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REMODEL - Robotic tEchnologies for the Manipulation of cOmplex DeformablE Linear objects

Deliverable 2.7 – Second assessment of system performance

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1 Scope

This deliverable reports the expected performance from the point of view of the different use cases that will be shown in the final demonstrators. The benefits on the quality of the work environment provided by the adoption of the REMODEL technologies will be analyzed with focusing on the improvement with respect to the previous condition of full manual work.

This deliverable will provide an evaluation basis for the project impact that will be assessed during the final evaluation at M48.

2 UC1 - Switchgear Cabling

This use case is devoted to the investigation of a robotized solution for switchgear wiring. Switchgear wiring represents a very challenging industrial application from the point of view of the manipulation tasks. Switchgears are basic components of power generation, transformer and distribution stations, commercial and institutional buildings, industrial plants and automated factories, automatic machines and civil houses.

2.1 Manual switchgear wiring

As a matter of fact, in switchgear wiring:

- human-like sensitivity is required to cope with unpredictable occlusions and assembly complexity due to the variety of layouts, see Figure 1 and Figure 2;
- the manipulation of Deformable Linear Objects (DLOs), i.e. the wires, is needed, see Figure 1 and Figure 2;
- paper documentation is largely used, see Figure 3, in particular for wiring, that implies long time and worker experience for documentation reading, interpretation and translation into the required assembly sequence;
- no standardized production lines exist due to the product variability of spatial allocation and dimensions, see Figure 1 and Figure 2, and the production is characterized by highly-customized, if not unique, products.

It results that, in most of the cases, **the switchgear wiring process is almost completely manually executed**. The complete **switchgear wiring** process consists of several single wiring operations, whose number and complexity depends on the particular design.

In the IEMA factory, all the wires composing the switchgear connection list are prepared by a devoted crimping machine (Komax Z630), that cuts the wires with proper length, size, color, label and arrange them into groups that are sent to the wiring stations. Therefore, with reference to see Figure 3, each wiring operation as executed by the worker consists of several steps:


Figure 1 - Typical switchgear wiring operations

1) Read the switchgear schematic and selects the connection to be performed on the basis of the state of the wiring process and of his/her experience and feeling about the process itself (from T = 4 to T = 20);
2) Locate the components to be connected on the switchgear (T = 38);
3) Select the wire labeled according to the connection at hand (T = 42);
4) One wire end is connected to the proper component according to the switchgear scheme (from T = 46 to T = 52);
5) The wire is arranged along the path in the wire collectors (from T = 61 to T = 66);
6) The second wire end is connected according to the connection list (from T = 69 to T = 72).
After the completion of these steps, the sequence restarts from the first one, taking into account another connection in the connection list.

The switchgear wiring process ends when all the connections in the connection list are executed. The whole wiring sequence is subject to interpretation of the worker, depending on his/her skills and experience. Moreover, the ergonomics of the wiring process is really poor, since it often implies repetitive and uncomfortable movements such as arm extension, wrist torsion due the continuous use of screwdrivers, back bending, crouch down and arm stretch up to reach the connection points.


Figure 2 - Horizontal and vertical switchgear wiring

Despite some automatic switchgear wiring solutions are available on the market, their applicability is still very limited due to the reduced flexibility, programming time and cost, then feasible for large scale and relatively simple products only, but not economically justified for small lots or single items, especially in the SMEs' market.


T = 0 [s] T = 4 [s] T = 10 [s] T = 16 [s] T = 20 [s]


T = 30 [s] T = 38 [s] T = 42 [s] T = 44 [s] T = 46 [s]

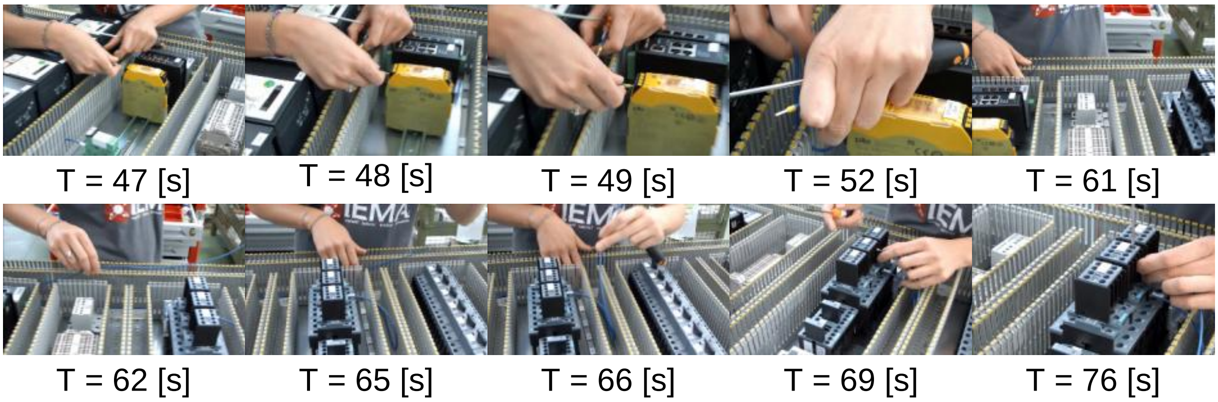


Figure 3 - Manual switchgear wiring sequence with paper based documentation

From the investigation carried out by IEMA, it comes out that despite the very large number of switchgear layouts, the 65% of the wiring involves the same component and connection types. Moreover, as can be seen in Figure 3, about 50% of the time is spent by the workers to read the product documentation. It follows that there is large margin to improve this situation by introducing innovative methods and technologies.

2.2 Selection of the testbed for robotized cabling

The specific objective for this use case is to investigate the wiring automation, by means of the REMODEL robotic platform, of the most common and repetitive connection types present in a switchgear, eventually during night shifts, in such a way to speed up the production and reduce the worker physical stress due to these repetitive and uncomfortable tasks. It is expected that REMODEL will reduce the average switchgear wiring time by the 30%. For the investigation and the development of this use case, the switchgear shown in Figure 4 is selected as application testbed.

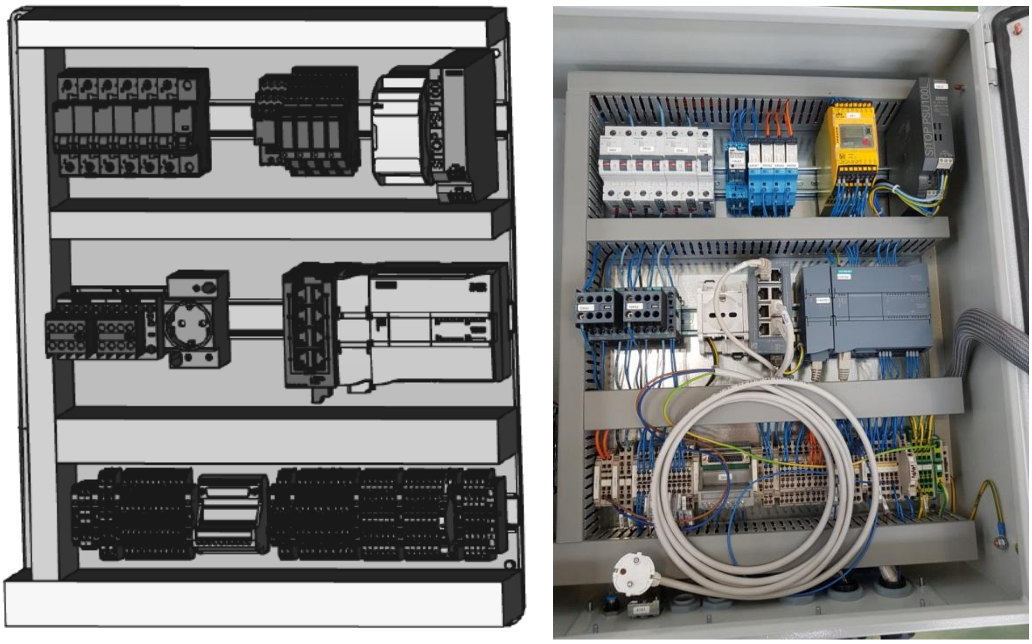


Figure 4 - 3D model and picture of the cabled switchgear selected for the use case development

This switchgear has been selected for defining the REMODEL specifications because it contains the most common elements and structure of a swithgear for automatic machines and it represent a continuity product, since IEMA expected to produce 40 to 50 items of that type each year in the next 5 years.

The component types usually present in a switchgear for automatic machines are:

- 24V Power Supply;
- Programmable Logic Controllers (PLCs);
- Control and auxiliary switches;
- Power line circuit breakers;
- Motor protection circuit breakers;
- Contactors;
- Connection terminal blocks.

Even restricting the analysis to a single component type, very different size and morphology can be found according to different specifications, electrical and mechanical characteristics, manufacturer and application. This fact makes the problem of adapting the behavior of an automatic cabling system particularly challenging. In the switchgear considered for the definition of the REMODEL specifications, 8 different components and 11 different connection terminal blocks from the most common types used in the switchgear design are present. The complete component list can be found in the attached document. In this switchgear, a PLC is also present. These components are characterized by a large number of variants as well as connection type and density, so in any case these part of the cabling will be managed by human operators, at least during the preliminary project developments. A specific analysis will be executed on the design and manufacturing procedure of this switchgear to define which part of the cabling can be managed by the robot and what must be managed by the human operator. In this phase, the objective will be to maximize the number of tasks executed by the robot.

2.3 Dimensions and space limitations

The structure of the switchgear allows an easy evaluation of a number of features:

- The limited distance between the components allows the evaluation of the system capabilities in terms of connection capabilities and wires routing management;
- The small distance among the wire collectors and components allows the evaluation of the wire connection techniques in limited and crowded spaces;
- The different terminal blocks allow the evaluation of clip type wire connection strategies.

From the design of the switchgear adopted for the experiment testbed the following data can be extracted:

- the minimum space between wire collector and components is 15 mm;
- the minimum distance among connections is in case of the connection blocks of the 24V power supply, which presents a connection distance among the pins of 5.08mm;

- the connection angle with the switchgear plane ranges from 0 deg (connection parallel to the switchgear plane) to 90 deg (connection perpendicular to the connection plane);
- the connection angle steps with respect to the switchgear plane are 0, 45, 60 and 90 deg;
- the maximum displacement between screws/clips base/axis and wire connections:
  - 0÷40 mm along x axis;
  - ±5 mm along y axis;
  - ±40 mm along z axis;
- max cable length: up to 1.5 m;
- cable section from 0.5 to 4 mm^2.

2.4 HW & SW Requirements

The switchgear wiring is carried out by using the dual-arm platform developed in WP6 at UNIBO. This platform is composed by two collaborative robots performing wire manipulation activities and the simultaneous execution of multiple wire manipulation sub-tasks, such as wire connection and routing. UCLV investigates the integration and the exploitation of tactile and proximity sensors for developing DLOs manipulation techniques in collaboration with UNIBO. The CAD platforms are conceived to help the designers' activities and for design reporting, but they do not address operative problems related to the manufacturing activities. The REMODEL software converts the switchgear design in the sequence of tasks the robot will execute to perform the wiring.

A pilot plant will be created at IEMA to reach TRL6 by the end of the project, provided with all the hardware for the execution of the wiring operations to show:

1. The abilities of connecting wires by means of the cable connection tool and the cable routing tool designed in WP6 or by using an additional arm, the control algorithms developed in WP5 and the vision and cable tracking provided by WP4 will be implemented in the dual-arm manipulator; The wires are assumed to be prepared by a devoted machine and stored in a proper warehouse located in a known position;
2. In case of components with screw-type terminals, the screwdriver used by the robot should be able to adjust the tightening torque and report this data in the production report;
3. The manipulation of the whole wire length by means of the cable routing tool and the manipulation by means of a gripper equipped with tactile, proximity and vision sensors will be tested on the switchgear wiring;
4. The robotic system will be integrated in the test plant as a final project demonstrator, as described in WP7, for the performance evaluation and the fine tuning of the planning and control procedures.

2.4.1 Extraction of the switchgear data from the CAD design files

From the EPLAN P8 software used by IEMA for the switchgear design, it is possible to export the design data by means of spread sheets reporting all the components, connection list and related information, see Table 1 where some lines from the component list of a switchgear design are reported.

EPLAN P8, thanks to the ProPanel plugin, allows also to export the 3D model of the switchgear in STEP format. The 3D switchgear model allows to estimate the location of the components, the distance between them and the path and length of the wires. The CAD design in STEP format can be useful for 3D scene reconstruction and simulation, and it can be processed to extract the switchgear information, in particular the component nominal positions, since it is a text file describing all the elements in the scene. Moreover, together with the STEP file, EPLAN P8 exports another text file (called WRI table) reporting the links between the component list shown above and the components in the STEP model in a hierarchical way, see Table 2 were the connection between the two files is reported. In this tables, a couple of different components have been highlighted in yellow and green respectively to shown how the components into the component list are linked to the VRML model through the WRI table.

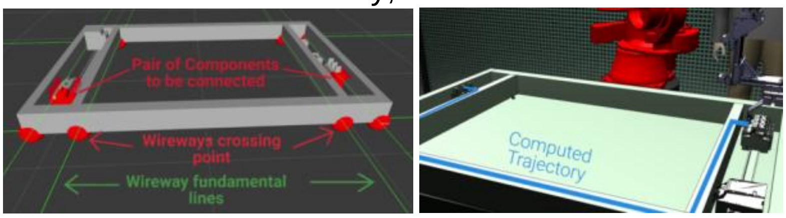


Figure 5 - 3D model, components, path corners and wire trajectory extracted from the switchgear design

Reference	Article N.	Q.ty	Description	Commercial Code	Manufacturer	Destination
=-F0030.1	6502086	1	INT.AUT.1P 10A (C)	SIEMENS 5SY4110-7	SIEMENS	Q
=-F0030.1	6502088	1	AUX 1NO+1NC	SIEMENS 5ST3010	SIEMENS	Q
=-F0030.2	6502084	1	INT.AUT.1P 4A (C)	SIEMENS 5SY4104-7	SIEMENS	Q
=-F0030.2	6502088	1	AUX 1NO+1NC	SIEMENS 5ST3010	SIEMENS	Q
=-F1500.1	6503798	1	INT.AUT.3P 4,5..A	SIEMENS 3RV2011-1GA20	SIEMENS	Q
=-F1500.1	6503808	1	AUX 1NO+1NC	SIEMENS 3RV2901-2E	SIEMENS	Q
=-F1500.2	6503798	1	INT.AUT.3P 4,5..A	SIEMENS 3RV2011-1GA20	SIEMENS	Q
=-F1500.2	6503808	1	AUX 1NO+1NC	SIEMENS 3RV2901-2E	SIEMENS	Q

Table 1 - The switchgear component table

…		DEF ID000074 Transform {
ID000071=-Q1500.3	6503377	translation 112.500000 -0.500021 9.999981
ID000072=-Q1500.3	6503809	rotation -1.000000 0.000000 0.000000 1.570797
ID000074=-F1500.1	6503798	children [Shape {
ID000075=-F1500.1	6503808	material Material {diffuseColor 0.400000 0.400000 0.400000}
ID000076=-F1500.2	6503798	geometry IndexedFaceSet { coord Coordinate {
ID000077=-F1500.2	6503808	5.150000 -51.828000 -51.700000, ... }
ID000078=-F1500.3	6503798	DEF ID000083 Transform {
ID000079=-F1500.3	6503808	translation 785.200000 0.000000 15.000000
ID000080=-F0030.1	6502086	rotation 0.707107 0.707107 0.000000 3.141593
ID000081=-F0030.1	6502088	children [Shape {
ID000083=-F0030.2	6502084	material Materia l{diffuseColor 0.800000 0.800000 0.800000}
ID000084=-F0030.2	6502088	geometry IndexedFaceSet { coord Coordinate {
…		-42.000000 26.210000 -35.857071, …}

Table 2 - Switchgear data exported from EPLAN P8: The WRI file linking the VRML model with the component table (left) and the VRML file showing the properties and the coordinates of the highlighted components (right)

These data can be extracted and exploited for the generation of the manipulator trajectories directly by means of simple text processing libraries. In Table 2 the data extracted from the CAD of the switchgear, such as the component locations and the crossing points of the wire collectors (or wireways), and the computed wire trajectory are visualized on the 3D model and on the platform simulator. The data extracted from the product design could be also presented to the human operator by means of suitable interfaces to monitor the robot activities and to speed the manual wiring up during the last phase of the production.

