested in simulation within the Gazebo environment and and experimental tests have been executed in lab environment to implement hose grasping with the UR5 and Robotiq gripper. This platform will be exploited to test the manipulation task on the extrusion line. Integration with the extrusion line is under development.

Figure 37: the platform developed by ENKI for medical hose manipulation (UC4).

As already mentioned in Section **Error! Reference source not found.**, suitable mechanical connectors have been developed to integrate the sensorized fingers in the Panda gripper (see Figure 9). By the end of the project, the use of the sensorized fingers or other custom solutions will be evaluated.

A devoted automatic tool for the preparation of the medical hose surface for quality analysis has been designed. After the evaluation of several alternative solutions, the design is now focused on multiple comb-type wheels that maintain the alignment for the hose during the execution of the cut. Figure 38 reports some CAD examples of developed tools. The surface preparation tool will be controlled by a local board and will be provided with a user interface to enable its usage by human operators.

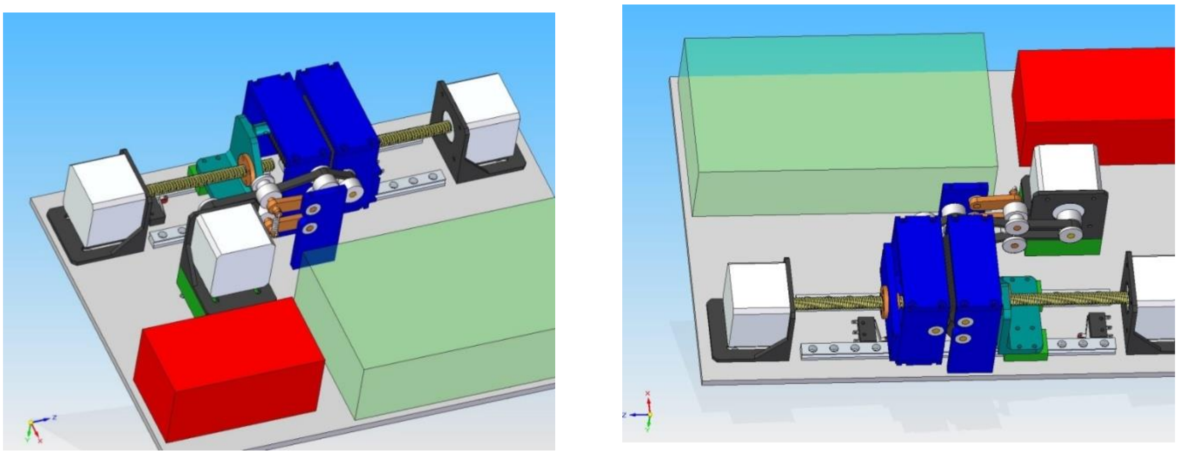


Figure 38. CAD model of the surface preparation tool for UC4: back view (a) and front view (b).

3. SOFTWARE INTEGRATION

In this section the overall software architecture of the project is presented. This architecture (shown in Figure 39. REMODEL system architecture) integrates the modules developed individually in the different work packages, and it is common for all the use cases.

