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Mechatronic Re-Design of a Manual Assembly Workstation into a Collaborative One for Wire Harness Assemblies

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Abstract: Nowadays, the wire harness assembly process is still manually performed due to the process complexity and product variability (e.g., wires of different kind, size and length). The Wire cobots project, in which this work was conceived, aims at improving the current state-of-art assembly process by introducing in it collaborative robotics. A shared workstation exploiting human abilities and machine strengths was developed to assembly automotive wire harness by means of insulated tape for a real industrial case. In the new workstation, the human deals with the complex task of wire handling, while the robot performs the repetitive and strenuous taping operations. Such a task allocation together with the workstation redesign allow for an improvement of the operator's well-being in terms of postural conditions and for an increase of the production efficiency. In this paper, the mechanical and mechatronic design, as well as the realization and validation of this new collaborative workstation are presented and discussed.

Keywords: wire harness; collaborative robot; ergonomics

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1. Introduction

Wire harnesses are used in several industrial fields, such as automotive and machine construction, as well as in information and communication technologies. A wire harness basically consists of a group of wires and/or cables that are used to transmit signals as well as provide electrical power. The harness is obtained by joining together the wires by means of tape, straps, ties, lacing, etc. The aim of a harness is to simplify wire installation by grouping these into a compact bundle which requires a single installation operation, decreasing the installation time. Nonetheless, the assembly of a wire harness is a very time consuming operation, due to its complexity. Indeed, it may include several deformable objects, the wires, of different kind, size and length [1]. The automatic manipulation of wires could be very helpful in the execution of these assemblies. However, it is still an open issue.

Currently, the investigations on such a topic range from the abstraction of the automatization process, the recognition of the system and the motion planning to the handling of the wires. In [2], limp components (among which wires) are classified to abstract and standardize the automatization of the assembly process of such components. In [3], image processing software is used to recognize possible errors in harness assembly, starting from real-time information on its color and location. In [4], a visual servoing-based system is proposed to detect the position and alignment of cables and connectors of a harness; such a study is preparatory to an automated mating process of plug-in cable connectors. The mating problem is addressed in [5,6]. In particular, in [5], a method is presented to grasp a wire connector and to mate it with a target connector. This is possible thanks to a high-speed visual feedback system that detects the position of the target while an eight-degrees-of-freedom robotic hand handles the connector to be mated with the target. In [6], the automatic mating of two wire connectors is obtained through a custom tool, a vision system and an impedance control. The custom tool is a cable connector feeding that allows aligning cable connectors so that they can be grasped straight and held firmly by the robot. The grasped connector is mated with the target (fixed) one thanks to image-based visual servoing and an impedance control to correct the positioning error of the visual system. In [7], a methodology inspired by human behaviors is proposed for robotic wire harness handling. The method involves a multipurpose gripper capable of both tracing a segment of a cable and grasping the connectors met during the tracing. The tracing is made exploiting force sensors, the knowledge of the harness CAD model and a force control strategy that avoids the breaking of the wire. Although such a methodology employs few and cheap sensors, its implementation requires the use of at least two robotic arms working cooperatively. Sampling-based algorithms based on the rapid-exploiting random tree (RRT) to plan the motion of robots dealing with wire harness assemblies are investigated in [8,9]. In [8], an improved RRT-based algorithm is proposed to generate assembly paths for flexible wires of a car production line under environmental constrains. In [9], a path planning algorithm is presented for assembly cables in aircraft with unreachable cabins. Such an algorithm allows for an obstacle-free assembly path and provides a manipulation sequence that can be used to guide the robot movements. However, in both works [8,9], the motion planner validation is carried out only through simulations. An experimental robotized wire harness assembly in a car production line is presented in [10,11]. Although these works demonstrate the possibility of automatic handling wires, such a result is obtained employing several sensors including cameras, laser sensors for measuring in real-time the 3D state of the wire harness, and three robot manipulators working cooperatively together. This leads to high plant costs to have, as stated by the authors, a success rate in wire handling of just 50%. A detailed review about the progress in wire harness assembly can be found in [1]. To date, despite the progress made, the automatic wire handling/assembling methodologies and technologies are still far from an industrial solution, especially for Small- and medium-sized enterprises (SMEs). Currently, the automated part of the process is the preparation of the single wire (e.g., cutting and stripping wire ends, crimping terminals, etc.) while the assembly of the harness is manually performed [4].

With the Wire cobots project, the authors investigated an alternative solution to a fully automated process for improving the harnesses assemblies in terms of reduction of both cycle time and worker effort. Such a solution relies in the development of a human-centered assembling system in which a collaborative robot assists the worker during the stressful operations, overcoming the issues related to both the technological aspects as well as the human occupation of a fully automated solution. This paper describes the technical realization of such a collaborative workstation developed for a real industrial case study.

The paper is organized as follows. Section 2 describes the manual wire harness assembly with reference to our solution. Section 3 briefly recalls the theoretical background underling the developed workstation. Section 4 outlines the conceptual design behind the new collaborative workstation, whose realization is discussed in Section 5. An evaluation of the developed workstation is provided in Section 6. Finally, Section 7 draws the conclusions and future developments.

2. Case Study Objectives

The Slovenian company Elvez d.o.o. [12] produces and assembles cable harnesses designed for the automotive sector. It is interested in speeding up the assembly of wire harnesses, the bottleneck of its production line. A manual assembly line made by two workstations is currently employed to assembly the wire harnesses. Such a line works on average six days per week with three shifts (8 h/shift) per day, producing on average 900,000 pieces/year. The assembly process consists in taping together three bundles of wires by means of isolating tape. The operator sequentially inserts the bundles into tailored assembly jigs and then fastens them together by means of an automatic taping pistol in seven different spots (see Figure 1). The whole assembly process consists of nineteen elementary tasks related to wire insertion and wire taping and takes on average 40 s/piece.

The company is looking for a robotic collaborative system that allows:

- improving the productivity, i.e., a cycle time shorter than the one of the current manual process;
- improving the operator's physical work conditions, i.e., improve the physical ergonomics; and
- guaranteeing a safe collaboration with humans.

The solution to this real-life challenge, outlined in the remainder of the paper, was developed inside the Wire cobots experiment [13], funded within ESMERA-FOCE (First Open call for European SMEs Robotic Applications, H2020—ICT 780265) [14]. Wire cobots is the results of a partnership between the Italian SME Carretta s.r.l. [15], a company specialized in the design and installation of industrial automation solutions, and the the research group of the Smart Mini Factory (SMF) laboratory of the Free University of Bozen-Bolzano [16].