2.4.2 Integration with the Komax machine for wire preparation

The integration with the Komax Z630 used in IEMA for wire preparation is considered. This allows to arrange the wires to be connected in a controlled way and ease the graping and manipulation by the robot for switchgear wiring. To this end, suitably designed wire collectors are allocated at the output oft he Komax Z630 and syncornized with the machine output double-gripper system to arrange the wires according to the order of wire production by the machine. After a batch of cables are produced by the Komax machine, the wire collector must be moved by the wiring station. To this end, the AGVs available in the IEMA plant can be exploited.

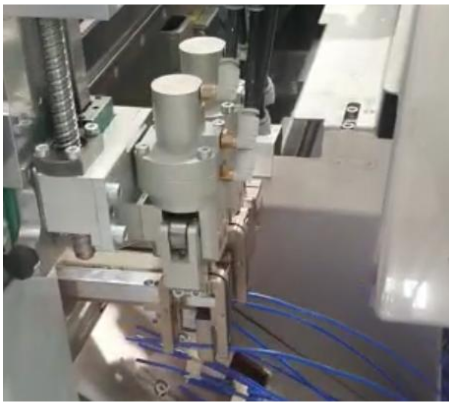


Figure 6 - The double-gripper wire output of the Komax Z630

The robot manipulating the cable is syncronized with the comax machine in ordert to grasp the cable as soon as the komax machine release it to avoid the cable falls in the collector, making the cable grasping very difficult. For this reason, the robot is expected to work at the same ratio of the komax machine, that is close to 5 seconds per each cable.

2.4.3 Tackling occlusions

The vision system moved by means of the robotic manipulator to reconstruct the scene and the location of the cables already connected is highly reccomended.

Two main working conditions should be managed by the vision system:

1. components localizations before executing the connections;
2. detection of connected cables to avoid entanglement during the execution of new connections.

During phase 1, the occlusions can be given by adjacent components and wire collectors, but in this phase these occlusions do not prevent the localization of the components, since the component type and 3D models are known. Therefore, their location within the switchgear is obtained form a frontal view only, since all the components are arranged along DIN guides attached to the switchgear backpanel. Finally, the 3D CAD model of the switchgear and its components (available from the components manufacturers and the switchgear design, see Figure 4) will be matched with the 3D environment reconstruction to obtain a fully detailed 3D model with suitable real-world reference positioning. For this purpose, a psecific component localization system hasbeen developed in T4.4.

During phase 2, the region occupied by the already connected cables needs to be detected to estimate which is the free region that the manipulator can exploit to execute the following connections. In this phase, the connection list is exploited to know the already connected components and pins. In some case, it could be important important to reconstruct, by means of the vision system, the cable encumbrance, in particular with respect to the switchgear plane and above the cables, while it is not necessary to reconstruct the environment under the cables. Therefore, the encumbrance of the connected cables can be reconstructud by means of proper scanning techiniques developed in T4.3 for 3D cable shape reconstruction. In this case, the occlusions given by the cables, in particular above the cable itself, are not relevant because i) the 3D model of the switchgear built during Phase 1 can be exploited: ii) the space above the cable can be considered free: iii) the region under the cable is not useful and will be not used for any operation related to the remaining connections.

2.4.4 Obstacles in robot trajectory

Given the 3D model of the switchgear built in Phase 1, the location of all the components is known, therefore the robot trajectory can be easily planned to avoid these obstacles. Anyway, the planned trajectories need to be dynamically updated with the information about the cable location gathered from the vision systems each time a new cable is connected. The new cables to be connected will be placed over the already connected ones, therefore only the space available over the previously placed cables needs to be detected to avoid entanglement and/or collisions.

Particular care needs to be taken about the cables connection point in case of adjacent cables. In this case, suitable motion strategies must be evaluated to insert the gripper in the available space, selecting proper approach trajectories to avoid collisions or to move away the cables on one or both sides (exploiting the cable flexibility) for positioning the gripper in front of the cable connection point.

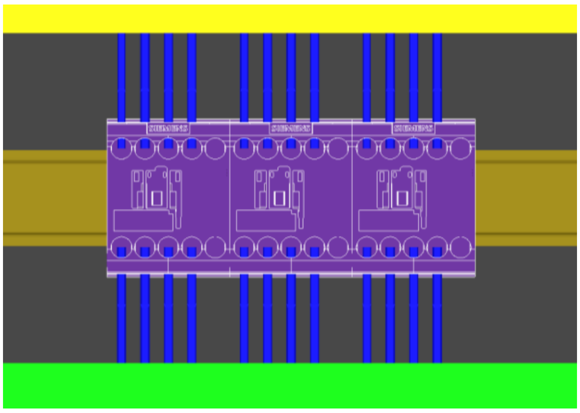


Figure 7 - Top view of a component block

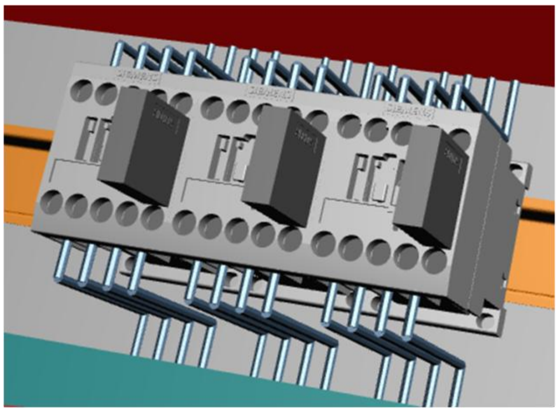


Figure 8 - 3D view of the component block

In Figure 7 and Figure 8 the case of adjacent cable connections on a generic component block can be clearly seen. In particular, from Figure 7 it can be seen that no occlusion about the gripper working region occurs when the scene is observed from the top, whereas in Figure 8, despite the approximation of the cable path shown in this figure, it is possible see that the space under the cable remains free.

2.4.5 Cable routing

A tool to control the wire during the routing phase is needed to avoid grasping, manipulation and regrasping problems, and to prevent the wire to be entangled on other objects or obstacles. This tool should be able to manage wire up to 1.5m long. The wire handling system will be moved by the manipulator over the switchgear surface in a coordinated way with the gripper/screwdriver to perform the wiring activities. In alternative to this system, the use of another robotic arm to handle the other cable end can be considered.

2.5 Description of the robot task (to be demonstrated during the demo)

In UC1 the robot is expected to show the capability of cabling a switchgear. This imply different steps:

1. First a robot arm takes one end of a cable from the wire warehouse;
2. The first robot then moves the end toward the cable router for cable storing or another robots takes the second cable end;
3. The first robot connects the cable end on the proper position;
4. The first robot starts the execution of the cable routing together with the robot holding the second cable end by means of the cable router or of a gripper;
5. When the second connection position is close to reach, the robot performs the connection of the second cable end;

In both the connection phases, the robot equipped with connection tools can be exploited. The switchger cabling then continues repeating the previous step from 1 to 5 for the next cable in the connection list. The connection list is organized according to the specific switchgear needs to manage the requirements of the product.

2.5.1 Analysis of the robot performance

For safety reasons, during the final demo the robotic system is expected to accomplish the task according to the following scheduling:

1. First a robot arm takes one end of a cable from the wire warehouse (10 seconds);
2. The first robot then moves the end toward the cable router for cable storing or another robots takes the second cable end (10 seconds);
3. The first robot connects the cable end on the proper position (20 seconds);
4. The first robot starts the execution of the cable routing together with the robot holding the second cable end by means of the cable router or of a gripper (from 20 to 60 seconds depending on the cable length);
5. When the second connection position is close to reach, the robot performs the connection of the second cable end (20 seconds);

The execution speed during the demo will be maintained very limited also to avoid problems and damages to the system in the development phase. After proper system tuning and proper optimization of the robot task, it is reasonably expected to reduce the execution time by a factor of 2, achiving then a connection speed that is close to human operators. This performance level is expected to be achieved 1 year after the REMODEL end.

2.5.2 Expected effort of human operators

The focus is posed in reducing the number of cabling tasks the human operator must accomplish to complete the production, in order to reduce in particular the duration of the repetitive task within the shift and the duration and speed required to complete the tasks due to their reduced number.

In comparison with conventional manufacturing, the introduction of the REMODEL technologies is expected to save 50% of human time for the switchgear cabling. The human operator activities will be restricted to the cabling of the connection that the robot for some reason is not able to perform (occlusions, cables external to the switchgear, components that are not fully known). Additional human interventions are limited to thecase of unrecoverable failure of the robotic system.

In terms of reduction of physical stressand risk of human operators, this will significantly reduce the duration of repetitive carriedout by the operator. Therefore,
taking into account the most critical activity during the cabling task, that is the usage of the screwdriver, the risk analysis can be:

Intensity of effort : 1
Duration of effort in the cycle: 1
Frequency of actions: 1
Hand and wrist posture: 3
Speed of carrying out the activity: 1
Duration of the repetitive task within the shift: 2

Strain Index: 6

From the analysis of the cabling task accomplished during the execution of UC1 with the introduction of the REMODEL technologies, the value of the Strain Index is reduced to low risk, while it was high in case of full manual activities. It follows that there is a high potential for the REMODEL robotic technologies to significantly impact into the quality of the working environment for this use case.

3 UC2.1 – Aerospace Wiring harness manufacturing

This use case is focused on the investigation of a robotized solution for wiring harnesses manufacturing for aeronautic sector. Wiring harnesses manufacturing is a very time-consuming work that is mostly performed manually on pin boards. Existing manual or semi-automated manufacturing techniques for wiring harnesses are characterized by highly labor-intensive operations and thus are very sensitive in terms of quality assurance

Figure 9. Wiring harnesses manufactured on pin boards

3.1 Use case description

ELIMCO is an SME specialized in the field of aerospace wiring harness manufacturing, The current process is completely manual and divided into two main steps:

1. Documentation interpretation and tools/components preparation.

2. Manufacturing, which vary greatly depending on the type of harness (airplane, helicopter), the model, and its dimensions.

The manufacture can be done either on a horizontal table or a vertical one. In some harnesses, mainly for helicopters like the Tiger/NH90 models, it is not necessary to use pins on the manufacturing table, but in the general case in airplanes, such pins are very important as they give a direction for the operator and greatly facilitate the manufacture process. The main manual operations performed in the current process are:

- Pin positioning based on the wiring harness drawings
- Cable manipulation and positioning on the table
- Taping of cables according to specifications of the plane manufacturer (in some cases, an additional redundant tightening of cables is done using thin strings).
- Manual twisting of cables
- Welding of cables ends with contactors
- Back-shells installation
- Finally, isolation and continuity tests that need to be done before the packaging of the harnesses.

Figure 10: Manual wiring harness assembly

3.2 Selection of the testbed

The specific objective for this use case is to show the robotized 1) **table preparation** (pin placement) and 2) **routing of cables** on the pin boards. A dual-arm robot and operators will work side by side in a human-robot collaborative environment. Due to the wide range of different activities carried out during the manufacturing process, which in some cases require specific tools and an extremely high-level of dexterity, it was decided to divide the tasks:

- Very complex and high value operations (requiring a big dexterity and specific tools) will be performed by the human operators.
- The dual arm robot will be in charge of some other tasks including pins fixation on the table and cable routing (based on CAD information) as well as some side-task that can be robotized during this process such as the quality control. These tasks require spending a large amount of time checking and revising documentation by operators; therefore, the robotization of these actions would speed up the process and ensure the correct positioning of pins and cables, adding traceability to the manufacturing process.

The combination of the operator actions and dual-arm robot ones should have an important impact on the reduction of operation time, increasing productivity in the manufacturing processes. A pilot plant is being created at ELIMCO to reach TRL6 by the end of the project, provided with all the hardware for the execution of the initial steps of the wiring harness manufacturing.

3.3 HW & SW Requirements

The wiring harnesses manufacturing is carried out by using the dual-arm platform developed in WP6 at TECNALIA. 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. The robots are installed in front of a workbench used for the assembly and inspection of wiring 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 11: Kuka LBR iiwa robots for ELIMCO use case installed at TECNALIA

In order to test the flexibility of the proposed REMODEL solution (hardware and software), it was decided to implement the robotic cell also at ELIMCO using a different layout. Specifically, it has been decided to place both Kuka LBR iiwa arms on both sides of the workbench. The main idea is to evaluate and compare both layouts (TECNALIA and ELIMCO layouts) and decide which offers the best performance and versatility. Additionally, it will allow testing the developed modules in different setups and validate the flexibility of the solution.

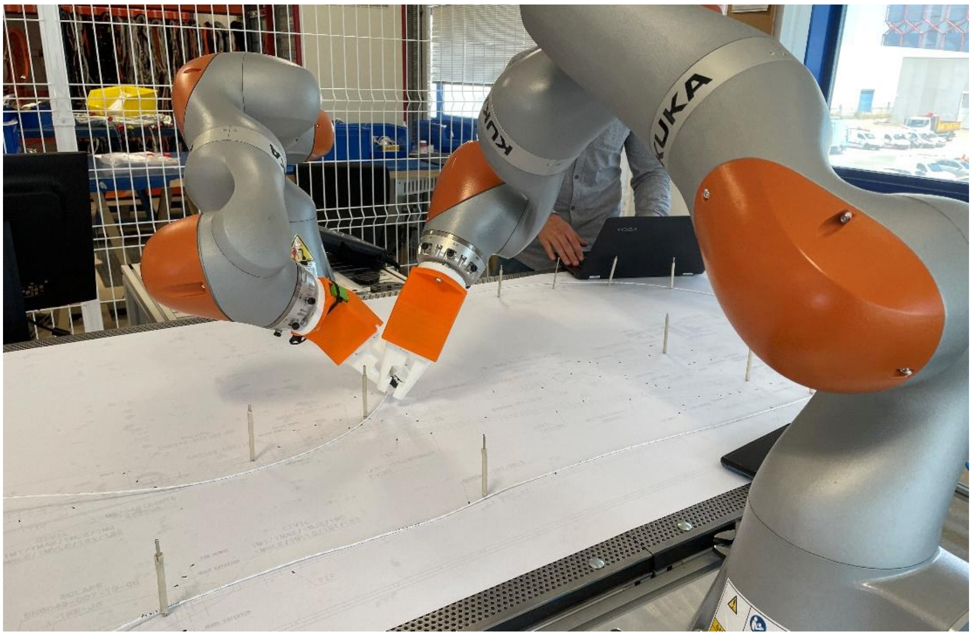


Figure 12: Setup at ELIMCO

In order to have add flexibility, a perforated workbench has been designed and manufactured for the use case. It is composed by two perforated steel sheets filled by a layer of foam where pins can be inserted and removed, maintaining its properties along time. The workbench allows an agile and rapid reconfiguration of the workspace, speeding up the preparation of the workbench when new references are included in production.

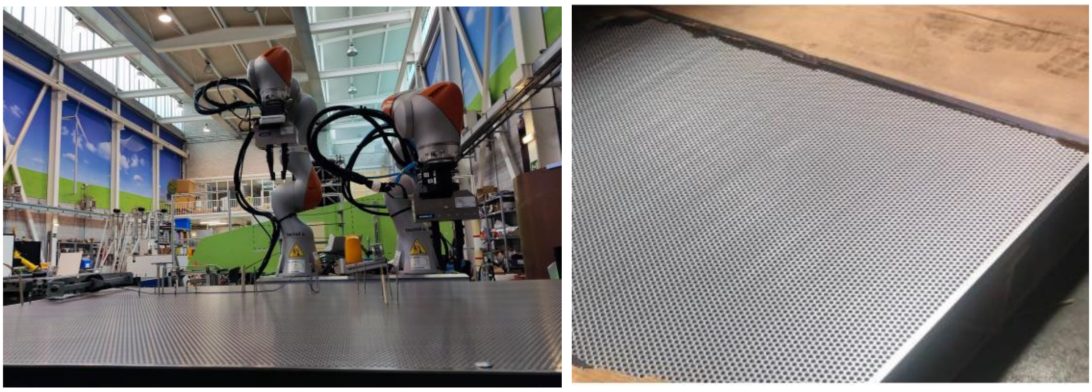


Figure 13: Perforated workbench

3.3.1 CADProgramming

Another important point is related to the extraction of information from CAD models. ELIMCO and TECNALIA are are working on an application (task T3.1) to generate the plans and get the necessary information to create robot programs in an agile and simple way from CATIA, the CAD program mainly used in the aeronautic sector.