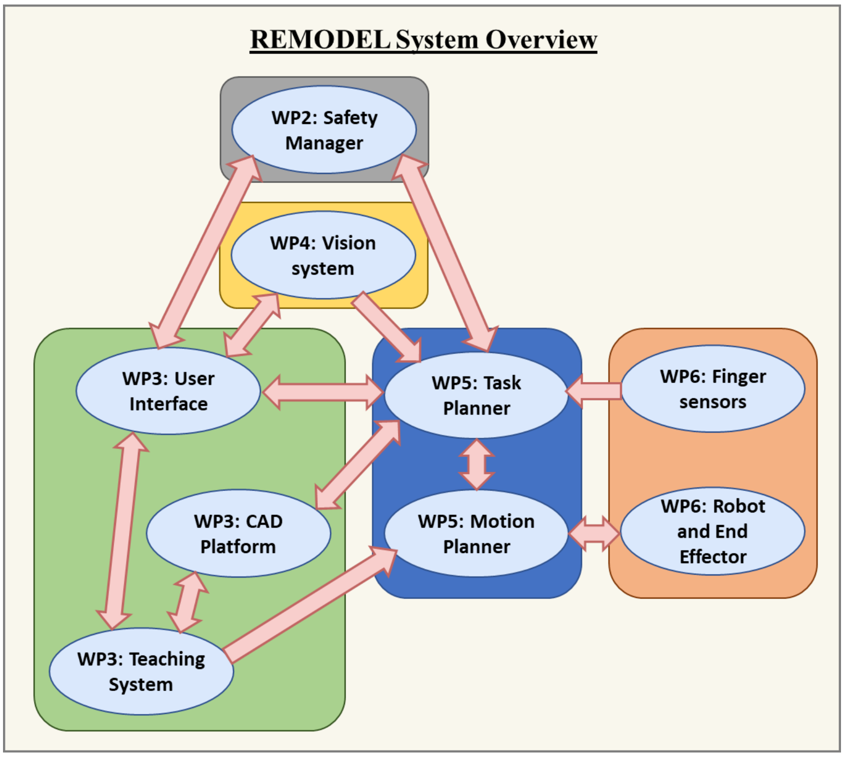


Figure 39. REMODEL system architecture

There are some differences on how each module is implemented for each use case, but the communication between them and the type of information they share is common for all of them.

ROS

Robot Operating System (ROS) is the primary middleware utilized by all the individual systems and sub-systems in this implementation to communicate with each other. The systems and sub-systems are modelled as nodes and they can communicate with each other through topics, services and actions. A dedicated Linux computer with ROS installed has the systems modelled into packages and enables the inter communication between them and with external devices, such as the robot, sensors, PLCs…

WP2: Safety manager

The REMODEL Safety Manager (RSM) manages the communication between the physical safety devices and the rest of the ROS system. It communicates with a safety PLC through and Ethernet/IP socket, however, the PLC is the device which executes the safety protocols and handles the information from the various safety devices of the robotic platform. And on the other hand, it communicates with the User Interface (UI) and the Task Planner through ROS Topics. The communication goes in both directions. Thus, the safety PLC can notify the RSM about some alarm and then it makes this information visible on the UI and informs the Task Planner to start some corrective action; but the communication can also start from the ROS system, when an alarm is detected by the Task Planner or with the UI stop button, this information is received by the RSM that informs the safety PLC to immediately stop the robot operation. This same process happens when resetting, it can be started from the PLC side notifying the ROS system, or the other way around, resetting through the UI. More information about this specific module will be available in M32 and M48 in the Deliverable 2.6.

WP3: CAD Platform

This module is the information system of the REMODEL system. It collects and processes data from different files and databases- providing useful information about the manipulated components, the workbench layout, and the process to different modules of the system through ROS Topics and Services. Especially, when the Task Planner needs any kind of information about the process (such as, the next operation to perform, the coordinates of some Point of Interest of the workbench…), it requests it to the CAD Platform through a ROS Service. The Teaching system can also require information to this module, for example, to be able to identify the specific positions in which the demonstrated processes take place. More information about this specific module will be available in M40 in the Deliverable 3.1.

WP3: User Interface

The User Interface (UI) allows the interaction between the user and the different ROS subsystems. It shows relevant information about the various REMODEL sub-systems to monitor it. This information is obtained from different ROS Topics i.e., the process information coming from the Task Planner or the safety status coming from the RSM. Additionally, it allows also to interact with the system, starting a stopping the process execution (through the Task Planner), resetting the alarms (through the RSM), controlling the Teaching system or calibration the vision system, also through ROS Topics and Services. This ROS communication with the UI happens through the rosbridge package. More information about this specific module will be available in M44 in the Deliverable 3.2.