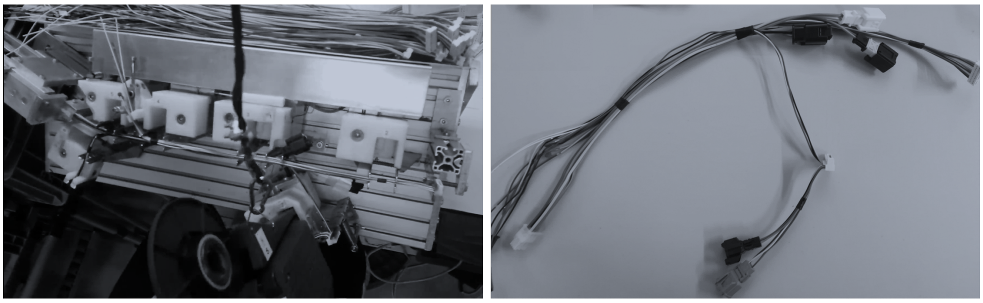


Figure 1. Manual assembly workstation at the ELVEZ d.o.o. company (**left**); and wire harness (**right**).

3. Methods

The new collaborative assembly workstation was developed according to the well-known Good Engineering Practice (GEP), which mainly consists of the following phases:

1. Problem definition
2. Background research
3. Requirement specification
4. Conceptual design
5. Detailed design
6. Assessment of requirement satisfaction

The first two phases are discussed in the Introduction, while the requirement specifications are identified in Section 2. The design phases are addressed in Sections 4 and 5. Finally, the verification of the fulfillment of all the requirements is described in Section 6. It is worth noticing that, for this last phase of the development process, two state-of-the-art methodologies will be used and are here briefly described.

The first one is the RULA (Rapid Upper Limb Assessment) method [17], which was used to quantify the improvement related to the physical ergonomics. The RULA method evaluates the body postures, load/force, coupling and muscle activity of two body regions (i.e., arm and wrist; and neck, trunk and leg) for each task of the assembly process. The values attributed to each task for the two body regions are then summarized into just two scores. This is done by employing so-called Table A and Table B of the method itself and a precautionary principle according to which the worst-case scenario is taken into account (i.e., each body region is scored with the highest value resulting from Table A and Table B). The final result of the RULA method is a single score denoting the necessity of intervention to lower the resulting risk level of the process analyzed. Such a single score is obtained by combining the scores of the arm and wrist region with the one of the neck, trunk and leg region according to so-called Table C (reported in Table 1). As can be easily inferred from

Table 1, the final score is an integer number ranging 1–7, in which a high score indicates a high priority of intervention.

Table 1. RULA score.

Table C		**Neck, Trunk, Leg Scores**						
		1	**2**	**3**	**4**	**5**	**6**	**7+**
	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
Wrist	3	3	3	3	4	4	5	6
and	4	3	3	3	4	5	6	6
arm	5	4	4	4	5	6	7	7
scores	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Score meaning:	
1–2	Posture acceptable if not maintained or repeated for long period
3–4	Further investigation is need, and changes may be required
5	Investigation and changes are required soon
7	Investigation and changes are required immediately

The second state-of-the-art method adopted is the so-called hybrid method defined by the ISO TR 14121-2:2012 [18]. This method was used for performing the mechanical risk assessment of the new workstation and, hence, to evaluate its safety. The hybrid method quantifies qualitative parameters describing the potential hazard by using numerical scoring and a risk matrix (see Table 2). The risk of a hazard is estimated by using the combination of the following four parameters:

1. Severity (Se): It denotes the severity of possible harm as an outcome from the identified hazard and can assume an integer value between one and four.
2. Frequency (Fr): It evaluates the average interval between frequency of risk exposure and its duration and can assume an integer value between two and six.
3. Probability (Pr): It is the probability of occurrence of a hazardous event and can assume an integer value between one and five.
4. Avoidance (Av): It is the possibility of avoiding or limiting harm and can assume an integer value equal to one, three or five.

The risk is estimated through the calculation of the risk class $(CI = Fr + Pr + Av)$ in accordance with the severity value Se and results in three different risk levels: low, medium and high (which are, respectively, represented by the colors green, yellow and red in Table 2).

Table 2. Risk matrix of the hybrid method defined by ISO TR 14121-2 [18].

	CI				
Se	**3–4**	**5–7**	**8–10**	**11–13**	**14–15**
4					
3					
2					
1					

4. Conceptual Design

The conceptual design for a new collaborative assembly station able to fulfill both the requests of the company is thoroughly described and validated in [19]. Here, a summary of the key concepts (illustrated in Figure 2) is reported for the reader's convenience.

Wire cobots aims at developing a human-centered assembly system for wire harness in which a collaborative robot assists the worker during the heaviest and most stressful operations, i.e., combining human inimitable ability with smart machines strengths. A new methodology has been finalized and adopted [19] to identify if a manual assembly process has the potentials (or not) for the integration of collaborative robotics solutions. The activities of the manual process are evaluated by means of an algorithm which analyzes five process critical issues taking into account: safety and ergonomics, product/process quality and economics. The process critical issues are properly weighted to differently stress the relevance of operator's physical well being and occupational safety, as well as production performance. As an outcome of such an algorithm, the taping process resulted the most promising activity in terms of collaboration potentials. Therefore, the taping activities have been demanded to the robot, while the worker deals with wires and connector handling as well as their insertion into the assembly jigs.

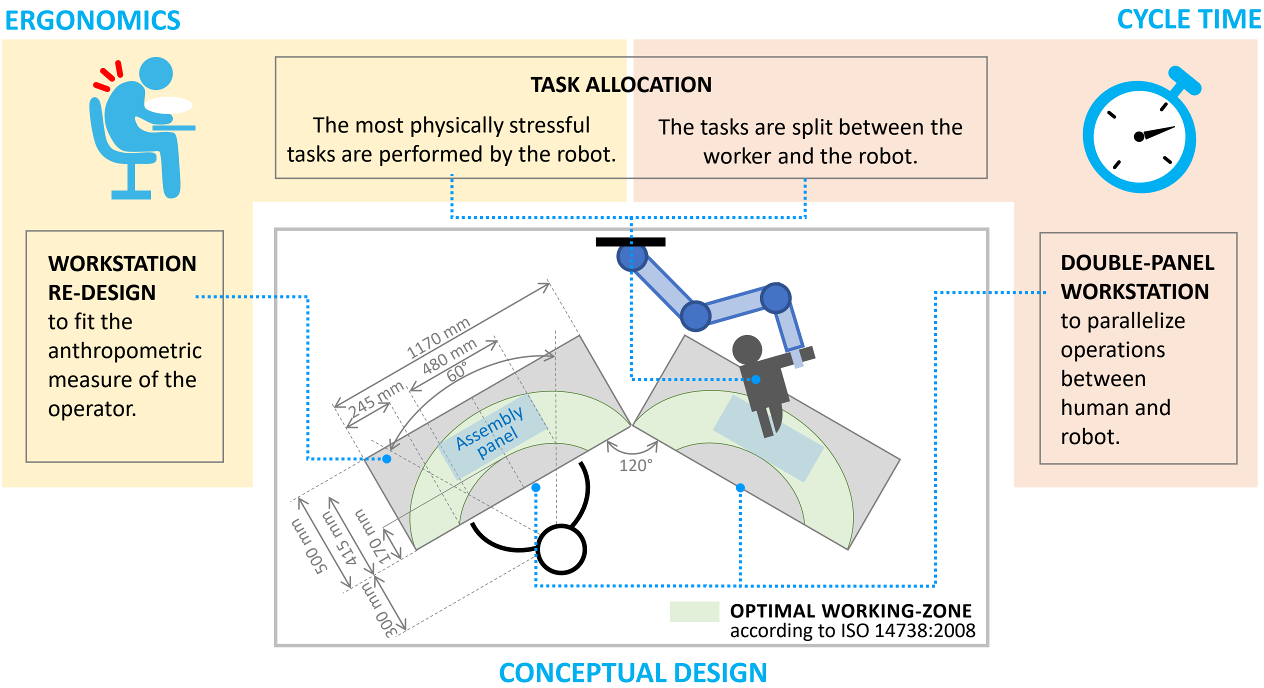


Figure 2. Key design drivers to fulfill the challenge requirements.