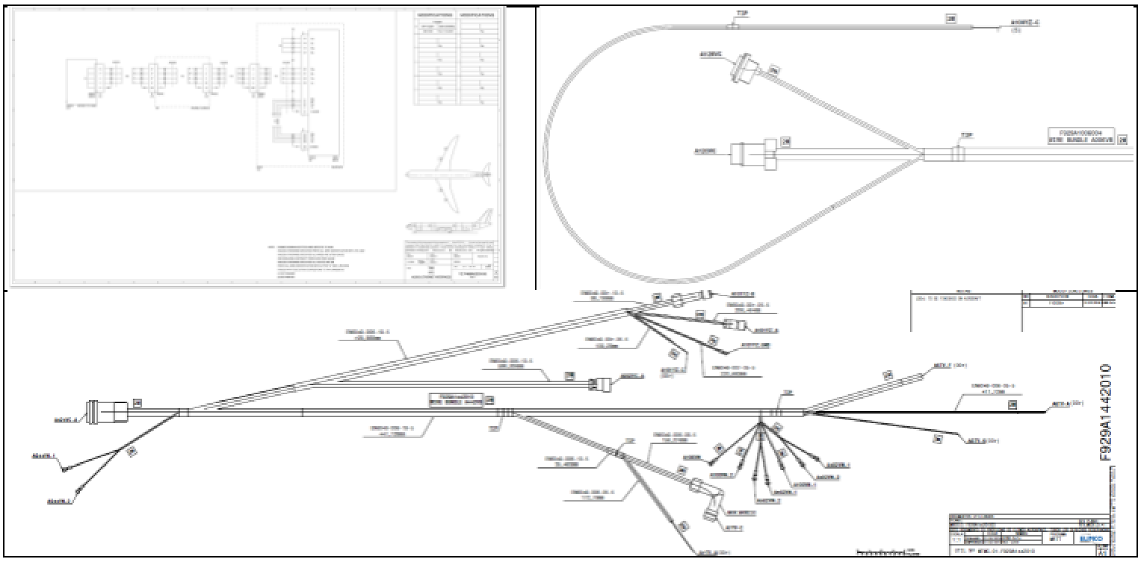


Figure 14: CAD of wiring harness for aerospace applications.

This application uses inputs such as the 2D/3D model and the Excel documentation of the wiring harnesses to obtain the strategic 3D poses of the different task points to create the cable routing paths. Users only need to select the initial, intermediate, and final points in the drawing to define robot paths for cable routing.

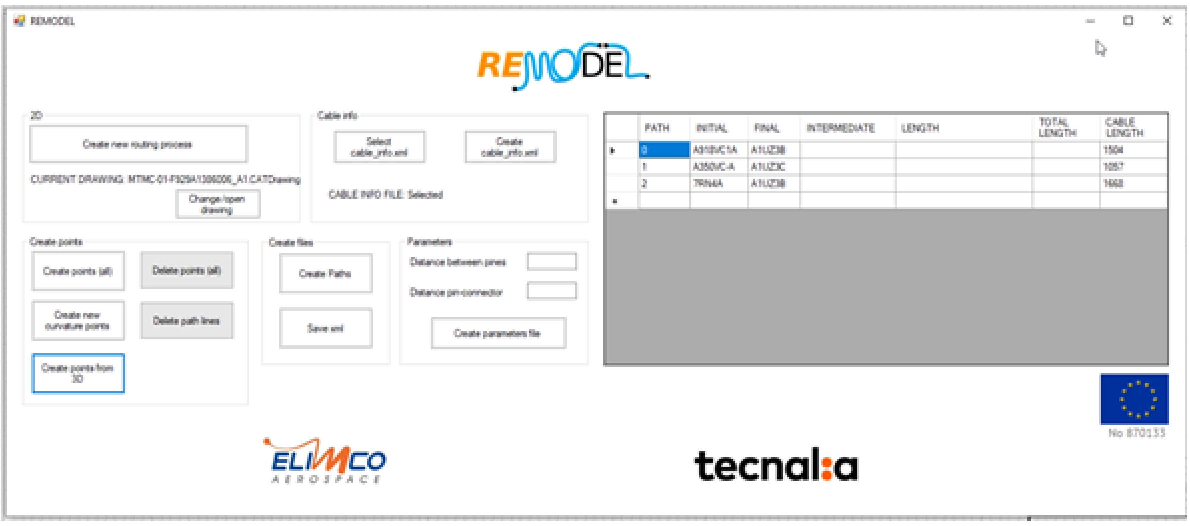


Figure 15: CADProgramming interface

The different files created in the application are sent to the robotic system afterward. The robot application reads the files and executes the implemented routines; the robot initially inserts the pins on the perforated workbench and then routes the wires on the correct path.

3.3.2 Grippers & Fingers

Two Schunk WSG50 parallel grippers have been selected for the wiring 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.

In addition, different works have been carried out for the design, installation and validation of specific fingers for pin insertion and cable routing. These fingers 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 wiring harness. This hybrid design is core for an efficient task completion, avoiding a tool exchange during the whole process.

Figure 16: Self-manufactured grippers used at ELIMCO in early stages of the project

Figure 17: Schunk WSG50 grippers with extended fingers in ELIMCO use case

3.3.3 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.

The camera has been mounted on the flange of one of the robots in an eye-in-hand configuration. 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 for quality checking.

3.3.4 Cable routing

During the wire harness manufacturing at ELIMCO, the different wires and cables are provided in kits previosly prepared by operators. In order to automatize the cable routing, a cable roll holder has been designed; this device will include different cables and wires which will be placed by operators to make them available for the robotic system.

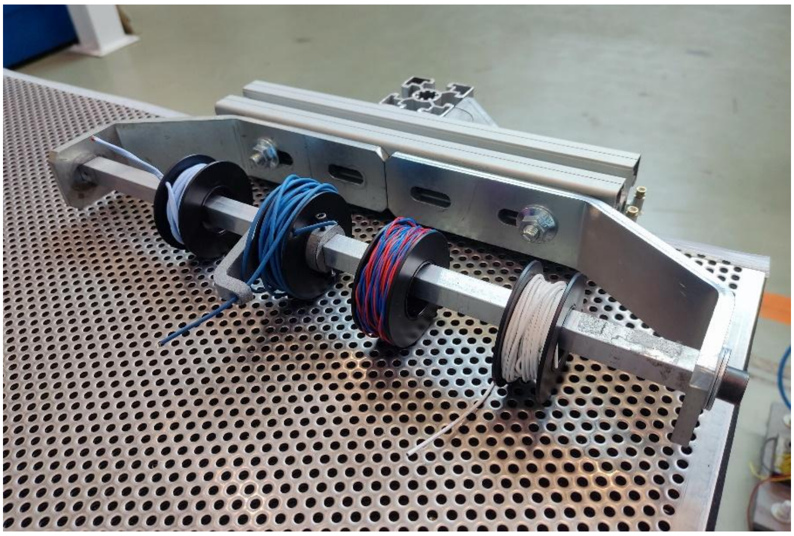


Figure 18 - Cable and wire holder

Based on this cable holder, the wires will be fed to the robotic system that will guide them along the routes defined by through the CAD application. Even so, the design could be modified in order to fit ELIMCO's production needs.

3.4 Description of the robot task (to be demonstrated during the demo)

In UC2.1, the robotic platform is expected to show the capability of assisting operators during the initial phase of wiring harness manufacturing. Specifically, the robotic system will be included in the next steps:

1. First, the robot programs are generated using CAD programming application. These configuration files are sent to the robotic system.
2. The robotic system loads the provided files and prepares the task sequence.
3. The robotic system inserts the pins in the perforated workbench following the CAD data.
4. One of the robots grasps each wire from the cable holder and routes it in the defined path, using the other robot to assist the first one when required (e.g. long wiring harness paths).
5. Finally, a reconstruction of the whole work environment will be carried out using the 3D vision system for quality inspection and traceability..

3.4.1 Analysis of the robot performance

For safety reasons, during the final demo the robotic system is expected to accomplish the task according to the following scheduling:

1. First, the robot programs are generated using the CAD programming application and these files are sent to the robotic system (10 min)

2. The robotic system reads de files and each robot picks up and inserts the pins in the specified position on the perforated workbench (7-10 min)

3. Finally, a robot takes each wire and routes it in the correct path with the help of the other robot arm (7-10 min)

4. Finally, a reconstruction the whole work environment will be carried out (3 min)

The execution speed during the demo will be maintained very limited to avoid problems and damages on the system and materials. After a proper system tuning and optimization of the robot task, it is reasonably expected to reduce the operator's execution time in a 20% at least. This performance level is expected to be achieved 2 years after the REMODEL end. Based on the automated workbench preparation and initial cable routing, a reduction of the actual operator's production time is expected thanks to the possibility of exploiting robots to carry out the initial steps of the assembly. This result can be achieved considering that the robot can also work during nighttime. ELIMCO expects a reduction of the time to market by 1 day. Considering the cost of 2 robotic platforms needed to cover the ELIMCO production, the net income is expected to increase by about 15%. This performance level is expected to be achieved 2 years after the REMODEL end.

3.4.2 Expected effort of human operators

- *In comparison with conventional manufacturing (without REMODEL)*
    - *Amount of work of saved to the operator (10-15% of total task time, depending on the complexity of the wiring harness)*
    - *Stress reduction (less repetitive tasks, lower risk of production errors)*
- *In support of the robotic system*
    - *tasks the robot can't perform and robot system failures*

The focus is on reducing the number of the initial wiring harness manufacturing tasks that the human operator must perform to complete production, replacing them with the CAD programming and cable routing. In such a way, it will increase production as operators will be able to focus on high added value tasks while robots carry out CAD data-based actions which will reduce errors due to misinterpretations of the documentation.

In comparison with conventional manufacturing, the introduction of the REMODEL technologies is expected to save 15% of human time for the wiring harness manufacturing. The human operator activities will be restricted to the platform programming and material supply on the initial steps of the production. Additional human interventions are limited to the case of unrecoverable failure of the robotic system.

In terms of reduction of physical stressand risk of human operators, this will significantly reduce the duration of repetitive carriedout by the operator

The risk analysis of UC2.1, the task of placing cables of the pin table is considered as the riskiest activity.

Intensity of effort: 1
Duration of effort in the cycle: 1
Frequency of actions: 1
Hand and wrist posture: 1
Speed of carrying out the activity: 2
Duration of the repetitive task within the shift: 2

Strain Index: 4

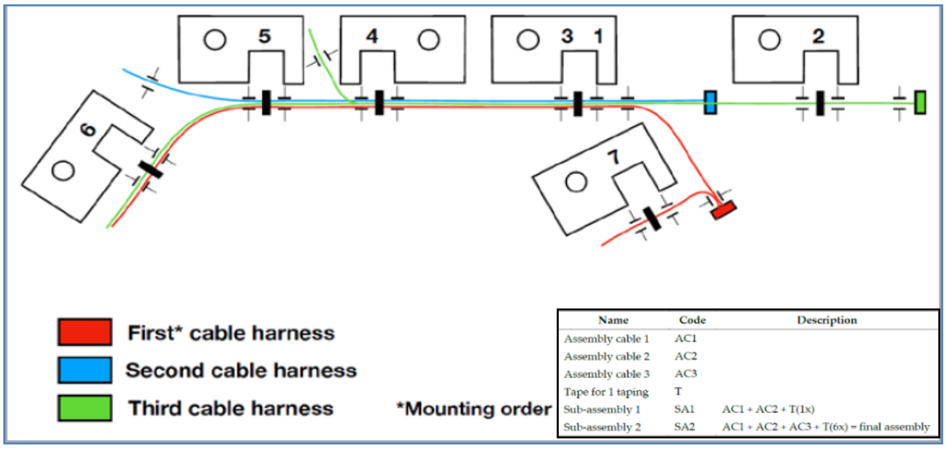
From the analysis of the common task accomplished during the execution of UC2.1, the Strain Index is significantly reduced thanks to the introduction of the REMODEL technologies, shiwing a high impact into the quality of the working environment for this use case. The focus has been posed to reducing the number of tasks carried out by the human operator, to reduce in particular the duration of the repetitive task within the shift and the duration and speed required to complete the tasks due to their reduced number.

4 UC2.2 - Automotive wiring Harness Manufacturing

The primary objective of the use case is to introduce robotic solutions to **primarily perform the task of cable manipulation for assembling the cable harnesses,** as per the requirements of the automotive manufacturerers. Cable harnesses are manufactured to interconnect modular systems internally or with other systems externally, for an automobile. The primary requirements of an automotive wire harness (to communicate between and integrate individual subsystems) are similar across all categories of vehicles, the size and complexity varies but the functionality remains the same.

4.1 Manual Automotive Wire Harness Assembly

The assembly stations have a worker who currently assembles the cables on specialized jigs and spot tapes them together in the required sequence and with suitable tolerances (with the help of jigs), by means of a spot taping gun. The jigs are specially manufactured and are unique to individual batches of the cable harnesses and have a lifetime till the production of the particular type of harness (or until worn or damaged). These jigs are essential to aid the worker, to properly place the individual groups of cables in sequence and to perform the spot taping operation with the required dimensional tolerances. The use case at hand consists of three groups of cables which require seven spot tapes at varying stages in the assembly operation. The pictorial layout and assembly information is provided in Figure 19.



Name	Code	Description
Assembly cable 1	AC1	
Assembly cable 2	AC2	
Assembly cable 3	AC3	
Tape for 1 taping	T	
Sub-assembly 1	SA1	AC1 + AC2 + T(1x)
Sub-assembly 2	SA2	AC1 + AC2 + AC3 + T(6x) = final assembly

Figure 19. Pictorial representation of the assembly operations and sequence

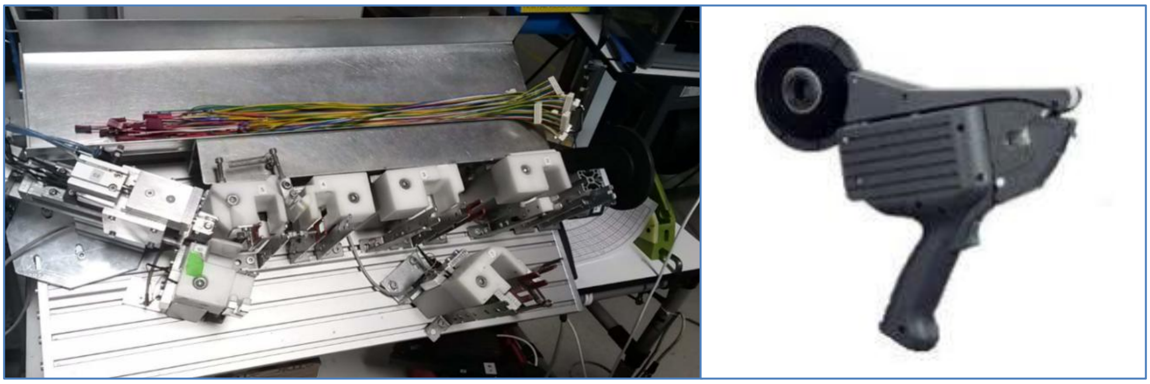


Figure 20. - Layout of jigs (left); The spot taping gun (right)

The present layout of the jigs in the assembly station and the spot tape gun are shown in Figure 20. The slots provided in the jig help the worker to place the gun and perform the taping operation in the required sequence.

The Assembly sequence

The sequence of tasks performed by the worker is illustrated in Figure 21. The table also denotes the time taken for each task and makes a value addition classification.

Nr.	Activity	Average task time (s)	VA / NVA Classification [a]
1	Taking 1st wire harness	2	NVA
2	Positioning 1st wire harness	1	NVA
3	Taking 2nd wire harness	3	NVA
4	Positioning 2nd wire harness	3	NVA
5	Adjusting 1st wire harness	2	NVA
6	Taking taping pistol	2	NVA
7	Performing 1st taping	1	VA
8	Depositing taping pistol	1	NVA
9	Taking 3rd wire harness	3	NVA
10	Positioning 3rd wire harness	5	NVA
11	Taking taping pistol	2	NVA
12	Performing 5 taping operations	10	VA
13	Depositing taping pistol	1	NVA
14	Manual taping	5	VA
15	Storing the wire harnesses	4	NVA

Figure 21. Cable harness manual assembly sequence and related time

Non-Value Added (**NVA**) task is a task, which creates production costs by absorbing resources and/or time without adding perceived value (and therefore satisfaction) to the final customer. Value Added (**VA**) task is a task, which generates production cost, but is also able to significantly increase the product value and satisfaction to the final customer. For a preliminary analysis, it is possible to consider grasping, handling, moving, positioning as NVA tasks; and insertion, fastening, fixing, assembly are VA tasks

The operation sequence and the individual actions of the operator as they perform the assembly task, with respect to the time elapsed is documented in Figure 22.