WP3: Teaching system

Currently the Teaching system is still under development and several strategies are being followed by different partners. However, the main outputs of this module, depending on the requirements of the specific use case, will be a set of trajectories that will be sent to the Motion Planner module and a list with the sequence of macro-actions and locations to perform the process, that will be sent to the CAD Platform that will store it as information about the process. The Teaching system will be commanded by the UI. All these communications will happen, again, through ROS Topics and Services. More information about this specific module will be available in M47 in the Deliverable 3.3.

WP4: Vision system

The overall perception tasks in WP4, including the vision system, can be divided into four critical subtasks important to the entire REMODEL system. Namely:

Implementation of the multi-level camera system

3D dynamic environment mapping

Cable detection and tracking

Functional component detection

In the first task a detailed and thorough benchmark of eight depth sensors has been conducted. This benchmark gave us more insight in the performance of each depth sensor and, thus enabling us to help with the selection of depth sensors for each use case. For more details, please refer to deliverable D4.1.

The second task is mainly about multi sensor fusion in order to get a complete and accurate reconstructed 3D scene of the environment, i.e. work cell. A working solution of the global and local sensor calibration within a simulation environment has been showcased. The remaining work in this task is to transfer our framework to real-world scenario and evaluate its performance. As for now, we anticipate that the outputs of the 3D dynamic environment mapping will be mostly used within the vision system pipeline and thus won’t be “visible” to the entire REMODEL system. The only aspect of the 3D dynamic environment mapping, which will be provided to the REMODEL system, is sharing a collision model with the motion planner. as well as information from the human intrusion detection module.

The detection modules still being under development in tasks 4.3 and 4.4 are expected to provide task specific information to the REMODEL system. We are anticipating that the main required output information of those two modules will be the 6D poses of the grasping points of the wiring harness, as well as the 6D poses of functional components. The mentioned 6D poses will be crucial for the manipulation modules within the REMODEL system. A third detection module with further detect human intrusions to the workcell and report their presence to the task and/or motion planner modules**.**

WP5: Task planner

The REMODEL planner will leverage on a set of low-level actions, implemented as ROS action servers with standardized interface, able to react to changing products and environmental conditions thanks to the input of the sensors (vision, force and tactile sensors) and of the production knowledge database (T3.1). Those low-level actions can be combined in macro actions or directly called by the REMODEL planner. Therefore, the REMODEL planner will establish for each task to be carried out along the manufacturing (e.g. the connection of a cable, the routing of a wire, the placing of a connector) which is the set and the order of low-level actions and macro actions, each of them addressing a subtask, required to accomplish the task itself. This selection will be performed on the base of the information provided by the product database (T3.1) according to the task and component description, by means of a proper association between task and component characteristics and the required actions to be involved in the task execution.

The REMODEL planner will be based on the FlexBE capabilities, in order to facilitate the definition of new behaviors (i.e. combination of low-level and/or macro actions) and to exploit its behavior engine to run and monitor the task execution. FlexBE behaviors will be defined as nested state machines, in which each state will address the execution of a single task operation.

A new REMODEL behavior generator exploiting XML notation for the automatic definition of FlexBE behaviors will allow for an easy and flexible implementation of new behaviors and macro actions during task execution.

The REMODEL planner will feature four levels of abstraction to properly address and generalize to all the REMODEL use cases:

A Use Case Supervisory level for the dynamic definition and implementation of each manufacturing application according to the information provided by the production knowledge database (T3.1)

A Task Supervisory level for the execution of each task behavior (e.g. full deployment of a single cable in a gearbox)

A Behavior Control Level for the execution of macro operations (e.g. the connection of a cable, the routing of a wire, the placing of a connector)

An Action Control Level for the execution of each single operation (e.g. detect the cable, pick the cable, place the cable) through ROS actions servers.