Due to the nature of the assembly process analyzed that mostly consists in sequential operations, the task division between the worker and the robot marginally reduces the cycle time. To avoid that the robot must wait until the operator ends his/her task and vice-versa, both the process and the workstation have been modified in a way that the assembly of two harnesses is partially overlapped by letting the working subjects operate in the same time on two different products. This has been obtained by properly designing and organizing the workstation in a double-panel workstation: while the worker operates on a product, the robot operates on a second one, and then the two are swapped.

To optimize the working postures of the operators, the new working area has been designed according to the EN ISO 14738:2008 guidelines [20]. It is inclined 30° with respect to the horizontal, which is the orientation that minimize the operator wrist twist. The angle with respect to the vertical axis between the two assembling panel is 120°. Such an arrangement of the assembling panels allows the operator to work on both panels with a minimal trunk twist and without colliding with the adjacent panel. To assure a constant production along all the daily work, the new assembly workstation can be automatically regulated in height. This allows adjusting the working area for fitting the operator's anthropometric measurements and further improve ergonomics of the workstation. Furthermore, the manual handlings are also considerably improved leading to a reduction of the related biomechanical overload. This is possible thanks to the robot contribution since the activity parallelization allows a reduction of the work rhythm.

5. Solution Implementation and Prototyping

The development of the conceptual design outlined in Section 4 has led to the realization of the prototype of the new collaborative workstation shown in Figure 3. It consists of the following parts, described in the next subsections:

- Two benches
- Two assembly panels
- Six boxes for the storage of the wires to be assembled and two boxes for the assembled harnesses
- A collaborative robot, a Universal Robot UR10
- An end-effector: the taping pistol Kaba Tec KTH Spot 9
- Two wire locking systems (one per panel)
- Buttons and lights to interface with the operator

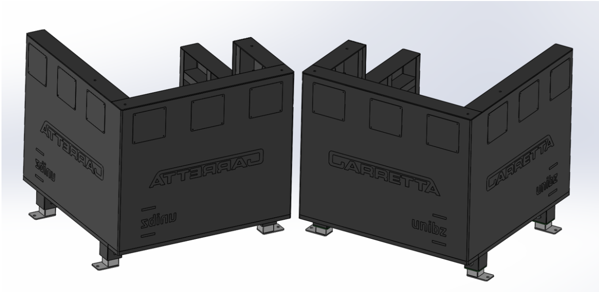
(**a**) Front view

(**b**) Back view

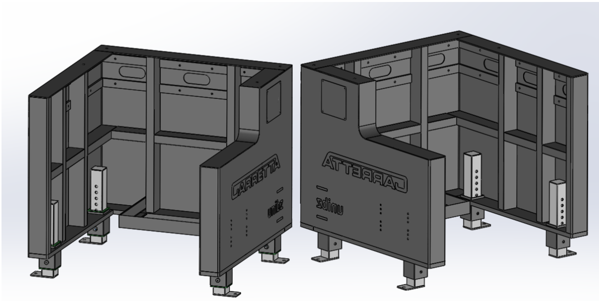
Figure 3. Prototype.

5.1. Metallic Carpentry: Benches and Assembly Panels

Two specular benches (Figure 4) have been designed to realize the workstation. The benches are independent, so they can be used also separately allowing for a modular design. They are entirely made of coated steel. Each bench weights 150 kg and measures: 900 mm $\times$ 860 mm $\times$ 925 mm (length $\times$ width $\times$ height). Such a sizing comes from a structural dynamics analysis towards to guarantee the stability of the system under the dynamic load due to the movements of the robot mounting on it. The bench height is adjustable so that it can fit the anthropometric measure of the operator working on it. In this first version of the prototype, the height regulation is performed manually, and the adjustment range is of 15 cm. The new release of the prototype will include actuators to automatically and continuously regulate the height.



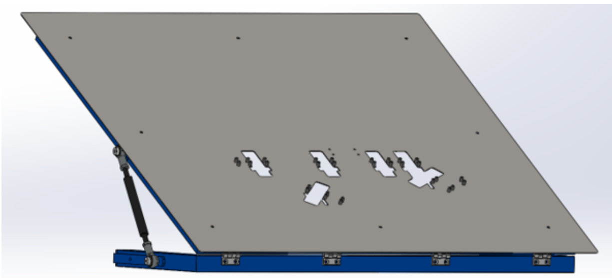
(**a**) Front view



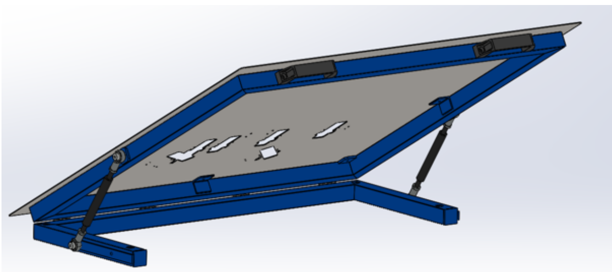
(**b**) Back view

Figure 4. Bench design.

The two assembling panels are fixed to the benches by means of tilting frames (see Figure 5) which allow adjusting the panel inclination by $\pm 10^\circ$ about 30°. The tilting frame is realized by means of a welded square section tubular structure made of steel. This mounting solution of the assembling panels allows easily interchanging the top of the workstation for working with different assemblies/products. The panels are sheets made of Anticordal 100 (Al 6082). The jigs for the right wire assembly have been obtained by means of laser cuttings. Plastic pins have been screwed on the panels to allow for wire bundle positioning.



(**a**) Front view



(**b**) Back view

Figure 5. Assembly panel design.

5.2. Storage Boxes

The positioning of the storage boxes for both the wire bundles and the harnesses has been based on ergonomics considerations in order to improve the operator's working postures. In particular, the boxes for wire supply have been placed on the assembly panels with the picking zone inside the optimal working area as defined by the ISO 14738:2008 guidelines [20]. Such an arrangement of the feeding boxes guarantees less effort for the operator picking the cables. The storing boxes for the unloaded of the assembled harnesses have been placed on the outer side of each assembly panel, but in the closest position to it that concurrently guarantees no interference with the operator's hip and legs and minimal trunk torsion (see Figure 3a).