Figure 22. Operation Sequence with respect to time

The finished cable harness is shown Figure 23, the spot taping locations are highlighted. Figure 24 denotes the distances between the successive spot tapings.

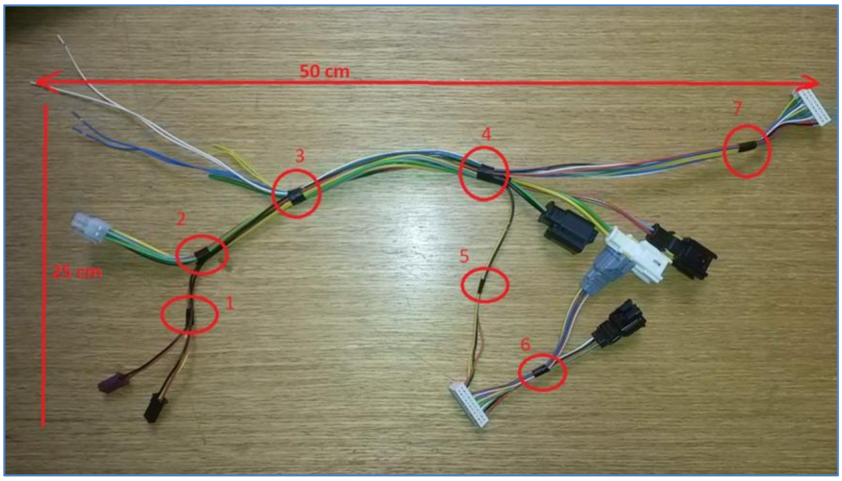


Figure 23. Output of the harness assembly process with the spot tapings highlighted

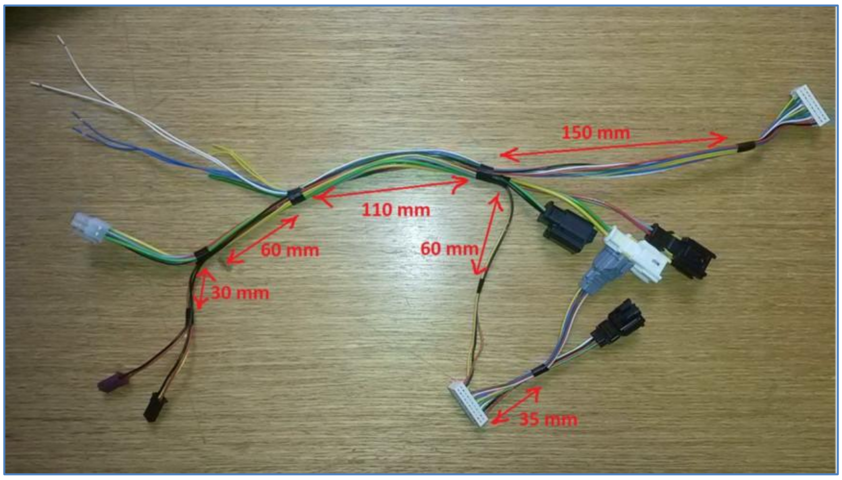


Figure 24. Cable Assembly with the dimensions between the spot tapings

4.2 Requirements of Robotized Assembly Platform

The specific objective for this use case is to investigate the individual elements of cable harness manipulation (picking, branch separation, routing, inspection, and taping) and automate it, by means of the REMODEL robotic platform. The objective is to eliminate the manual performance of repetitive NVA tasks by workers, in such a way to speed up the production and reduce the worker physical stress due to these repetitive and uncomfortable tasks. The goal is to utilize the existing production spaces in ELVEZ (which have a human-centric design), where the cable harness assembly takes place, to introduce the REMODEL system. The manipulator of choice is a dual-arm robot/ cobot, as it would have the closest resemblance to the human worker (for whom the production spaces were designed), this promotes easy integration into the production line without much layout modification requirements. The implementation of a robot-based system is estimated by ELVEZ to reduce the cycle time for producing an individual assembly by 4 seconds.

The finalized product which is the primary focus of REMODEL for this specific use case is shown in Figure 23. This is in turn comprised of 3 individual cable groups, which have a primary connector head with multiple cables terminated to it. Most of the cables from the main connector head have their other end terminated to other connector heads and have unique cable groups (which are common for all products belonging to the same group but differ from the other two groups significantly). The major connector head types present in the final assembled product are Molex, Lumberg and Tyco, and capacitors. For the ease of explanation in this report, the various cable groups are classified based on their termination to the secondary connector heads. The cables connected to these connecter heads have a dimension range from 1.34mm to 2.36mm.

The operation sequence performed by the human worker is highlighted in Figure 21. However, the assembly sequence with respect to the ELVEZ platform at a component level is depicted in Figure 25 and Table 3. The position of the Jigs (J), Guides on the jigs (C) and the spots for taping (S) are indicated in Figure 25. The Table 3 describes the entire operation sequence at a task and sub-task level, indicating which component goes where and its corresponding sequence in the entire assembly.

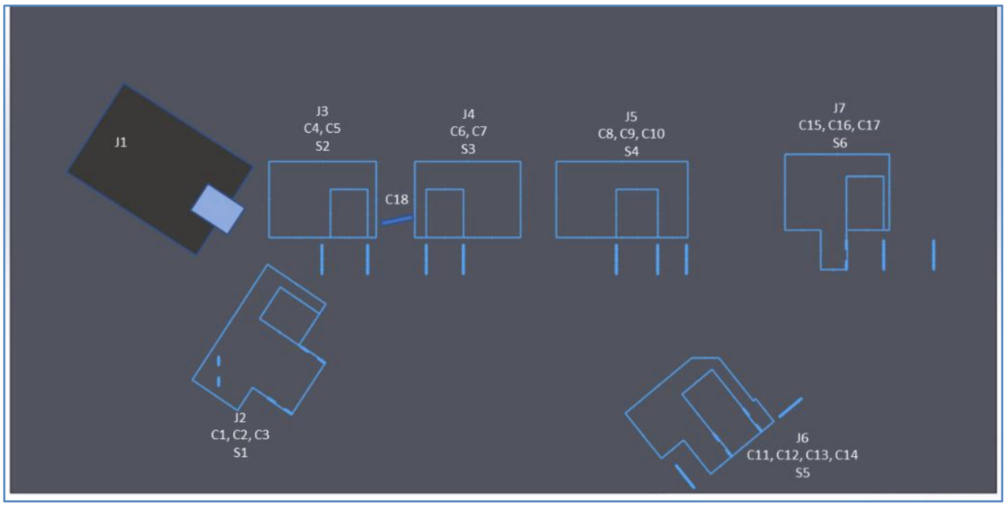


*Figure 25. ELVEZ Layout overview- Jig (**J**), Guide (**C**) and Spot Taping spots (**S**)*

Sequence number	Operation	Start Connector	End Connector	Sequence		
				Jig sequence (**J**)	Guides **C**	Taping Spot **S**
1	Placing Connector (PC)	Molex (MO_1)	-	J1-	-	-
2	Routing Cable (RC)	Molex (MO_1)	Tyco (TY_1)	J1-J2-J3-J4-J5	C4-C5-C6-C7-C8-C9	-
			Molex (MO_2) Molex (MO_3)		C4-C5-C6-C7-C8-C9-C10	-
3	Placing Connector (PC)	Lumberg (LU_1)	-	J6-	C14-	-
4	Routing Cable (RC)	Lumberg (LU_1)	Molex (MO_4) Molex (MO_5)	J6-	C14-C13-C12-C11	-
			Tyco (TY_2)	J6-J5-J4-J3-J2	C14-C10-C9-C8-C7-C6-C5-C3-C2	-
5	Spot Taping (ST)	-	-	J5-J6	-	S4-S5
6	Placing Connector (PC)	Lumberg (LU_2)	-	J7-	C17-	-
7	Routing Cable (RC)	Lumberg (LU_2)	Tyco (TY_3)	J7-J5-J4-J3-J2	C17-C16-C15-C10-C9-C8-C7-C6-C5-C4-C3-C1	-
			Epcos (EP_1) Epcos (EP_2)	J7-J5-J4	C17-C16-C15-C10-C9-C8-C7-C6-C18'	-
8	Spot Taping (ST)	-	-	J7-J5-J4-J3-J2	-	S6-S4-S3-S2-S1

Table 3. Operation Sequence- Connectors placed, cable groups routed and Taped

The Elvez layout shown in Figure 20 is the existing version used in the manual production lines. The layout design has been modified into a more generic platform, more suited for a robotic production line. The generic Elvez platform has a more minimalistic design setup as shown in Figure 26. The key features of the modified platform are the generic replacements for the jigs and guides (which are tailor made to cater the physical variations and requirements for the different variants the wire harnesses). There are two variations to the guides (as shown in Figure 27): Type 1 is intended for enabling easy routing of the cable harness across the Elvez platform. It permits for an easier insertion of the cable into the chamber and facilitates individual cable separation by the robot, without the risk of the cable harness slipping out and getting misaligned. Type 2 is more suited for performing circular motions with the robot manipulator, with the protruding cylindrical structure acting as the medium against which the cable is rotated, it also has provision for supporting the cable layed onto it (but it does not prevent the slip of the cable harness). Additionally, a secondary platform has been designed to hold the individual wiring harnesses initially, from which the robot can pick them to start the assembly operation. This is the Cable Holder Platform, and it is composed of a set of guides where the wiring harnesses are placed manually, so the robot knows where to pick them up (see Figure 36.c).

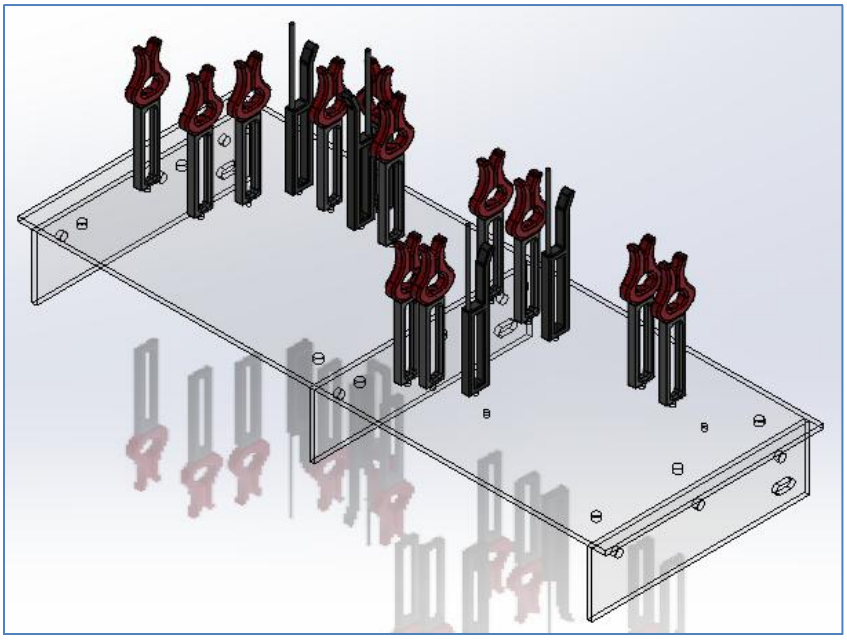


Figure 26. Cable routing platform - Robot-centric

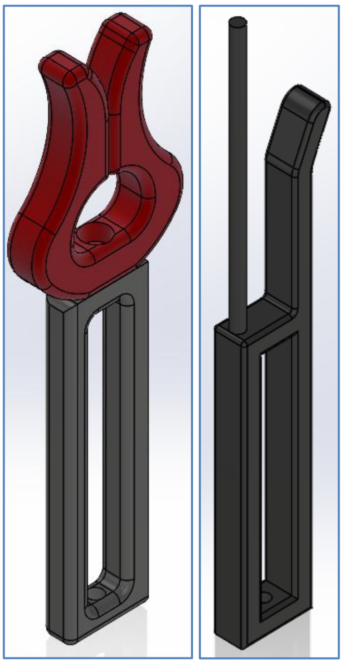


Figure 27. Routing Guide/ Type 1 (left); Rotating Guide/ Type 2 (right)

The spot taping gun (real gun shown in Figure 20) is utilized with minimal modifications to its internal taping mechanisms, as there was little documentation available and minimal help was provided by the manufacturer. Therefore, the simplest way to automate the spot tape tool was to operate the trigger by using an Arduino controlled stepper motor, the 3D model of the modified gun with provisions for the Tool changer module, Arduino bread board, the L293N motor driver and the stepper motor is shown in Figure 31.

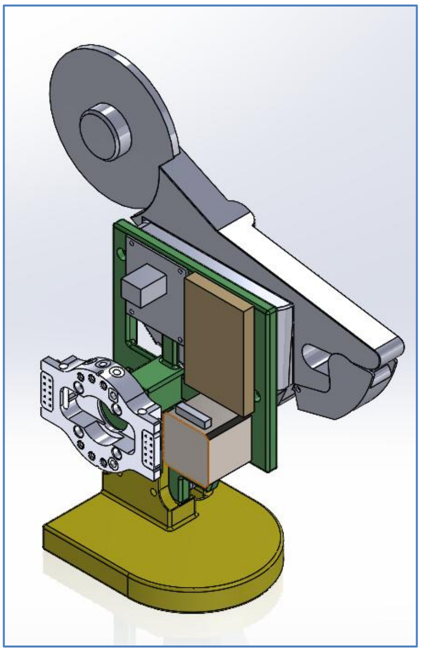


Figure 28. Spot Taping gun with attachments for automated activation of the trigger

4.3 Dimensions and Space Restrictions

- The distances between the placements of the various jigs and guides are determined with minimum tolerance to accommodate the right length of cable groups between the different taping actions.
- The connector heads are inserted into a mold which has +1mm tolerance to enable insertion and reduce the chance of slip/ disengagement during operation. (Only the primary connector heads are inserted into molds for this implementation).
- The guide setup for the Elvez platform is also accommodating for the insertion of the taping gun between them. The heights of the guide are also finalized to provide a 12mm clearance between the tip of the taping tool to the base of the Elvez platform (from the point of action where the cable groups are to be taped/ maximum penetration depth)

Some of the important dimensions to consider:

- The Elvez platform base: 640mm X 240mm X 5mm
- The distance between gun and platform base at maximum insertion depth: 12mm
- The distance between the guides at taping site: 26mm – 30mm
- Angle of Rotation for J2 equivalent (Figure 25): 65^{o}
- Angle of Rotation for J6 equivalent (Figure 25): 38^{o}
- Primary connector WH1: Molex- 14mm X 14mm X 20mm
- Primary connector WH2: Lumberg- 27mm X 11mm X 7mm
- Primary connector WH3: Lumberg- 30mm X 11mm X 7mm
- Individual cable diameter range- 1.34mm – 2.36mm
- Individual cable length range- 380mm – 430mm

- Figure 23 and Figure 24 give dimensional information of the final assembled products

4.4 HW and SW Requirements

HW Elements

The hardware aspects of the robotized setup comprise of the dual arm manipulator, the safety system, the end of arm tooling with automatic tool changing (ATC) system, and the vision system.

The dual-arm manipulator utilized in the current implementation of the Elvez setup is the Yaskawa SDA10F industrial robot, as shown in Figure 29. The 15 axes robot has a weight of 220kgs and a payload of 10kg in both arms, with a maximum working range of 845mm.

Figure 29. Yaskawa SDA10F Dual-arm manipulator

And therefore, the constructed cell (containing the ELVEZ test bed) has safety implementations which comply to the guidelines and requirements of **ISO 10218:2011**. The layout of the safety devices employed around the various sides and access points to the robotic cell are shown in Figure 30. The devices primarily used for the current implementation of the Elvez usecase are physical E. Stop buttons, Omron industrial light curtains, and Omron retro-reflective door switches (the provided hyperlinks lead to the product page). The safety PLC used is an Omron CSG320 with provisions for Digital and Analog input and outputs. The safety logic is 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.