System failures in the execution will be specifically handled on the corresponding level according to the severity of the problem.

The Use Case Supervisor (Figure 40) will generate and implement the ordered sequence of tasks provided by the production knowledge database (T3.1). The Use Case Supervisor will be also connected to the User Interface defined in T3.2 to enable the user to monitor and interact with the execution of the robot tasks. By exploiting the REMODEL task behavior generator, it will define and implement the FlexBE state machine for each specific task through dynamic composition of macro operations and actions.

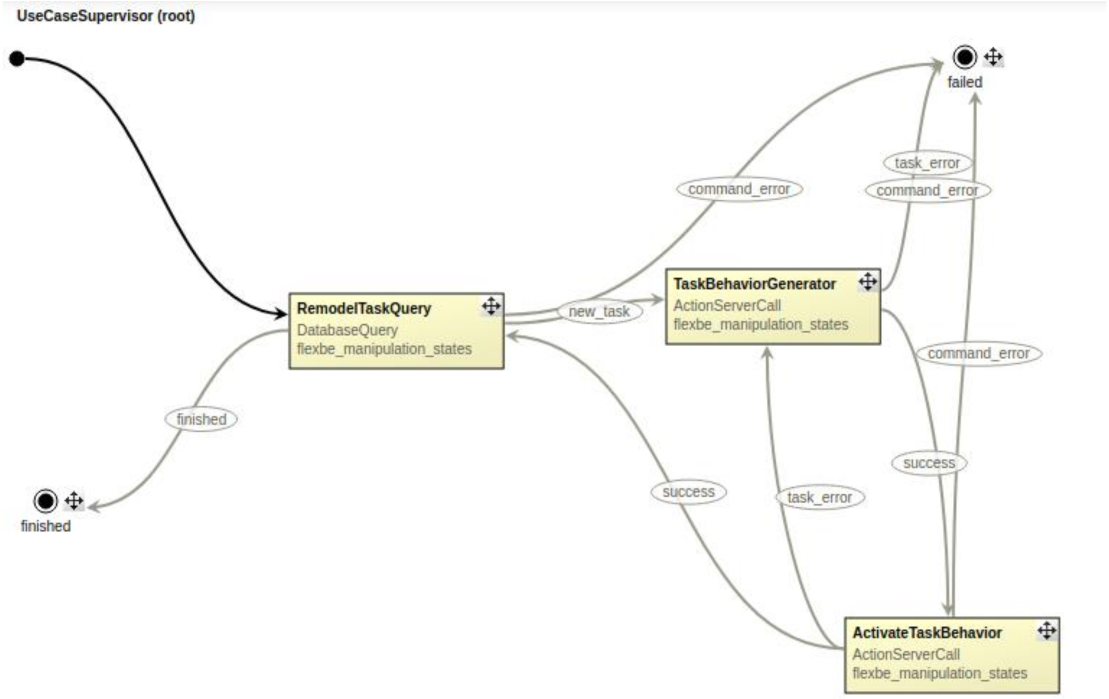


Figure 40: The Use Case Supervisor.

At the beginning of the process or every time a task is completed successfully, the supervisor will automatically load the information for the next task from the production knowledge database (T3.1) and implement its new state machine if not available or simply launch it if already available. In case of failure in the execution of a task, the supervisor will exploit the information provided by the system (sensor data, failure information) to rebuild the state machine or change the parameters to address the arisen problems, eventually by including some action to repeat the required measurements. The generation of task behaviors and failure policies will be implemented according to the user specifications. The vector of task parameters will be passed along the state machine and implemented in each step of the work at the action server level.

Each task behavior (see Figure 41) is composed as a series of actions (yellow blocks) and low-level behaviors describing macro-actions as placing a connector or routing a cable (purple blocks). The task supervisor monitors the execution of each task and send any failure information to the use case supervisor in case a new planning is needed.