5.3. Collaborative Robot Placement and Selection

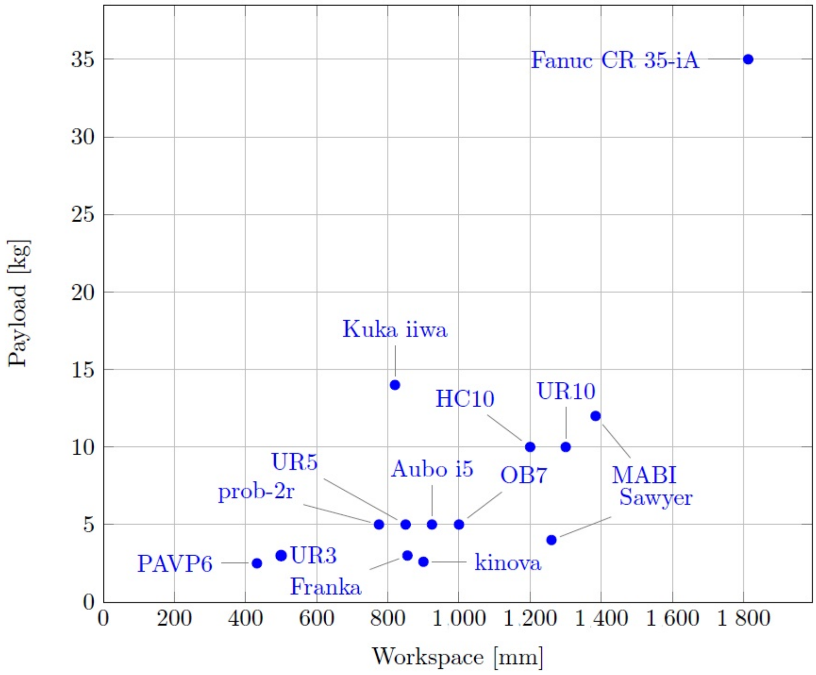
A crucial aspect in the selection of the most suitable collaborative robot to add in the workstation is its placement. Once the robot base has been defined, it is possible to compute the maximum distance that the robot should cover, which in turns provides an estimation of the minimum robot reach.

For safety reasons, it has been decided to not let the robot and operator work on the same side of the assembly panels. Such a decision comes from the following evidence:

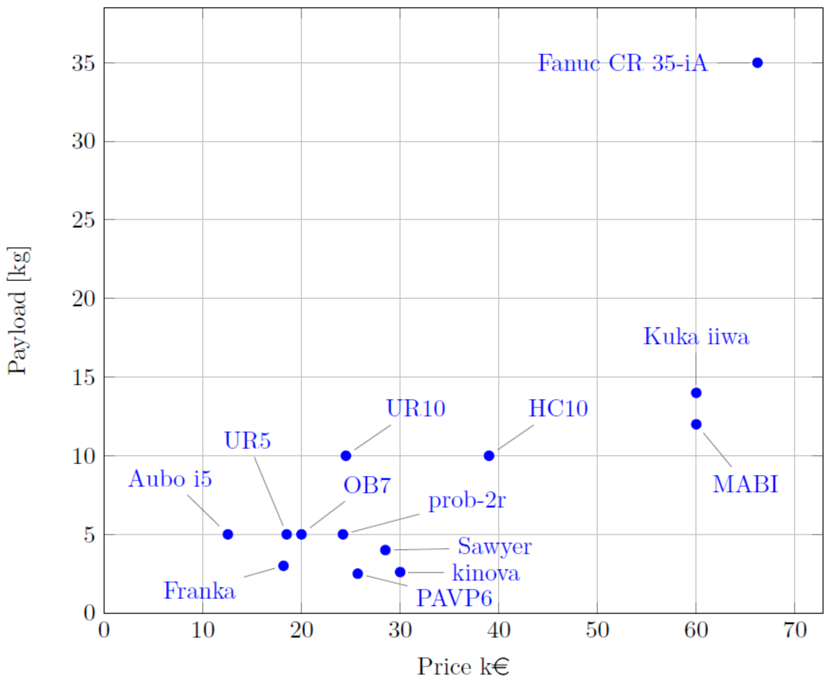
- The working area of each panel is quite small (about 450 mm × 220 mm).
- The robot must cover a large area moving between the two panels (the minimum distance between their farthest points is 1.6 m). This means that its dimension will not be compact.

The sharing of a small working area with a relative big robot could cause idle times [21] or, even worse, collision between the operator and the robot that should be prevented [22]. Therefore, the collaborative robot has been placed at the back side of the workstation; basically, the worker and the robot operate one in front of the other with the assembling panels interposed. This solution allows a reduction of the effort required for the further definition of the safety measures needed for the mitigation of the residual mechanical risks. To equally and easily reach the taping poses of both panels, the robot base has been centered with respect to them. The other two coordinates in the space to place the robot base have been determined by looking for the position that minimizes the distance to reach the farthest poses while preventing collision with the benches. From such an analysis, it results that the maximum distance between the farthest poses and the optimal placement of the robot base is 1270 mm. This is the lower reach limit for the selection of the collaborative robot.

Market research has been performed to identify the collaborative robots suitable for such an application. The robot comparison has been made in terms of reach and payload. The latter must be adequate for moving the adopted end-effector that weights about 2.5 kg. The results of the market research are summarized in Figure 6, where more than ten collaborative robots are compared in terms of workspace (expressed as maximum reach), payload and price. As shown in Figure 6a, there are only a few robots with a reach larger that 1270 mm and a sufficiently large payload for a flexible use of the robot. Among them, the Universal Robots UR 10 [23] has been selected since it not only satisfies the requirements in terms of reach and payload, but it also has a very convenient price/payload ratio (see Figure 6b).



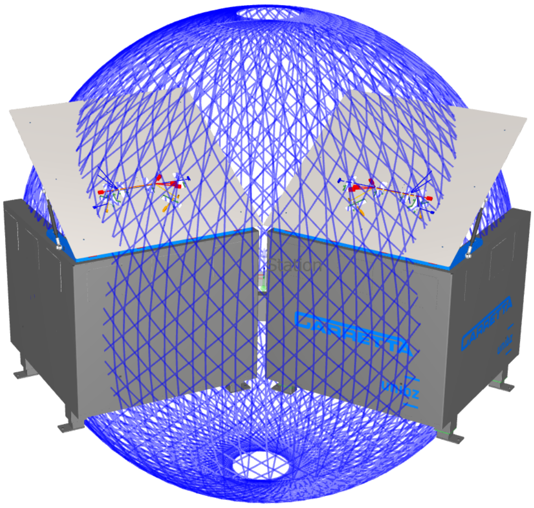
(**a**) Payload vs. workspace



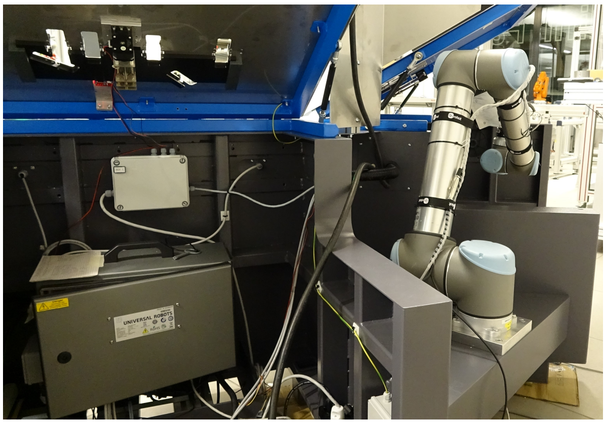
(**b**) Payload vs. price

Figure 6. Market research for collaborative robots.