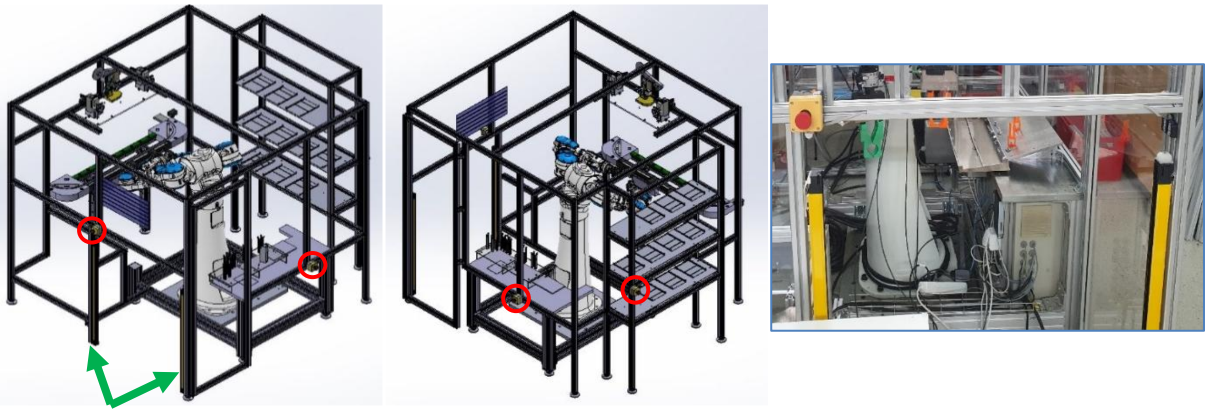


Figure 30. Safety devices installed across the cell (red circles: emergency stop buttons, green arrows: light curtains)

The robot interacts with the Elvez platform to perform the various tasks i.e., picking, routing, cable separation, inspection and taping by utilizing dedicated tooling, as per requirement. The primary tooling utilized in the Elvez usecase include the electrical gripper [Weiss WSG50](#) and the Onda spot taping, as shown in Figure 31. The gripper can grasp, center and route the cables (with specially designed fingers), whereas the gun is utilized maily to perform the taping action.

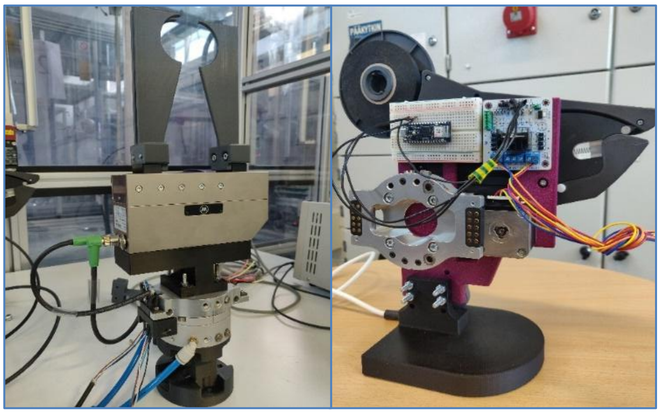


Figure 31. WSG 50 gripper (left); Onda Spot Taping gun (right)

All the end of arm tooling utilized by the Yaskawa have a tool changing module (tool-end) attached to them and the other end (robot-end) is fitted to the robot. The tool changer operates pneumatically and the air supply to the ATC module, by utilizing the internal air lines of the robot. The ATC platform is where the robot can switch between the grippers and the guns between both the hands.

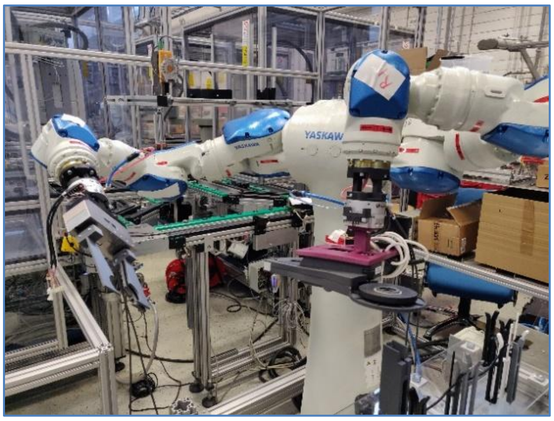
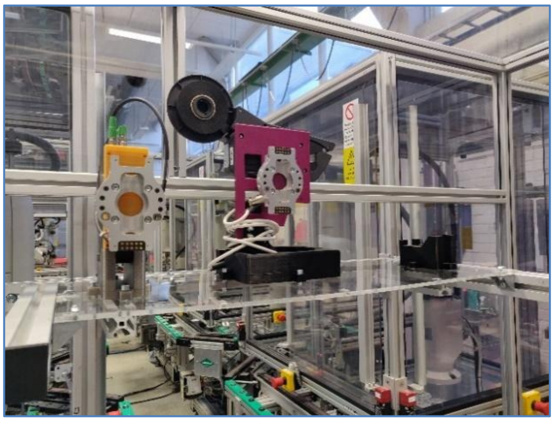



Figure 32. Robot with the tools and ATC modules attached (left); The ATC platform (right)

The Robotic platform currently utilizes a vision system to detect the cable groups and perform cable separation (prior to routing it) and it is also useful to determine if the separation and routing have been properly performed. The camera is used as an eye-in-hand camera and is fitted to the front face of the WSG 50 gripper. The camera used is the OpenCV AI Kit: OAK – 1 4K camera, as shown in Figure 33.

Figure 33. OpenCV AI Kit: OAK – 1 camera

SW Elements

The ROS system of the robotic platform is composed by multiple interconnected modules as can be seen in Fig XX. Some of these modules are described in the following subsections.

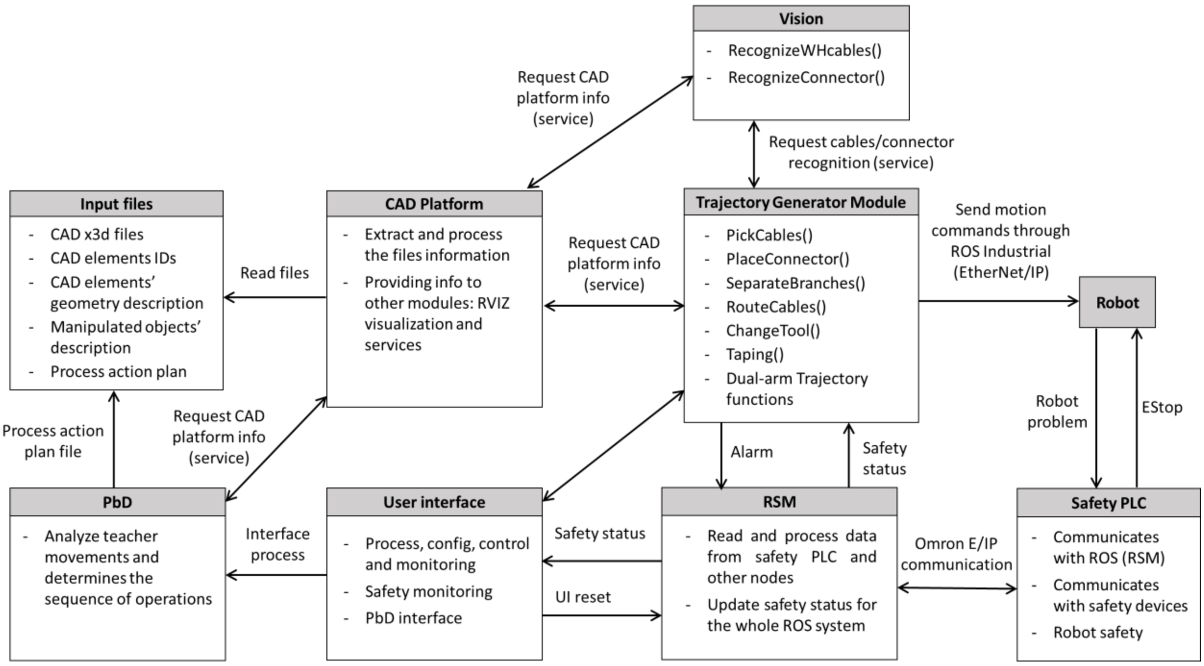
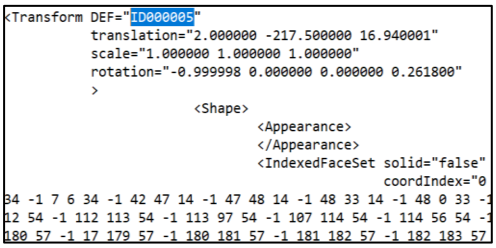


Figure 34. UML class diagram of the ROS system of the ELVEZ UC (UC2.2) robotic platform

4.4.1 Extraction of the WH and platform data from the CAD Platform

In order to make the robotic system highly reconfigurable, all the actions of the robot are parameterized and depend on the information about the cell setup, the components, and the assembly process, which is provided by several input files. This way, the whole process can be reconfigured just by updating these files. However, getting useful information from these files is not a trivial task, as some of them are difficult to analyze, such as 3D CAD models, and sometimes it requires post-processing, to merge complementary data extracted from different files. Due to this, the CAD Platform Interface was developed, which consists of a ROS package that reads, analyzes, and combines the data of the multiple input files, obtaining all the useful information about the process, which is provided to the rest of the nodes of the system through ROS services.

The input files can be classified into three groups depending on what kind of information they provide. The first group comprises files that contain information about the working environment, in particular about the cable routing, cable holder, and Automatic Tool Changing (ATC) platforms. Each of these platforms is described by three files: A CAD file in x3d format, from which the relative pose of each element of the assembly with respect to its parent element is obtained; an xml file that describes the geometry of every different element present in the platform, including their dimensions and their keypoints (e.g. the center point of a guide) with respect its own origin frame; and a csv file that relates every element in the CAD file with its model in the xml file (see Figure 35). The information of these files is processed and combined, obtaining the keypoints of every element referred to the origin of the platform. This information, as well as the dimensions of each of the elements, can be requested by means of ROS services. Additionally, the keypoints and 3D models of the platforms are used to publish TFs and markers for the setup visualization in RVIZ (see Figure 36).



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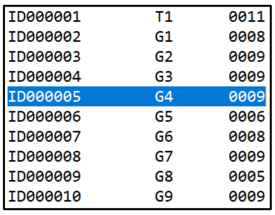
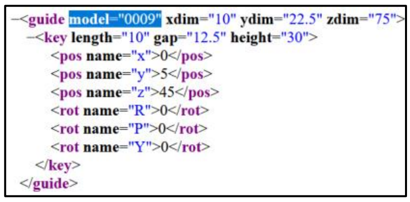
        scale="1.000000 1.000000 1.000000"
        rotation="-0.999998 0.000000 0.000000 0.261800"
        >
                <Shape>
                        <Appearance>
                        </Appearance>
                        <IndexedFaceSet solid="false"
                                coordIndex="0
34 -1 7 6 34 -1 42 47 14 -1 47 48 14 -1 48 33 14 -1 48 0 33 -1
12 54 -1 112 113 54 -1 113 97 54 -1 107 114 54 -1 114 56 54 -1
180 57 -1 17 179 57 -1 180 181 57 -1 181 182 57 -1 182 183 57
```

a. x3d CAD file



ID000001	T1	0011
ID000002	G1	0008
ID000003	G2	0009
ID000004	G3	0009
ID000005	G4	0009
ID000006	G5	0006
ID000007	G6	0008
ID000008	G7	0009
ID000009	G8	0005
ID000010	G9	0009

b. csv file with IDs



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  -<key length="10" gap="12.5" height="30">
      <pos name="x">0</pos>
      <pos name="y">5</pos>
      <pos name="z">45</pos>
      <rot name="R">0</rot>
      <rot name="P">0</rot>
      <rot name="Y">0</rot>
    </key>
  </guide>
```
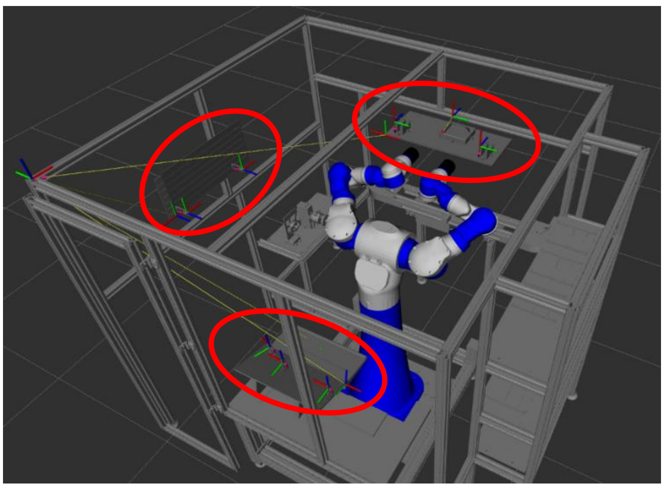

c. xml file with the models' description

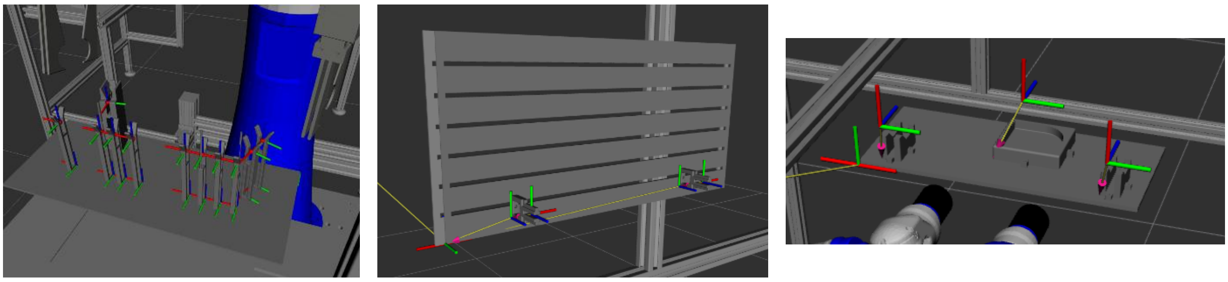
Figure 35. Relation between the files describing the cable routing platform. In the x3d file (a), it specifies the ID of the component (ID000005), the csv file (b) relates this ID with a label (G4) and a model number (0009), whose geometry and keypoints are described in the xml file (c).

The second group corresponds to those files providing information about the manipulated objects. It is composed of a csv file that provides information (e.g. dimensions, color) about the different components composing the wire harnesses, i.e. cables and connectors, and an xml file that describes the arrangement of these components in the initial wire harnesses which have to be assembled in the process. This information is merged and provided in ROS services, being of special interest for the identification and manipulation of these objects.

Finally, the last group is the one that provides information about the process. It is composed of a single file that contains the high-level action plan of the process, specifying the sequence of skills, the platform elements where to perform them, and the manipulated objects (e.g. Route Cable1 through Guide1 and Guide2). There are three possible skills: Pick Cable, Insert Connector, and Route Cable. As with the first two groups, this information can be also requested using a ROS service.



a. Robotic cell



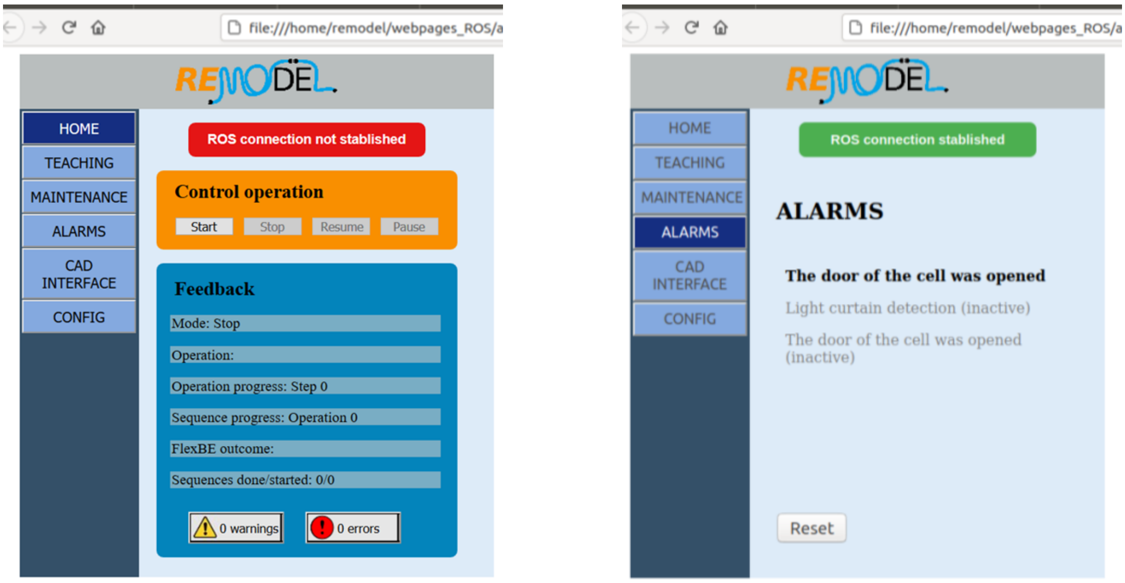
b. Cable Routing Platform c. Cable Holder Platform d. Automatic Tool Changing Platform

Figure 36. TFs and Markers of the UC2.2 robotic cell setup published by the CAD Platform

4.4.2 User Interface (UI)

Web-based interface to monitor and control the system. The interface is composed by different sceens with different functionalities, and all of them are accessible from any screen through a navigation panel, situated in the left side of the interface. Currently, just the ‘home’ and ‘alarms’ pages have been developed (see Figure 37), but new pages will be implemented for commanding the teaching system and for the configuration of system/robot parameters. The ‘home’ page allows the operator to control and monitor the process execution. It contains some buttons to start, stop, pause or resume the process, and some fields to visualize the process feedback. The ‘alarms’ page shows the safety status of the system and the detected alarms, active or inactive (the ones that are not active at the moment but haven’t been reset since their detection). As can be seen in Figure 37.b, this page also contains a reset button to clear the errors, however, this function is disabled for this use case as it must be ensured that the user is outside the robotic cell to reset the errors and restart the robotic operation.