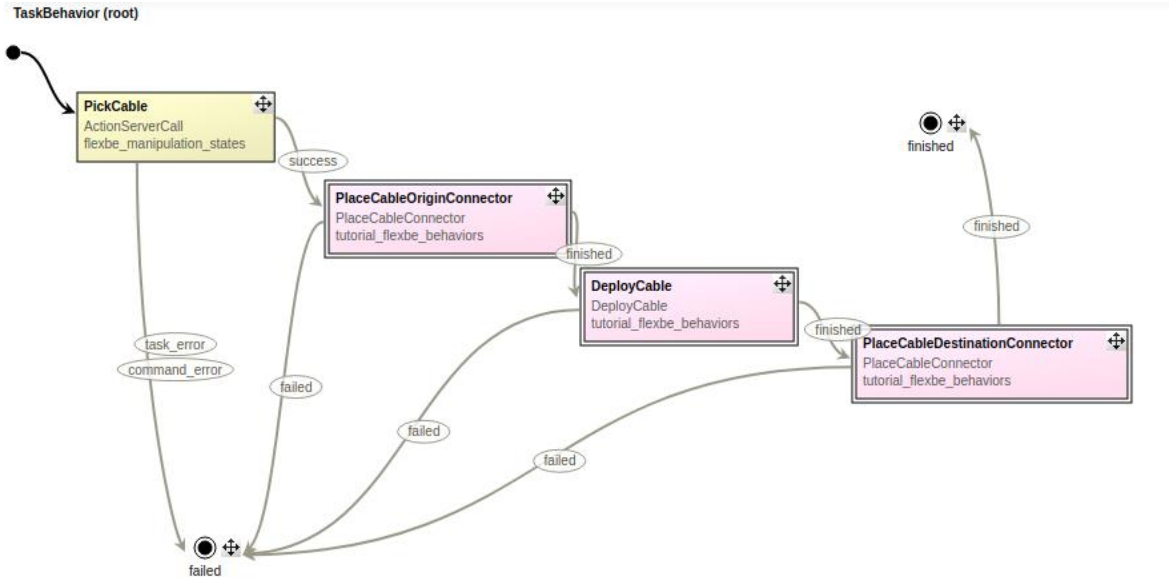


Figure 41: The Task Supervisor.

Each low-level behavior is defined as a state machine implementing several actions and failure policies. Behaviors that have been defined previously can be nested inside a new behavior according to the task needs. Any new behavior will be generated through the REMODEL behavior generator during the planning phase of each task.