The UR10 is a six-axis anthropomorphic robot with a non-spherical wrist designed for both assembly and workbench tasks. This robot has an almost spherical workspace (see Figure 7a) with radius of 1300 mm (without considering the additional 180 mm of end-effector). The UR10 has a payload of 10 kg, more than sufficient for moving the adopted end-effector. The robot is integral with the workstation. A steel base has been designed, which allows fixing the robot between the two benches, as shown in Figure 7b. An internal compartment in the bench has been realized to house the robot controller unit.



(**a**) Workspace referred to the robot flange



(**b**) Integration of the robot in the workstation

Figure 7. Collaborative robot UR10.

5.4. End-Effector

To let the robot perform the taping operations, the taping pistol Kabatec KTH Spot 9 currently adopted by the company Elzez has been used as end-effector. To this end, it has been mechanically and electrically connected to the robot. The mechanical connection has been realized by means of a specially shaped metal bracket, fixed directly into the side of the pistol by means of inserts/screws (see Figure 8).

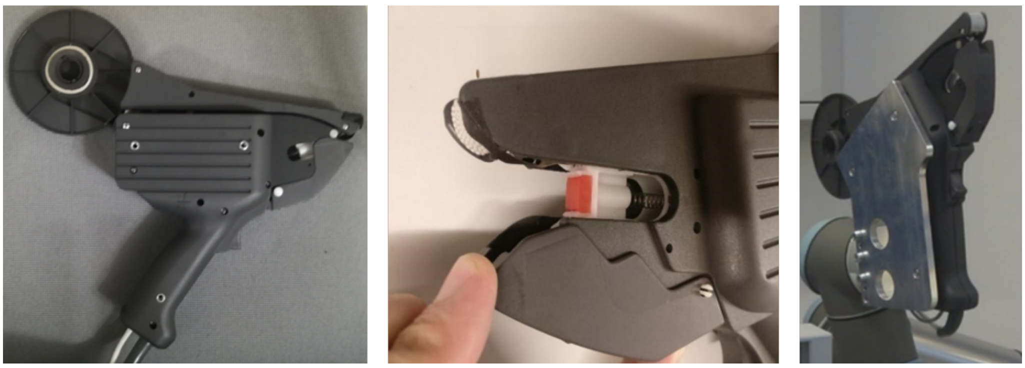


Figure 8. End effector: Kabtec KTH Spot 9.

All the command and monitoring signals available in the control logic of the taping pistol have been taken out of it and managed by means of an ad-hoc board. This allows directly activating and monitoring the pistol by means of the robot controller. In particular, the following signals have been identified and used in the control logic of the system:

- Start taping.
- Check tape fault (roll end and/or tape torn). This condition has been managed by bringing the robot in a maintenance position and informing the operator in charge by means of an optical signaling device and a pop-up on the teaching pendant of the robot.
- Status of the taping operation based on the work cycle of the motor.
- Status of the safety device, i.e., the tilting component on the tip of the pistol (see the central picture in Figure 8). The pistol motor starts only if it is in a closed position.

5.5. Locking System

Having placed the robot at the back side of the workstation, the approaching direction of the taping pistol to the wires is inverted, as schematically represented in Figure 9. This lead to a practical issue: the pistol does not tape the wires together but just pushes them outside the jigs, since there is nothing that keeps the wires in place. To overcome this issue, we designed a wire locking system. Such a system must leave totally accessible the jigs to let the operator insert the wires and must lock the wires when the robot works on them. This has been realized adopting an auxiliary panel placed on the rear of the assembly panel that moves parallel to it (see Figure 10 left). By moving the auxiliary panel back and forth, the L-shaped stops (see Figure 10 right), fixes on it and opens and closes the jigs where the wires are inserted by the operator. The auxiliary panel is made of Polizene 1000 and has been realized by means 3D printing; the stops are made of aluminum and are screwed on the panel.

The auxiliary panel is actuated by means of a linear guide (T8-Z60) consisting of a leadscrew/nut mechanism and a stepper motor. A mechanical endstop attached to the assembly panel is used for the homing of the stepper motor. The motor is controlled by an Arduino Nano board. In particular, this latter listens for the enable signal from the robot and drives accordingly the output of the motor drive (i.e., L298 H-bridge) to obtain the desired closing and opening motion.

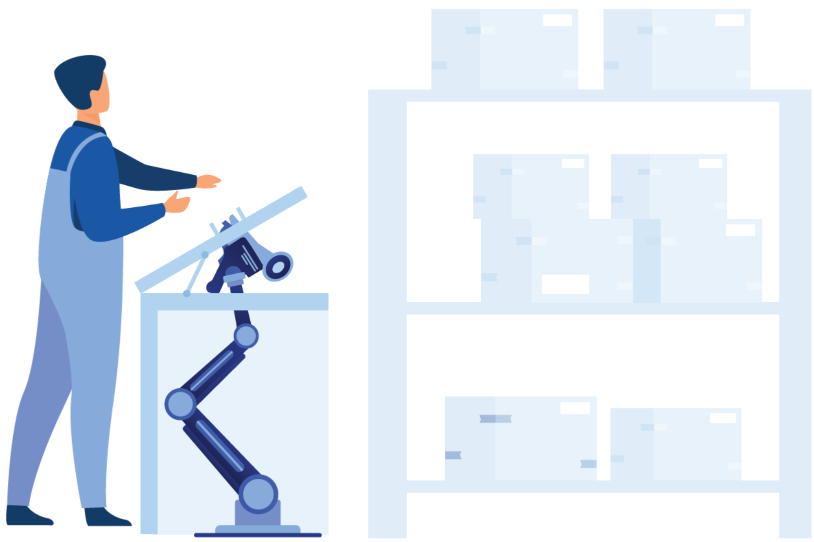


Figure 9. Approaching direction of the taping pistol.

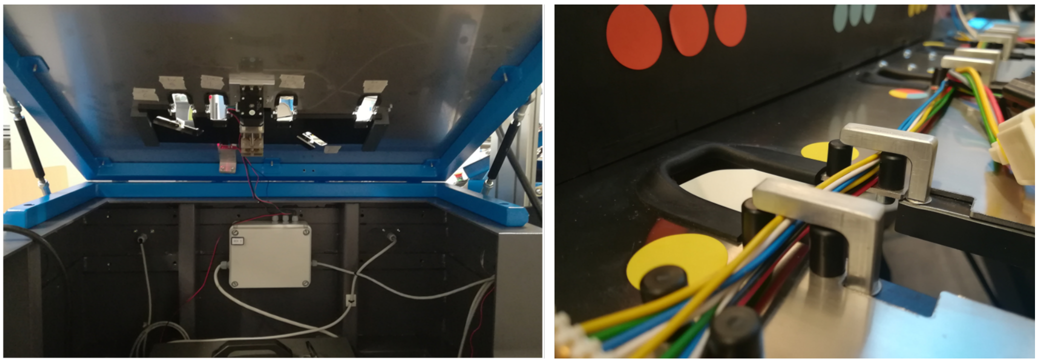


Figure 10. Locking system.