The UI communicates with ROS using roslibjs and rosbridge, and it sends/gets information to/from other nodes through ROS topics (with publishers and subscribers in both sides) and services.



a. Home page of the UI *b. Alarms page of the UI*

Figure 37. REMODEL User Interface

4.4.3 Teaching by Demonstration Module

To fully exploit the flexibility and reconfigurability of the robotic system, an easy, fast and intuitive programming methodology has been developed. The developed teaching by demonstration module is able to learn which operations the robot has to perform just by analyzing the movements of the operator when performing the task, requiring no robotic expertise nor manual programming. This module focuses on understanding and digitizing the demonstrations instead of mimicking the operator's movements, therefore, its output is the high-level action plan of the process, i.e., the sequence of operations and locations (e.g., Place Connector1 in Guide1; Route Cable1 and Cable2 through Guide 2-3-4, etc.). Then, the optimal trajectories for each of these individual operations (e.g., Place or Route) are generated by parameterized functions, based on the keypoints and dimensions of the elements in the assembly platforms (provided by the CAD Platform).

The teaching system is composed by five modules, all of them containerized and interconnected by ROS. Three of these modules are in charge of processing the manipulation data gathered by the sensory system and converting it from the lowest level, consisting of the sequence of raw data coming from all the sensors, to the highest manipulation level, the processes. The first module discretizes the sensory data into different sequences of primitives, one for each analyzed variable (e.g., a sequence of primitives for the hand rotation (+Yaw rotation, -Roll rotation,…), another one for the hand configuration (hand open, hand closed,…), or another for the hand movements (+x, -z, +z, …)). Then, the second module evaluates and merges all these sequences, identifying the performed operations and segmenting the demonstration into a sequence of operations. For this, Optimized Multiorder Multivariate Markov Models are exploited, defining one model for each operation, and monitoring the likelihood of the sequences of primitives to be explained by any of these models. These models are multiorder because not just the information from the previous state is used like in conventional Markov Models, and they are multivariate because they consider information from different variables in the same model (e.g., the sequence of hand rotations, hand configurations, and hand movements). Regarding the term optimized, it is used because the order and the weight of each of the variables of these models are determined by an optimization process to maximize the operation recognition. Finally, the third module evaluates the resultant sequence of operations and selects the most likely process from a list of possible processes, making the system more robust against not-perfect segmentations.

In order to use this system, it has to be calibrated and the models have to be trained. Therefore, a forth module is used to train the system, analyzing all the recorded demonstrations, and generating an Optimized Multiorder Multivariate Markov Model for each operation and manipulated object. Finally, the fifth module is used to interface and calibrate the system.

The system is independent from the sensors utilized as long as they provide information about the operator's movements or interactions with the manipulated objects. Due to the multivariate nature of the Markov Models utilized, multimodal sensing can be exploited, utilizing several sensors that provide different information about the manipulation (hand and fingers movements, rotations, orientation, pressure…). In the ELVEZ UC (UC2.2), the initial tests have been performed using datagloves that capture the hand orientation, as well as the pressure and bending degree of the fingers, and a motion tracker, that captures the position of the hand (see Figure 38).

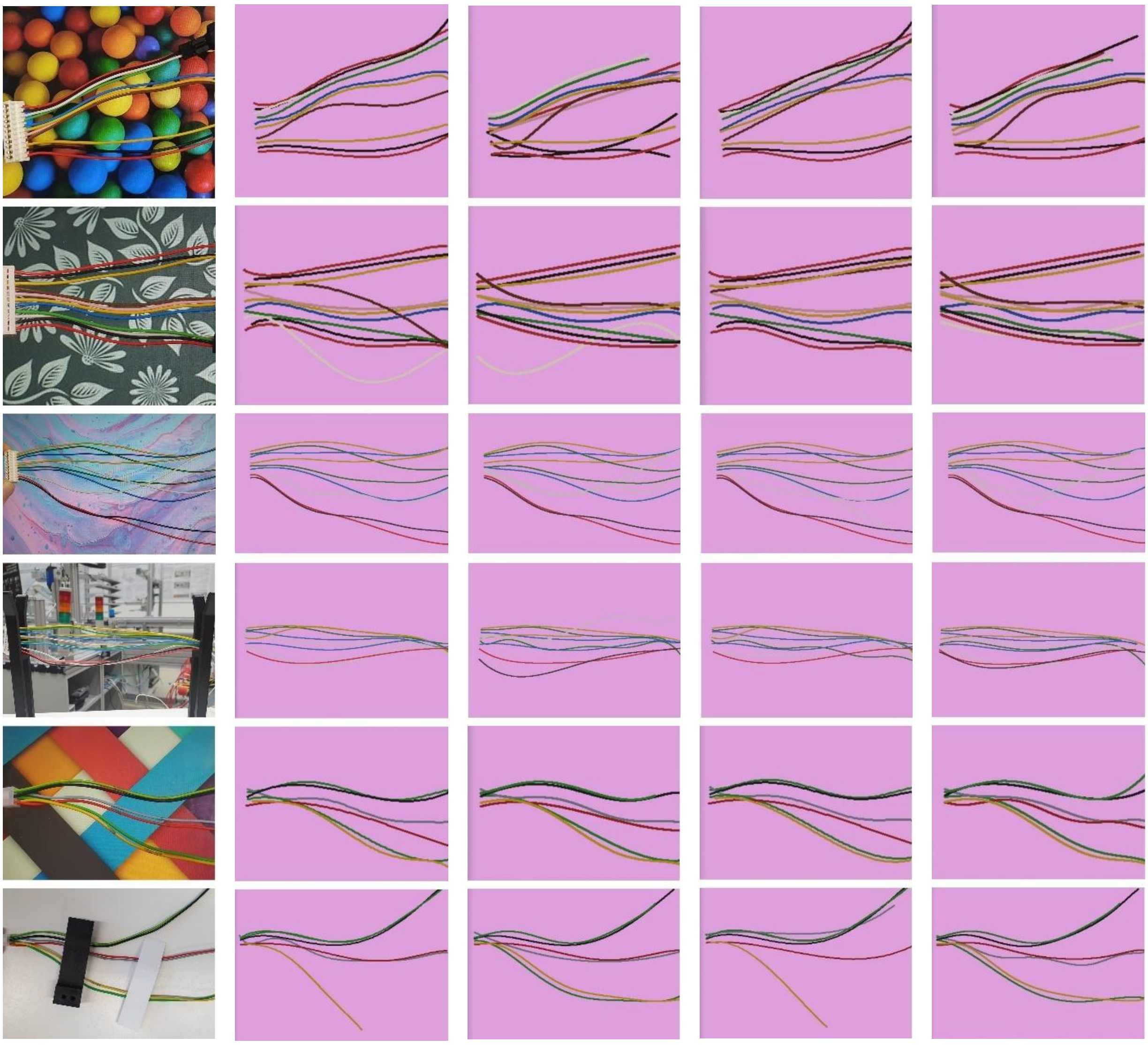
Figure 38. Sensors utilized to record the operator movements by the teaching by demonstration system: Dataglove and motion tracker.

4.4.4 Vision based identification of wire path and branch separation

The wiring harness assembly process requires routing the different cable branches of the harnesses through different paths, therefore, the robot must be able to identify and separate the required cable branches. Additionally, the dimensions and distribution of the cables add extra complexity to this problem, as the cables have a very small diameter and the distances between them are very small. The developed system uses computer vision to identify and model the cables of the wiring harnesses from 2D RGB images.

First of all, the system preprocesses the image, identifying the main wiring harness connector, which is used to determine the millimeters per pixel of the image and the initial position of each cable (the connector dimensions and cables distribution are requested to the CAD Platform). Then, the shape of each of the cables or the harness is estimated individually. First, the required cable is segmented using a binarization filter that considers both the edges detected in the image and the color of the cable (provided by the CAD platform). Then, the points of the cable are determined from the segmented image. For this, two algorithms can be used, the Forward Propagation (FWP) which calculates the points of the cable forward starting from the already known initial point, and the Backward Propagation (BWP) which calculates all the possible cable lines backward, starting from the end of the image, and selecting finally the most likely one (considering also how well the lines match with the initial cable point). Once the cable points are calculated, they are used to estimate the cable shape modeling it by polynomial regression. Finally, an unsupervised evaluation module analyzes the obtained result based on some parameters, validating or rejecting it. In case of failure, this module tunes some of the system parameters and repeats the process, making the system more robust against unexpected situations and unknown light conditions.

The selection of the algorithm will depend on the system requirements, as the FWP is faster but less precise than the BWP, and the use of the evaluation module (FWP-C and BWP-C) increases the performance but also the computation time. However, all of them show good results recognizing the wiring harness cables, even with complex backgrounds and occlusions as can be seen in Figure 39. The polynomial lines calculated for the cables can be used to determine the optimal grasping point between two cable groups for the robot, to perform the wiring harness branch separation.

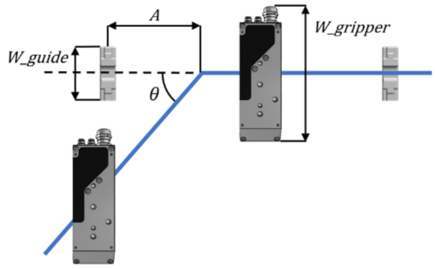


a. Input image b. FWP c. BWP d. FWP-C e. BWP-C

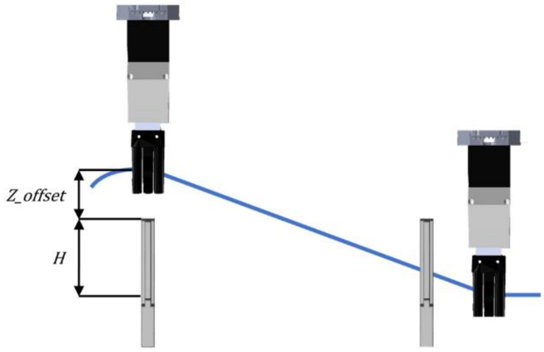
Figure 39. Comparison of the four algorithms of the system for the shape estimation of wiring harness cable with complex backgrounds and occlusions.

4.4.5 Parameterized manipulation operations

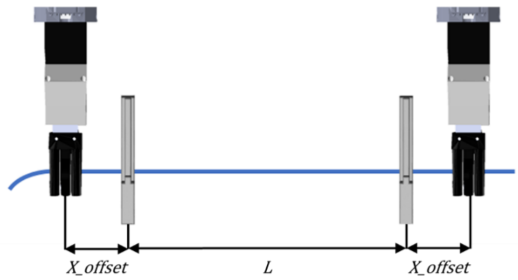
As introduced in the teaching by demonstration module (Section 0), the teaching system is used to digitize and understand the process performed by the operator, generating a high level action plan with the sequence of operations that the robot has to perform, however, all the robot trajectories are determined and optimized for each operation based on the keypoints and dimensions of the elements of the mounting platforms, such as the guides to route the cables. Due to this, all the operations are defined as parameterized functions, that define all the robot movements relative to the keypoints of the target platform elements. An example of this is shown in Figure 40 for the cable routing operation where it can be seen that the generated robot trajectory depends on the input parameters of the function and the position of the routing guides (all this information is requested to the CAD Platform). In particular for cable routing, the cable is slided towards the next guide by one of the robot arms, the arm moves to the side to slide some extra cable length required for lifting the cable later while keeping its tension. Before lifting the cable, the other arm of the robot goes to the last guide through which the cables were routed and grasps them, preventing the cables to go out. Then, the routing hand grasps the cables, lifts them over the guide, and finally inserts them, performing circular movements to not lose the tension of the cables.



a. Sliding additional cable length before lifting. Top view



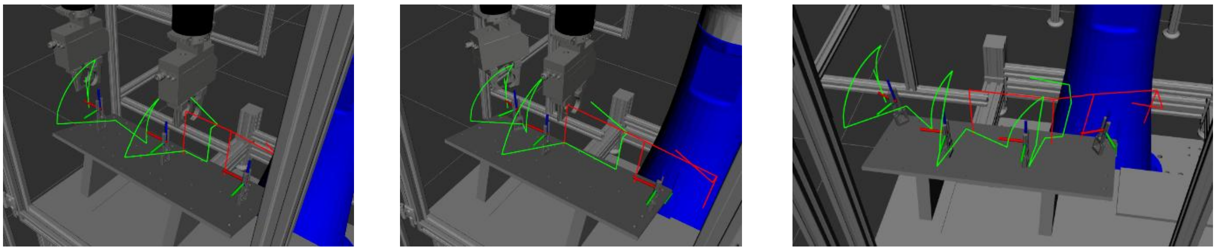
b. Minimum cable length for lifting the cable. Front view



c. Minimum cable length for inserting the cable

Figure 40. Parameterized cable routing operation. The cable radius used is the maximum of the b and c figures.

These parameterized operations make the system much more reconfigurable, as the robot trajectory adapts to any setup configuration. This can be seen in Figure 41, where the trajectories generated for each arm are shown (right arm in green and left in red) for three different configurations of guides in the cable routing platform. Finally, once all the waypoints are generated, they are used to plan and execute the robot trajectories. Some MoveIt-based functions have been developed for this, allowing the generation of more advanced single and dual-arm trajectories.



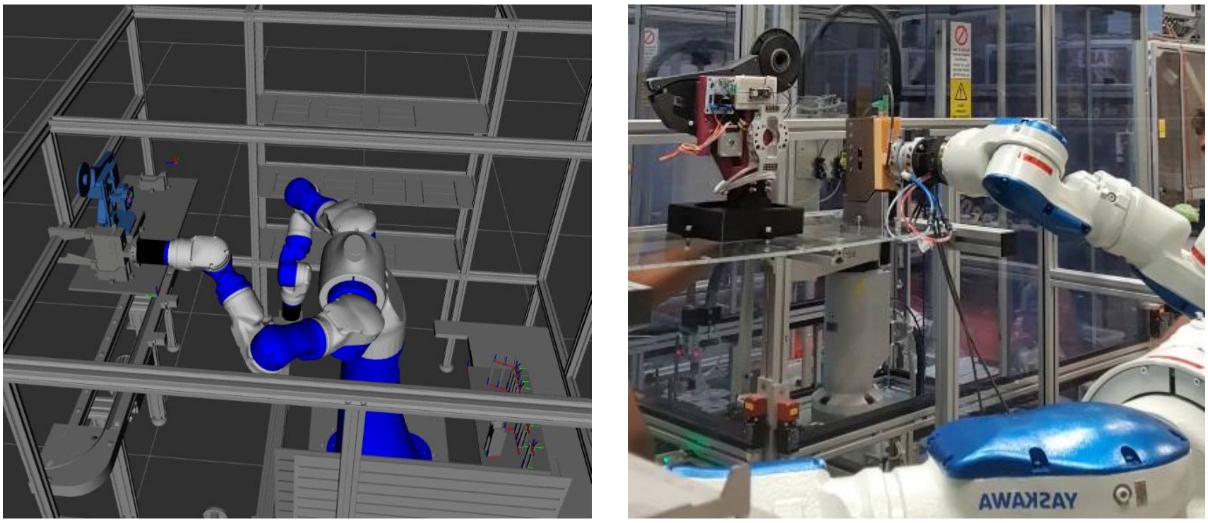
a. Straight cable b. One change of direction c. Two changes of direction

Figure 41. RVIZ visualization of the robot trajectories generated for three different configurations of guides in the routing platform (right arm in green and left in red)

4.4.6 Automatic Tool changing between gripper and gun

Due to the changing shape of cables, most of the operations that the robot has to perform for the wiring harness assembly require dual-arm manipulation, thus the two arms of the robot have to be equipped with grippers. However, this assembly process requires also the use of a taping gun to bundle certain groups of cables, therefore, one of the robot arms needs to be equipped as well with an automatic cable gun. Due to this, the implementation of the automatic tool changing (ATC) is necessary to change the robot end effector whenever is needed.