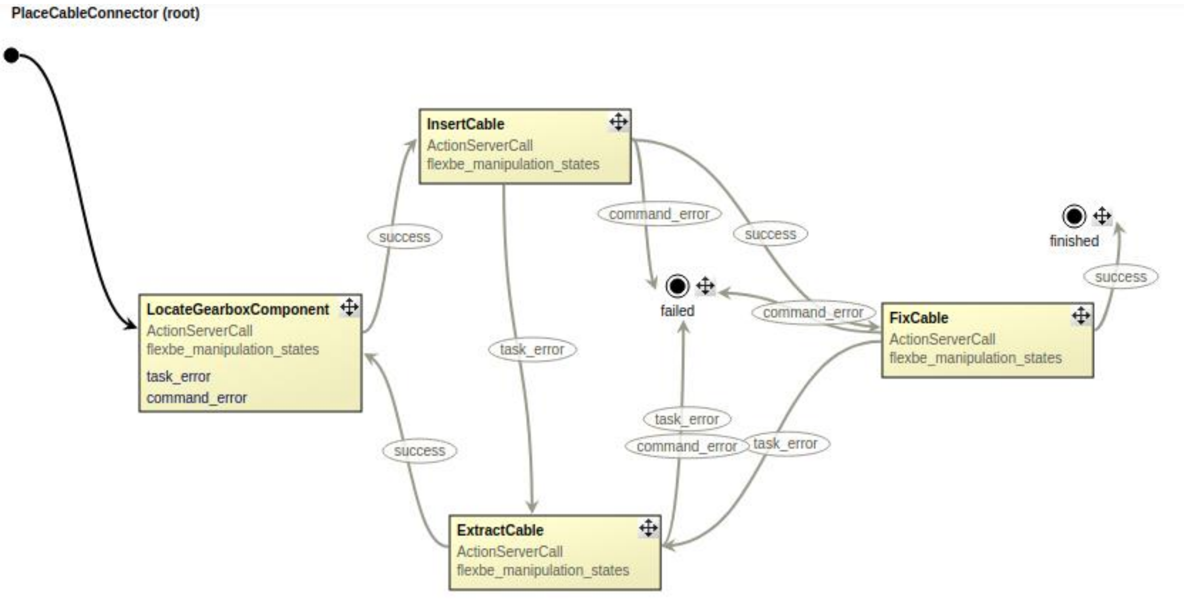


Figure 42: The state machine for the place connector operation.

In Figure 42 an example of a state machine for the placement of a cable connector is proposed. For a different task, the sequence and type of action servers to call will change accordingly. The system is characterized by three actions and a failure recovery state. By traversing the state machine, the system will localize the requested component and connector through the product data and a vision system (LocateGearboxComponent state). and will perform the insertion of the cable (InsertCable state) and the fixing of the connector (FixCable state). In case of failure for environmental causes (wrong detection, unsteady deployment, etc.) a recovery action will be attempted (ExtractCable state) and the localization will be performed again. The number of attempts for each state and their recovery policies will be defined according to the user request. In case of repeated failures or in presence of external factors affecting the task, the system will mark the operation as failed and send all data available to the supervisory level for real time modifications of the state machine.

WP5: Motion planner

The MOVE-RT package is used by UNIBO as motion planner and controller for UC1 since it addresses the need for a standardized modular approach to the task priority control. A detailed description of the MOVE-RT functionalities and interfaces as well as its source code is available at https://dei-gitlab.dei.unibo.it/lar/move_rt. MORE-RT is particularly suitable for mobile manipulators operating in dynamically changing environments and in presence of human operators. Task priority control enable the real time execution of several robotic tasks running in parallel and organized according to a specific hierarchy establishing the priority among tasks, i.e. lower priority tasks do not influence on the behavior of higher priority ones. Common tasks for a robotic manipulator are singularity avoidance, joint limit avoidance, collision avoidance, joint speed limitation other than conventional end-effector position control. This motion planner and controller receives the trajectories and the execution commands directly for the task planner through the implemented action command interface.

WP6: Finger sensors

This subsystem consists of two ROS nodes. The first one reads data from the tactile and proximity sensors and it makes them available by publishing the information on specific ROS topics (more details on this can be found in Deliverable 6.2). The second node, instead, elaborates data coming from the tactile sensor to obtain parameters representing an approximation of the wire shape, which can be a first or second order polynomial, and it publishes these parameters on specific ROS topics (more details on this can be found in Deliverable 5.2). Both these nodes are the same for all the use cases and, by the end of the project, the development of custom nodes depending on the needs of the application will be evaluated.

WP6: Robot and end effector

This last subsystem is not really a ROS module. It refers to the communication between ROS and the robots, using ROS Industrial packages, and end effectors (EE), also including the mechatronic tools for grasping and manipulation developed in WP6 (more information about this can be found in Deliverable 6.3), through specific ROS packages. These commands will be sent mainly from the Motion planning module, and the robot and EE will also send their status as feedback to the ROS system.

4. CONCLUSION

This deliverable tries to summarise the progress of the REMODEL project in the aspects of the individually developed hardware, software, and their integration in all the use cases. The hardware developments section highlights all the equipment utilized by the individual test-bed owners of the current versions of the use cases. The software development secion describe the individual sub-systems developed and their interactions with each other, in the REMODEL system architecture.