5.6. Workstation Architecture

The assembly cycle of the new workstation has been rearranged as follows:

1. The worker picks the first two bundles of wires with connectors and inserts them into the assembly jigs of Panel 1.
2. While the worker removes the previous assembled wire harness from Panel 2, the robot tapes the wire harness on Spot 1 of Panel 1.
3. The worker picks and inserts the third bundle of wires on Panel 1 and moves onto Panel 2.
4. While the worker performs Task 1 on Panel 2, the robot applies the isolating tape on the remaining six spots on Panel 1.

The developed workstation has been designed to be human-centered, therefore it is the human operator who decides the timing of the process and communicates to the robot when it can start with the taping operations. To this end, a two-hand control has been implemented on each bench. The benches are also provided with emergency stops and led lights which provide the status of each workbench according to the following codification:

- Green: The operator can start to work on that workbench.
- Orange: The robot is working on that workbench.
- Red: Alarm, the process is stopped for malfunction. The red light is currently turned on on both the workbenches. When this scenario happens, the operator is guided through the messages on the robot teach pendant toward the problem solution.

The control architecture of the workstation is entirely managed by the robot control unit, as shown in Figure 11. The UR10 is controlled by a Mini-ITX single board computer and a safety PLC. The PLC handles the implementation of the physical human–robot interaction features of the robot and represents the gateway to the internal bus of the robot arm. The Mini-ITX installed on these robots runs a Linux operating system and is connected to the teaching pendant where the GUI Polyscope is provided.

5.7. Robot Programming

To develop custom applications for UR, two main possibilities are available [24]: a script language called Polyscript and a visual version of this language based on a three-node paradigm called URP format. Polyscope gives the operator access to the robot functionalities and provides an integrated development environment (IDE) for programming in URP format.

We developed a URP program composed by two taping tasks (one for each workbench) and a transition between the workbenches. All motions are composed by trajectories with trapezoidal velocity profiles in the joint space. Each taping consists in an entrance sequence, a taping procedure and an exit sequence; the related waypoints have been exported from the workstation simulations made in RoboDK software (see Figure 12). When the operator enables the robot, it immediately communicates with the Arduino Nano board to lock the wires. Once the robot is positioned in the taping position, the tape command is sent to the pistol and the robot waits until the pistol communicates that its working cycle is terminated. When the taping task on a panel is over, the locking system is opened and the robot moves directly to the other panel waiting to restart its cycle.

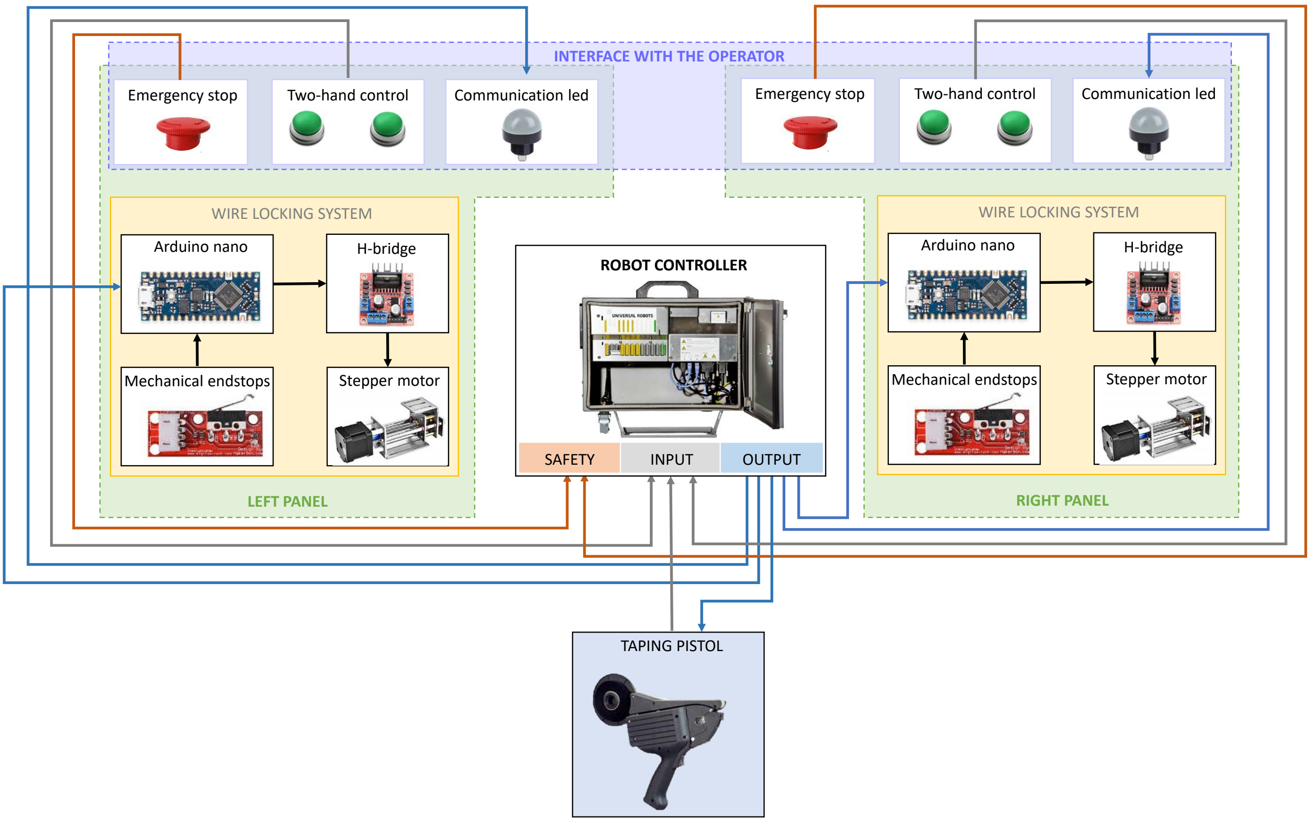


Figure 11. Functional scheme.