A MoveIt-based tool changing function has been developed to dynamically detach and attach new tools to the robot wrist (see Figure 42.a), update the robot collision matrix, and automatically update the transformation matrix between the robot wrist and the tool actuation frame, considered for the trajectories generation. Additionally, the CAD Platform provides information about the keypoints of the tools when placed in the tool changing platform (see Figure 36.d). The pneumatic lines for the tool changing are activated by the robot I/Os which are controlled by ROS services.



a. ATC in ROS. RVIZ visualization b. ATC in the real robot

Figure 42. Automatic tool changing

4.4.7 Performing the taping

The taping action for the spot taping gun is performed by activating the trigger of the gun by utilizing an external stepper motor. A specialized adapter was designed and created for the robotic taping application, and it consists of the spot taping gun mounted to the adapter, which is fitted with an Arduino nano ioT 33, L298N motor driver module and the 1A Bipolar stepper motor and the tool-end of the ATC module, as shown in Figure 31. The Arduino is connected by wireless network to the ROS workstation, and it has the server running with the control parameters to operate the setepper motor (i.e., the degree of rotation, the power ratings, the pinout configuration, the time delays, etc.). The ROS based client connects with the Arduino nano and publishes a message request to activate the stepper, to trigger the taping gun. The L298N is a dual H-Bridge motor driver, and it acts as the intermediatory between the Arduino and the stepper and regulates the supply to the different windings as required (Figure 43). When the stepper is rotated, it is physically fitted to the trigger of the gun, which inturn performs the taping action.

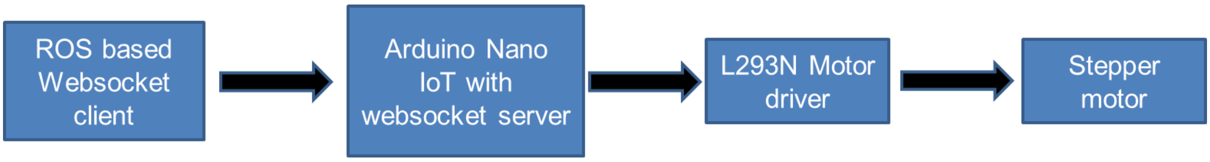


Figure 43. Communication for the taping gun actuation from ROS

Regarding the robot movements, the arm with the gripper grasps and pulls the cables putting them in tension and then the arm with the taping gun inserts it in the required taping position and sends the signal through ROS to actuate the gun (see Figure 44).

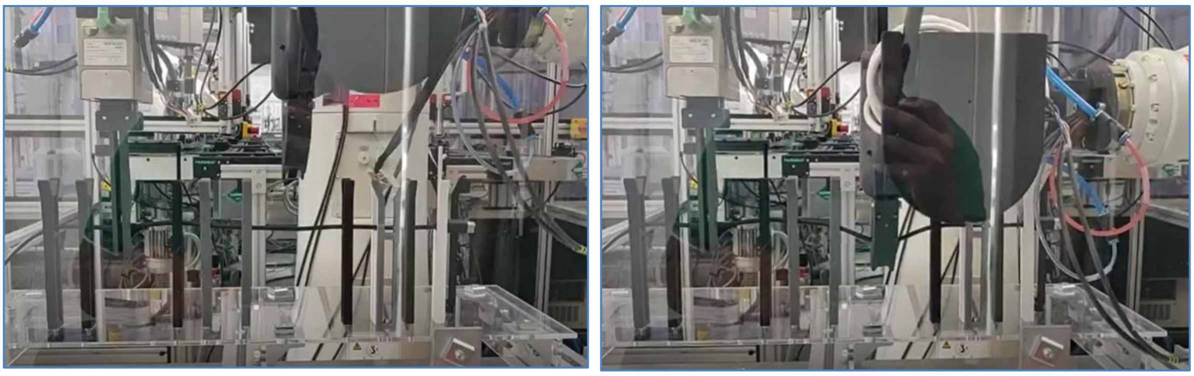


Figure 44. Spot Taping- Before insertion (left); After insertion and taping (right)

4.4.8 Safety system and REMODEL Safety Manager (RSM)

The safety system is composed by the physical safety devices, a safety PLC, and the REMODEL Safety Manager (RSM). The safety PLC is responsible for the fast and reliable emergency stop of the platform. It receives the signals from the safety devices, stopping the robotic platform immediately if a risk situation is detected. Additionally, it communicates with the ROS system through the RSM updating the safety status. The RSM is the ROS node developed to act as an intermediary between the physical safety devices and the rest of the modules of the ROS system. This node doesn't need to be that fast and reliable as it is not in charge of stopping the platform.

It receives the active alarms and the safety status from the safety PLC (using an Omron E/IP library) and communicates it to the rest of the modules of the ROS system by publishing the updated data on different topics. Additionally, the communication can happen also in the opposite direction, informing the safety PLC about an error or a risk situation detected by the ROS system, in order to stop the platform. In Figure 45 an example of the safety system communication can be seen, exchanging information between the physical devices and the ROS system (in this case the UI) through the RSM.

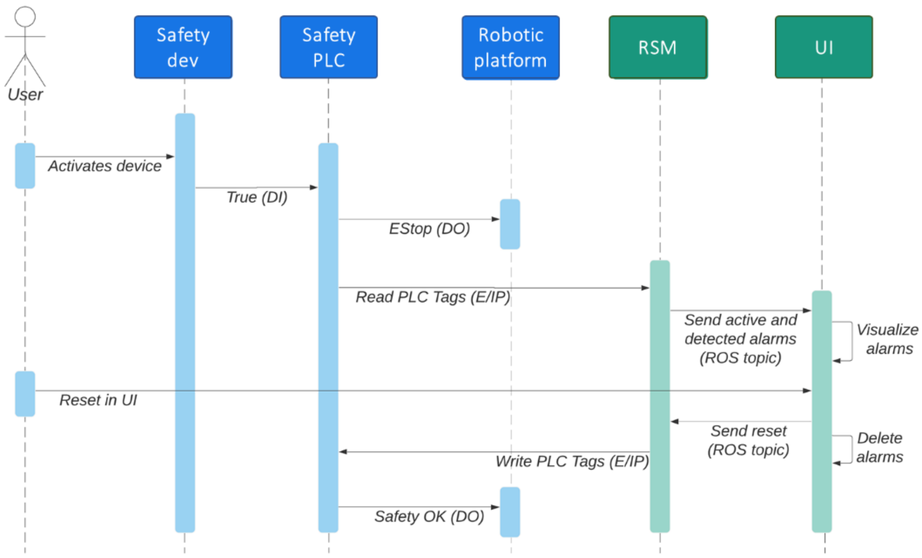


Figure 45. UML sequence diagram of the REMODEL safety system. The blocks in blue are physical devices and the blocks in green are ROS modules. In this figure two examples of communication are shown. In the first one, a safety device (e.g., light curtain) is activated and the signal is propagated; the safety PLC performs the emergency stop of the robotic platform and updates the safety status to the RSM, that publish this information in the ROS system, so the UI can display the alarm. In the second case, the communication happens in the opposite direction, so the reset signal of the UI is received by the RSM, that sends this information to the safety PLC.

4.5 Description of the robot task (Demonstrated during the demo)

In the ELVEZ UC (UC2.2) the robot is expected to show the capability of assemblying a group of wiring harnesses. This implies different steps:

1. First the robot picks a wiring harness (WH) from the cable holding platform with both arms.
2. The robot does a torso and a dual-arm movement to align the connector with the insertion mold and the WH with the separation guide and inserts it.
3. The robot takes a photo of the WH in-between the mold and the separation guide with the eye-in-hand camera, processes the image and calculates the grasping point. Then the other hand separates the required group of cables.
4. The robot arm routes the separated group of cables through the required guides. Steps 3 and 4 are repeated for all the cable groups with different routing paths.

5. If any taping operation is required, one of the robot arms performs an ATC, changing its gripper for the taping gun, then it goes to step 6. If no taping is required, it goes again to step 1 for the next WH.
6. The robot arm with the gripper grasps and pulls the cables to put them in tension and the other one performs the taping. If another taping operation is required, this step is repeated.
7. The robot arm with the gun performs an ATC, changing the gun for the gripper, and goes again to step 1 for the next WH.

4.5.1 Analysis of the robot performance

For safety reasons, during the final demo the robotic system is expected to accomplish the task according to the following scheduling:

1. First the robot picks a wiring harness (WH) from the cable holding platform with both arms. (10 seconds)
2. The robot does a torso and a dual-arm movement to align the connector with the insertion mold and the WH with the separation guide and inserts it. (20 seconds)
3. The robot takes a photo of the WH in-between the mold and the separation guide with the eye-in-hand camera, processes the image and calculates the grasping point. Then the other hand separates the required group of cables. (30 seconds)
4. The robot arm routes the separated group of cables through the required guides. Steps 3 and 4 are repeated for all the cable groups with different routing paths. (30 seconds)
5. If any taping operation is required, one of the robot arms performs an ATC, changing its gripper for the taping gun, then it goes to step 6. If no taping is required, it goes again to step 1 for the next WH. (30 seconds)
6. The robot arm with the gripper grasps and pulls the cables to put them in tension and the other one performs the taping. If another taping operation is required, this step is repeated. (15 seconds)
7. The robot arm with the gun performs an ATC, changing the gun for the gripper, and goes again to step 1 for the next WH. (30 seconds)

The execution speed during the demo will be maintained very limited also to avoid problems and damages to the system in the development phase. After proper system tuning and proper optimization of the robot task, it is reasonably expected to reduce the execution time by a factor of 4, achiving then a connection speed that is similar to human operators. This performance level is expected to be achieved 1 year after the REMODEL end.

4.5.2 Expected effort of human operators

The focus is posed on reducing the number of routing and taping tasks the human operator must accomplish to complete the production, to reduce the duration of the repetitive task within the shift and the duration and speed required to complete the tasks.

When compared to the conventional manufacturing practices followed in Elvez, the introduction of the REMODEL solutions is expected to reduce the cycle time of production by 20%. The requirements for the human operator would be to oversee the production and to clear any errors caused due to the failure of the adhesive tape in the spot taping tool. An additional thing can be to clear the failed execution of operation if none of the self correcting measures made by the system are successful.

In terms of reduction of physical stressand risk of human operators, this will significantly reduce the duration of repetitive carried out by the operator. Therefore, considering the most critical activity during the assembly process, i.e. the act of cable placement on the jig and using the taping gun, the risk analysis can be:

UC2.2 Risk Analysis

Intensity of effort : 1
Duration of effort in the cycle: 1
Frequency of actions: 1
Hand and wrist posture: 1
Speed of carrying out the activity: 3
Duration of the repetitive task within the shift: 2

Strain Index: 6

From the analysis of the cabling task accomplished during the execution of UC1 with the introduction of the REMODEL technologies, the value of the Strain Index is reduced to low risk, while it was high in case of full manual activities. It follows that there is a high potential for the REMODEL robotic technologies to significantly impact into the quality of the working environment for this use case.

5 UC3 - Wiring harness assembly

5.1 Use case description

The third use case is focused on the assembly of cockpit wiring harnesses. Within this use case, there are two different sub-tasks and two different types of cars and that means as well two similar, but not the same assembly processes.

Assembly of the cockpit wiring harnesses is also made manually. The main two task related to wiring harnesses are:

1. **Grabbing, carrying and assembly of cockpit wiring harness on the cockpit table**: this type of action is very difficult due to variety of sizes of the harness and its complexity. The simplest cockpit wiring harness may have weights of 10 kg, but the most equipped just about 15 kg and over 3 m of length.

2. **Electric tests called ECOS (i.e. Electric Check Out System) – plugging and unplugging of cockpit connectors** – testing if all required functions of the cockpit are correct. That phase is very important for entire cockpit assembly process. In case of the malfunctioning of any of the cockpit components, the cockpit has to be replaced to the correct one (that generates very high costs of correction). So that is necessary to check out all required electric functions before shipment to the main assembly line (assembly line no. 1) . The ECOS device is used to both models of car, namely Transporter T6.1 and Caddy 5. There are some differences between this two types of car – especially plugs.

The main goal is to obtain an implementation of the robotic/automatic solution for assembly of cockpit wiring harness. On the one hand, VWP wants to improve current conditions of work to their workers. On the other hand, enterprise wants to reduce the execution of tasks time according to the rule: every single second counts. The plant usually produces 750 cars per day in the proportion of 630 Caddy 5 and 120 T6.1 and these numbers are equal to quantity of wiring harnesses – each single car may have only one cockpit wiring harness.

5.2 Description of the robot task (to be demonstrated during the demo)

As Mentioned in the Section 4.1, there are two main tasks to be performed by the robots:

a. **Grabbing, carrying and assembly on the cockpit table,**
b. **Testing - ECOS – Electric Check Out System of Cockpit Functions.**

Reagarding to the first ones (point a), an expected tasks of the robot are as follows:

1. Cockpit wiring harness is contained in a box and must be delivered in a known configuration (the best case – almost the same position, with largest part pointed upwards). The wiring harnesses are delivered to the line in correct sequence of orders (prepared by an external company for the proper cockpit).
2. The vision system (or optical sensor) of the robot must detect the wiring harness in the transporting box and confirm correct position (chosen points) to grab it. There is a possibility to send beforehand an information to the robot about the specification of the wiring harness – type of vehicle and amount of plugs (concerning equipment of car).
3. Robot is grabbing and carrying the cockpit wiring harness (up to 15 kg) above the cockpit table to execute assembly tasks.
4. The second robot distributes the wire harnesses on the cockpit table.
5. Finally, after all the cabling has been assembled, the first robot places the main part wiring harness on a cockpit table.

Figure 9 - view of the prepared cockpit wiring harness on the cockpit table

Regarding the second task (point b), an expected tasks of the robot are as follows:

1. ECOS – is performer by connecting suitable wiring harness plugs to the connectors of the ECOS Device. The ECOS device with all connectors is continuously moving with motion of the line and transporting rack.
2. The robot must detect that transporting rack and cockpit on the hanger are in the right position to start working. Then it is necessary to detect the position of plugs. The robot should receive information about the amount of plugs from the internal control system concerning to so called PRNR i.e. specification of manufactured car.
3. Robot must take the connectors from transporting racks and then connect all plugs to the test device. Some of them can hang down from the cockpit – it may be difficult to grab them. The number of plugs depends on the equipment of the car. Some of the plugs are present in each car.
4. The plugging and unplugging require two hands/arms – robot should grab the connector in one hand and to the other hand plug and then connect them.
5. The branches hanging from the cockpit must be collected and protected by the robot to avoid any damage during transportation or successive assembly phases. They must be attached with Velcro fastener to the topside of cockpit cover.

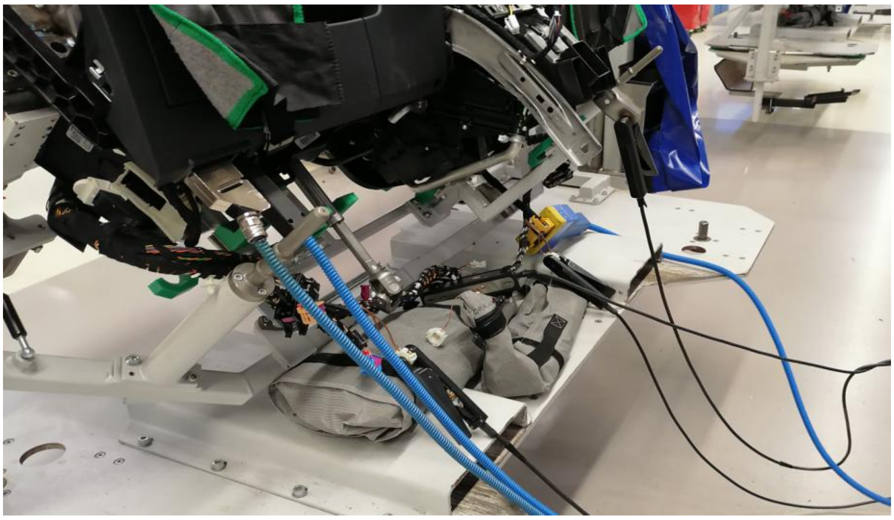


Figure 10 – cockpit during the ECOS testing (with plugged connectors)

5.3 HW & SW requirements – VWP

This section describes the hardware and software requirements of VWP's use case. After the analysis of the use case, the robotic system should meet the following requirements:

Hardware requirements

- Some robotic solutions must be able to work like human movement - using both hands / arms - to perform assembly tasks, e.g. connecting connectors and plugs, guiding the cockpit harness,
- Dual arm robot or two separate robots must be equipped with grippers able to grab and pick up different types of wiring harnesses – e.g. different thickness,
- The robot should be equipped with a vision system to detect the right position of connectors, plugs, wiring harnesses and so on,
- The process must take place in static mode or in the future the robots will be on a platform (seventh axis) moving along the production line to simulate static work
- Robot should be equipped with safety measures to ensure safe work and preventing it from being switched on by unauthorized persons
- Robot should have all supporting devices to allow human-robot collaboration, Robot should have speed sufficient speed to do tasks in less than tact time (<102 seconds) – crucial requirement (execution time + return to the next cockpit),

Software requirements

- The main requirement - REMODEL robotic system should be integrated with each required assembly system (FIS-eQS, protocol PMON) in order to do its tasks during real production (readout of car equipment and that means as well amount of plugs and which connectors to use to ECOS; how to arrange the cockpit wiring harness and so on),

- The REMODEL robotic system commands both robots,
- Robots programs will be as close as possible to the VW standard,
- The REMODEL robotic system manages the interaction of devices (screens, projectors, etc. …),
- The REMODEL robotic system informs about the status of the task and the sequence step by means of interacting devices,
- The REMODEL robotic system analyses data received from the sensors to detect the placement of the assembly parts,
- The wiring harness documentation is prepared in CATIA with possible export to most common CAD formats.

  The REMODEL robotic system analyses data received from the safety sensors in order to adapt its behavior to operators' presence.

5.4 Assembly line requirements:

This section summarizes the requirements and specifications of the assembly line at VWP:

- Continuously moving assembling line in tact time – 102 seconds (robot must perform its actions much faster in order to return to the next cockpit),
- The cockpit must go out from the line without faults and errors, because each mistake costs a lot after assembling of cockpit to the car.
- Length of one tact amounts 5 meters and width 4,4 meters,
- The area of one tact amounts about 22m2 (not too much to rebuilt totally the workstation or to install the robot cell),
- The cockpit transporting rack moves with set speed (not real),
- There is needed to take into consideration the precision of cockpit transporting rack position, serving to synchronization robot with the rack,
- On account of two-handed tasks, 7-axis robots could be needed,
- Documentation of robotic system must be in polish language (until demonstration),
- The main goal of project: to achieve results in order to fully automate these tasks,
- Control system of the cockpit transporting rack is designed and produced by LJU Automatisierungstechnik GmbH.

5.4.1 Analysis of the robot performance

Not yet determined due to working on too small robots which are not able to lift whole cockpit wiring harness from transportation box. Estimated time of robot performance should be determined by the end of 2022. There is plan to start testing on the final robots in August/September 2022.

Current total time of performing tasks on the basis of manual work is as follows (only tasks which will be automated):

a. **Grabbing, carrying and assembly on the cockpit table –** about 36 seconds in Caddy 5 and about 58 seconds in Transporter T6.1,
b. **Testing - ECOS – Electric Check Out System of Cockpit Functions -** about 61 seconds in Caddy 5 and about 86 seconds in Transporter T6.1.

5.4.2 Expected effort of human operators

In the evaluation of the strain index for this use case, the manouvers executed by the human operators to allocate the branches of the wiring harness in the proper place are taken into account.

Intensity of effort : 1
Duration of effort in the cycle: 1
Frequency of actions: 1
Hand and wrist posture: 1
Speed of carrying out the activity: 2
Duration of the repetitive task within the shift: 2

Strain Index: 4

From the analysis of the wiring harness allocation task accomplished during the execution of UC3, the Strain Index is significantly reduced by the REMODEL technologies. The focus is posed to reducing the number of handling tasks the human operator must accomplich to complete the wiring harness allocation, in order to reduce in particular the frequency of the repetitive task within the shift and the duration and speed required to complete the tasks due to their reduced number.

6 UC4 – Hose manipulation

Hose manipulation (UC4) for medical applications consists in the execution of quality checks on a flexible tube (hose) by grasping it at the output of the extruder and manipulate it in different ways.

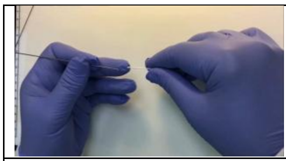
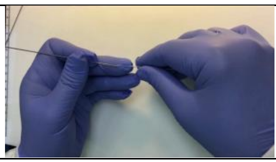
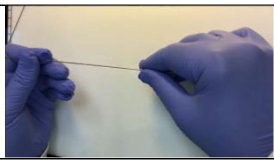
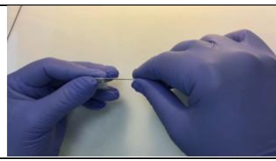
6.1 Production of hoses for medical applications

A large set of medical activities implies the use of hoses to deliver liquids or gases, or execute suction of blood and other organic fluids through vacuum pumps. These hoses are usually made of silicone or other plastic polymers, and they are characterized by large deformability and limited stiffness. Some of these devices can be up to 3 meters long, and can be equipped with suitable connection terminals at one or both ends. Due to obvious sterility requirements, these medical devices are almost always single-use. For this reason, they are produced in very large numbers by specialized companies, such as ENKI, and several quality checks must be executed inside a clean room. Very limited cases apart, the inspection processes are performed manually or in an assisted way by means of devoted tools. In Figure 46 a detailed view of the ENKI production line, of the final product and how the operators perform quality checks are shown.

Figure 46 - Details of the ENKI production line, the extruder, the final product and the operators performing quality checks

6.2 Quality check execution by human operators

The product selected for the development if this use case is a catheter with 1.73mm external nominal diameter and 0.88mm internal nominal diameter. In Figure 47, two sequences showing how the internal lumen dimension check is executed by means of a couple of go not go gauges with 0.84 mm and 0.92 mm respectively to and how the cutting of the hose section is performed by means of a razor blade are reported. From this sequence it is possible to see that these tasks require the worker to perform very precise manipulation and insertion maneuvers. Moreover, in the hose cutting task, the hose should be rotated while cutting to avoid deformation of the hose section.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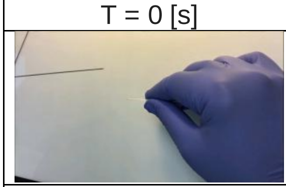
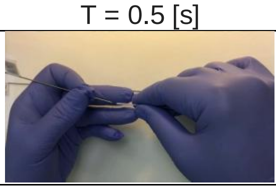
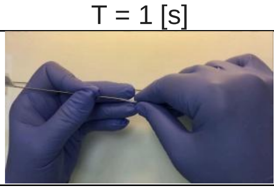
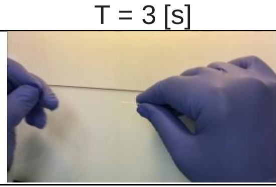
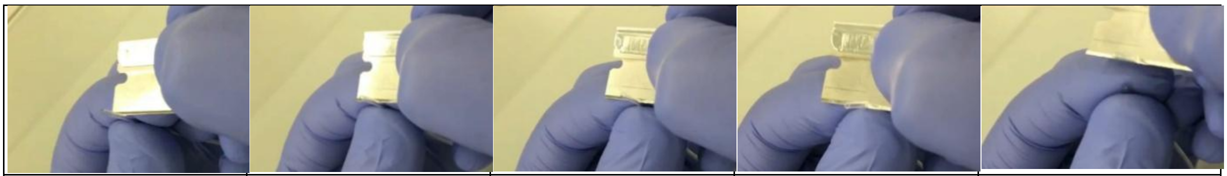
			
T = 5 [s]	T = 7 [s]	T = 8 [s]	T = 9 [s]



T = 0 [s]	T = 1 [s]	T = 2 [s]	T = 3 [s]	T = 5 [s]

Figure 47 - Medical hose go not-go check and cutting sequence

The main obstacles toward the automation of this process are represented by the limited cost per item, the variety of length, size and thickness together with the compliance of the material that makes difficult to hold the hoses during the inspection, to cut them properly and to insert the go, not-go gauges. These obstacles make automatic machines devoted to this this task economically difficult to sustain for SMEs, not advantageous in terms of speed, difficult to update and to adapt to the variety of products.

The specific objective for this use case is to exploit the REMODEL robotic platform equipped with proper auxiliary tools to execute the aforementioned task, in such a way to reduce the worker psychophysical stress due to this repetitive task and to speed up the production by moving the workers to more qualified activities. The target performance is to achieve at least the same execution speed of the human worker.

6.3 HW & SW requirements

The integration of the robotic platform in the ENKI production line is carried out with particular attention to safety requirements. For this reason, the safety features developed in **T2.5** and the dynamic environment reconstruction developed in **T4.2** will be exploited to guarantee the robot will remain safe in all the operative conditions. Due to the fixed base of the robotic platform, the use of pressure-sensitive flooring will be particularly useful in this case. The user interface developed in **T3.2** will be specialized for this use case, giving particular attention to the possibility of taking control of the robot by the worker to change the task or to stop it for safety reasons. The robotic platform will be exploited to grasp the hose from the pile and insert the go not-go gauges in the hose verifying if the insertion is successful or not, cut the hose in specific points with the razor blade for camera inspection. The development of specific tools for the hose cutting will be taken into account in **T6.3**. The final demonstration at TRL 6 will be implemented in the production line at the ENKI factory.

6.3.1 Integration with the extruder output

The robotic platform is integrated at the output of the extruder, just after the device used to cut the hoses to the desired length. The robotic platform will be synchronized with the cutting device in order to grasp the hoses in a known position. An alternative is to use the vision system to detect the hoses and grasp them from the pile where they are collected at the end of the production line.

6.3.2 Internal diameter check with the go no-go gauge

Once the hose is grasped, the internal diameter must be checked with a go no-go gauge. To this end, the gauge can be fixed in a known position in such a way the robot must properly align the hose with the gauge at perform force controlled insertion test. The test will be passed in case the insertion is performed or not within proper insertion force ranges.

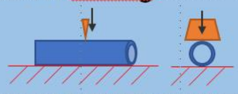
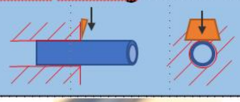
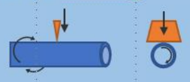
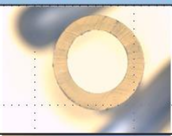
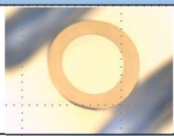
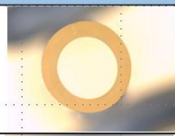
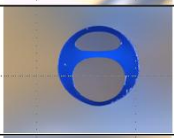
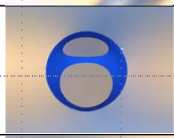
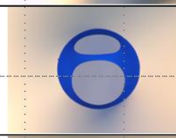
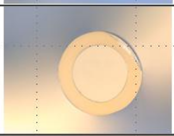
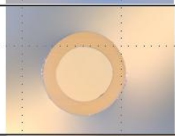
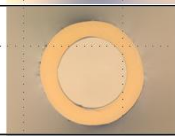
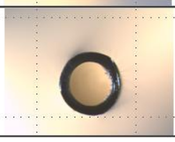
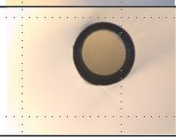
Cutting strategy / Material type	Linear cutting 	Block cutting 	Rotative cutting 
• Soft material • Single lumen			
• Medium material • Multi lumen			
• Hard material • Single lumen			
• Triple material (hard+soft+medium) • Single lumen			

Table 4 - Different hose type and cutting strategy

6.3.3 Hose cutting

Some hose sample must be cut to perform visual check in specific points along the hose. In *Table 4* the different kind of hose and the result of different cutting strategies applied to these products are reported. From this analysis, the rotative cutting strategy offer the best results for the vision inspection. For this reason, the design of a specific tool has been carried out in WP6. After the execution of the cut, the robot puts the hose section in front of a camera used for quality check. This camera is at a known position, therefore the robot puts the hose in front of the camera in a specific position and at a specific distance.

6.4 Description of the robot task (to be demonstrated during the demo)

In UC4 the robot is expected to show the capability of executing quality checks in medial hoses. This imply different steps:

6. First a robot arm takes the sample from a known position;
7. In case of visual inspection, the robot puts the sample in cutting tool, activate the cutting procedure and release the sample until the cutting is finished;
8. The the robot takes the sample and put into under the microscope;
9. In case of insertion of the go not-go gauge, the robot moves the hose toward the first gauge and measure the insertion force;
10. In case the insertion force is higher than a specific threshold, the insertion is classified as failed;

11. The insertion is repeated for the second gauge.

For the go not-go gauge, a speciment passes the quality test is the insertion in the first gauge is successful while the insertion in the second fails.

6.4.1 Analysis of the robot performance

For the sample preparation, during the final demo the robotic system is expected to accomplish the task according to the following scheduling:

1. First the robot arm takes the sample from a known location (5 seconds);
2. The robot then moves the sample toward the cutting tool and insert it (10 seconds);
3. The cutting tool is started and the sample is prepared (10 seconds);
4. The robot moves the sample under the microscope (10 seconds).

For the go not-go gauge insertion, during the final demo the robotic system is expected to accomplish the task according to the following scheduling:

1. First the robot arm takes the sample from a known location (5 seconds);
2. The robot then moves the sample toward the first gauge and insert it (10 seconds);
3. The robot then moves the sample toward the second gauge and insert it (10 seconds).

The execution speed during the demo will be maintained very limited also to avoid problems and damages to the system in the development phase. After proper system tuning and proper optimization of the robot task, it is reasonably expected to reduce the execution time by a factor of 2, achiving then a testing speed that is much faster than humans for the sample preparation and close to human for gauge insertion. This performance level is expected to be achieved 1 year after the REMODEL end.

6.4.2 Expected effort of human operators

The focus is posed in reducing the number of quality checks the human operator must accomplish along the production, in order to reduce in particular the duration of the repetitive task within the shift and the duration and speed required to complete the tasks due to their reduced number.

In comparison with conventional manufacturing, the introduction of the REMODEL technologies is expected to save 70% of human time for the quality checks of medical hoses. The human operator activities will be restricted to the measurement in case of visual inspection. Additional human interventions are limited to thecase of unrecoverable failure of the robotic system.

In terms of reduction of physical stressand risk of human operators, this will significantly reduce the duration of repetitive carriedout by the operator. In the evaluation of the strain index for this use case, the curring of the tube for the preparation of the tube surface for the visual inspection and the gauge insertion are taken into account as the more risky and difficult for the human operator:

Intensity of effort : 1
Duration of effort in the cycle: 1
Frequency of actions: 1
Hand and wrist posture: 3
Speed of carrying out the activity: 1
Duration of the repetitive task within the shift: 1

Strain Index: 3

From the analysis of the hose quality check tasks accomplished during the execution of UC4 with the introduction of the REMODEL technologies, the value of the Strain Index is reduced to low risk, while it was high in case of full manual activities. It follows that there is a high potential for the REMODEL robotic technologies to significantly impact into the quality of the working environment for this use case.

7 Conclusions

This deliverable describes the use cases and focuses on the type of demonstration is expected, the performance that will be shown in the final demonstrators and how the performance are expected to evolve after the end of the remodel project. The data reported in this deliverable establish the expected performance to evaluate the REMODEL impact. The risk analysis has been updated taking into account the benefits provided by the REMODEL technologies. The capability of the system of reducing the operator stress in executing the considered use cases will provide an evaluation of the improvements the REMODEL technologies will bring to the quality of the working environment along the development of the project.