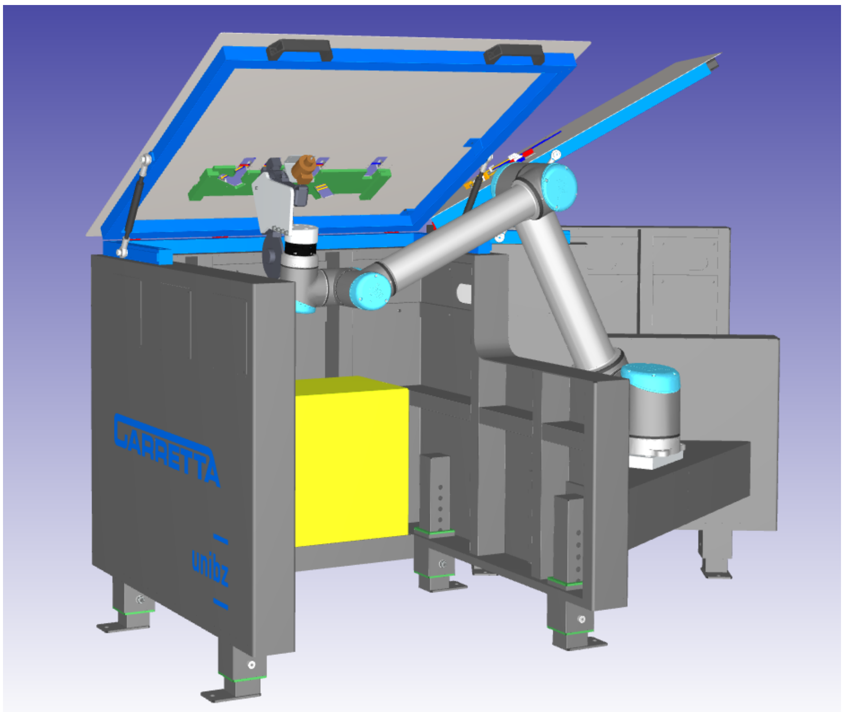


Figure 12. Workstation simulation in RoboDK.

5.8. Human–Robot Collaboration and Safety Measures for Preventing Mechanical Hazards

Safety is a crucial topic of industrial human–robot collaboration [25,26], since collaborative systems allow for the sharing of the workspace and for physical human–robot interaction. This makes unsuitable the safety solutions employed for "traditional" robotic systems [27] and requires the development of other solutions to ensure operator's occupational safety. The safety standards and deliverables on the topic are still under development; the first guidelines have only recently been published in ISO/TS 15066:2016 [28]. Such a technical specification examines in depth the preliminary concepts introduced by the ISO 10218-2:2011 [29] and defines the requirements for different operations involving collaborative industrial robots to minimize the mechanical risk. The focus on the mechanical hazard is strictly related to the nature of human–robot interaction in industrial settings: unexpected and unwanted contacts could be very likely. These can generate different kinds of collisions and crushes [28], therefore they have to be identified (by means of a risk assessment procedure [18]) and properly managed.

The new workstation design, according to the formal definition, is a co-existence solution, since the robot supports the operator without providing a real hand-by-hand physical interaction. In particular, it is possible to identify three areas with different conditions of the human–robot interactions and, hence, of hazards. The first zone (human area) is located in front of the panels where the operator can freely move and perform the assembly tasks. The second zone (robot area) is located behind the panels where the robot can move in a non-collaborative way. The shared area is the taping zone. In that area, the human and the robot tool must safely coexist. By implementing that division, we introduced specific physical borders. As a result, when the robot is in the robot area, it can operate with high motion performance (therefore in a not-collaborative way) by avoiding the possibility to harm the human at the same time. Nevertheless, some potential mechanical hazards (H) have been identified for each of the three interaction areas, and described below:

H1 An unauthorized presence of an operator into the robot operating zone could cause an unconstrained dynamic impact with the robot parts (transient contact), a crushing and/or rubbing between robot parts and/or workstation parts and/or a trapping between robot parts and/or workstation parts. This could involve all the human body parts.

H2 The presence of body parts in the shared area could cause the human's clamping into the cable locking system or the crushing and/or rubbing between robot tool and panels holes during the taping operations. This could mainly involve the hands and fingers.

H3 The introduction of body parts in the frontal space between the two panels could cause an unconstrained/constrained dynamic impact with the robot system parts during the motion of the robot between the two panels. This could mainly involve the lower arms, the wrist joints and the hands/fingers.

To prevent these potential hazard, the following safety measures (SM) have been outlined:

SM1 Use of proper machine guarding (physical or optical) located around the robot operating zone to prevent unauthorized entry.

SM2 Adjustment of holes perimeter/stops/robot tool surfaces to reduce hazardous edges and increase the contact surfaces.

SM3 Use of a dual-hands command (one for each panel) located at the lower edges of the human area to force the operator to move the hands away during taping operations.

SM4 Safe programming of robot trajectories.

SM5 Use of audio/visual signals to communicate the motion and the state of the robot.

SM6 Information/education/training program for operators.

Some of the proposed measures will be finalized as soon as the final version of the workstation is integrated into the production environment to reduce any residual risk.

6. Results

To experimentally assess the proposed collaborative workstation, several wire assembly tests were carried out on the developed prototype (see Figure 13). The workstation was evaluated in terms of satisfaction of the requirements defined in Section 2, whose evaluation is discussed in the following subsections.

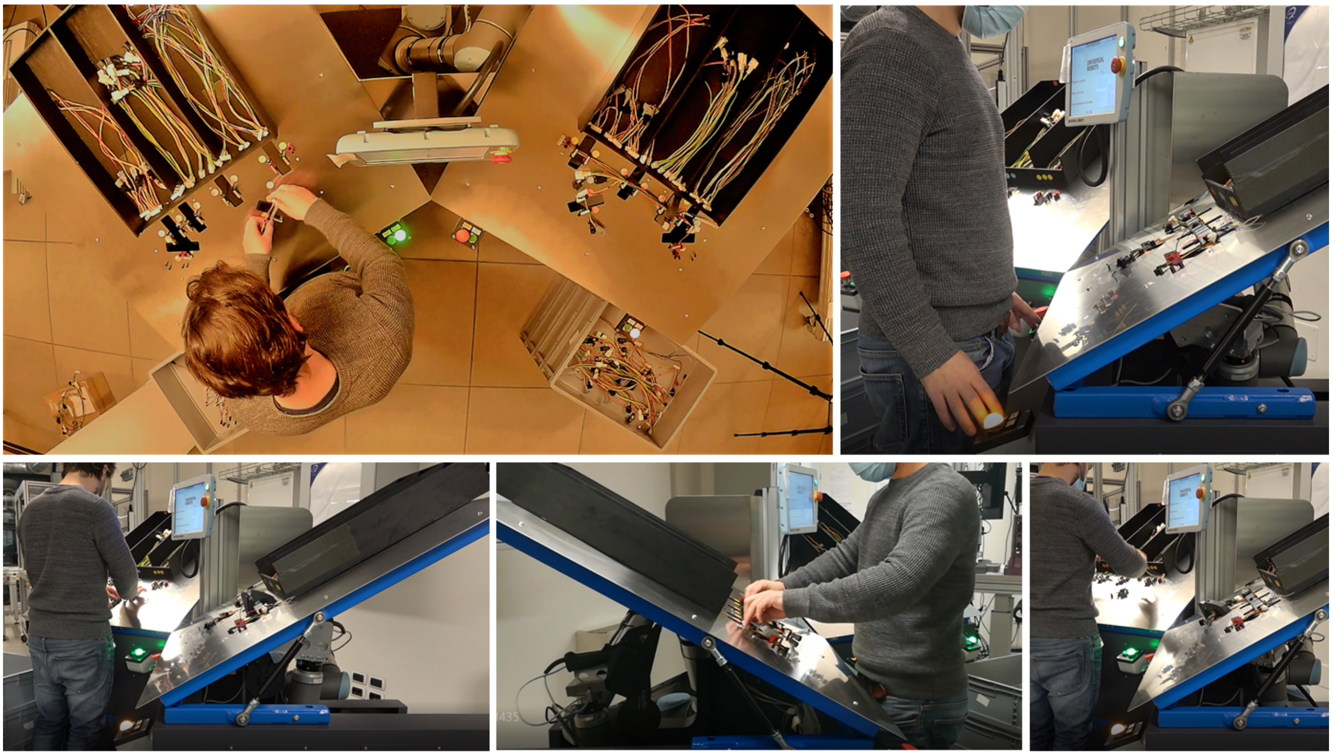


Figure 13. Experiments with the new collaborative workstation.

6.1. Cycle Time Improvement

The average value of the cycle times recorded for the different tests carried out was taken as the reference cycle time for the new workstation. It results equal to 35 s/harness versus the 40 s/harness of the manual workstation. Therefore, the new workstation leads to a 12.3% reduction of the cycle time. This results in a more efficient assembly cycle. Thanks to the productivity increase, a quite short payback period of less than 1.5 years was estimated for the company, considering a price of about 55,000 € for the final commercial version of the workstation.

6.2. Improvement of the Operator's Working Conditions

The improvement of the operator's working condition qA evaluated in terms of physical ergonomics. In particular, a RULA analysis Qa performed on both the manual assembly process and the collaborative one. Table 3 shows the score attributed to each body region for the two workstations.

The comparison of the results shows that all the values related to the postures of the different body regions are equal or lower in the collaborative solution with respect to the manual workstation. Such a result is much more evident by looking at the final RULA scores in Table 3. According to these values, the risk level for an operator that works in the manual workstation is very high. Conversely, the new collaborative workstation keeps such a risk very low, even if it still has margins of improvement. Overall, the workstation scores were reduced by 50% for the left part of the body and 57% for the right part of the body. The new solution not only reduces the biomechanical overload related to working postures but also provides a better balance of the workload between the left and right parts.

Table 3. Partial and final RULA scores.

Body Region	Body Part	Manual W.S. Scores ($S_{m,i}$)		Collaborative W.S. Scores ($S_{c,i}$)		Score Variation ($S_{c,i} - S_{m,i}$)	
		Left Side	Right Side	Left Side	Right Side	Left Side	Right Side
Arm and wrist analysis	Upper arm posture	4	6	2	2	−2	−4
	Lower arm posture	3	3	3	3	0	0
	Wrist posture	3	4	2	2	−1	−2
	Wrist twist posture	2	2	2	2	0	0
	Muscle use	0	0	0	0	0	0
	Force/load	0	0	0	0	0	0
Neck, trunk, and leg analysis	Neck posture	4		3		−1	
	Trunk posture	4		2		−2	
	Leg posture	1		1		0	
	Muscle use	0		0		0	
	Force/load	0		0		0	
Final RULA scores (*)		6	7	3	3	−3	−4
Improvement (percentage reduction of the final W.S. scores)						50%	57%

(*) the final scores are inferred from Table C of the RULA method, see Table 1.

6.3. Safety Assessment

The reduction of the identified mechanical risks could be evaluated according to the hybrid method. In particular, the different values of Se and CI before and after the introduction of the proposed safety measures (see Section 5.8 for details) were used for such an assessment. Of course, the new values must be significantly better than the old ones, and the related risk assessment must result in a green condition, which means that the residual risk is acceptable and under control. Table 4 summarizes and confirms the reduction of the identified mechanical risks according to the proposed safety measures (both described in Section 5.8).

Table 4. Reduction of the identified mechanical risks according to the proposed safety measures (SM).

	Parameter	Prototype NOT Implementing the SM	Prototype Implementing the SM	Potential Improvements
		Robot Operating Zone		
Mechanical hazard:	*Pr*	3—Possible	1—Negligible	−2
H1	*Fr*	3—Interval between exposure is more than two weeks but less than or equal to a year	2—Interval between exposure is more than a year	−1
	Av	3—Possible	1—Likely	−2
Safety measures:	*CI*	9	4	−5
SM1, SM4, SM5, SM6	*Se*	3—Normally irreversible injury—it will be slightly difficult to continue work after healing	3—Normally irreversible injury—it will be slightly difficult to continue work after healing	None
	Risk level	High	Low	
		Collaborative Operating Zone		
Mechanical hazard:	*Pr*	3—Possible	2—Rarely	−1
H2	*Fr*	5—Interval between exposure is more than an hour but less than or equal to a day	4—Interval between exposure is more than a day but less than or equal to two weeks	−1
	Av	1—Likely	1—Likely	None
Safety measures:	*CI*	9	7	−2
SM2, SM3, SM5, SM6	*Se*	2—More severe scratches, bruises, stabbing, which require medical attention from professionals	1—Scratches, bruises that are cured by first aid or similar	−1
	Risk level	Medium	Low	
Mechanical hazard:	*Pr*	3—Possible	1—Negligible	−2
H3	*Fr*	4—Interval between exposure is more than a day but less than or equal to two weeks	2—Interval between exposure is more than a year	−1
	Av	3—Possible	1—Likely	−2
Safety measures:	*CI*	10	4	−6
SM1, SM4, SM5, SM6	*Se*	2—More severe scratches, bruises, stabbing, which require medical attention from professionals	2—More severe scratches, bruises, stabbing, which require medical attention from professionals	None
	Risk level	High	Low	

7. Discussion and Conclusions

In this paper, we describe in detail the technical realization of a collaborative assembly workstation developed for a real industrial case study: the assembly by means of insulated tape of wire harnesses for the automotive sector. The main goals were the enhancement of the cycle time and of the operator's work conditions in terms of physical ergonomics, while guaranteeing a safe interaction between human and robot. To reach such goals, the manual assembly workstation was wisely redesigned to meet the operator's anthropocentric measurements; the heaviest operations (the taping ones) were allocated to the robot; the assembled process was modified so that two harnesses are concurrently assembled; and safety measurements were taken to lower the risk level.

The solution outlined in the paper was implemented through a TRL 7 prototype that was intensively tested in a relevant industrial environment. According to the achieved results, both company requirements were fully satisfied. In particular, the implemented technical solutions allow a sensible reduction of the cycle time (−12.3%) and a considerable improvement of the postural work conditions (57% for the right part and 50% for the left part according to the RULA method). Thanks to the safety measurements outlined, the mechanical risk assessment results in low residual mechanical risk.

As additional benefits, the new workstation is modular (the two benches can be used separately) and flexible (easy interchange of the workstation top). Indeed, provided that suitable workstation tops are designed, the solution presented in the paper could be employed for different wire harness assemblies as well as for other activities such as screwing, small assemblies, light pick and place, polishing, gluing, etc.

The developed prototype is at its final stage. Nevertheless, some final works are needed for the realization of an industrial and final version of the product. Further details about the progress of the project can be found on the website [https://www.wirecobots.com/]. The future improvements will mainly address the following points:

- *Flexibility.* Although the mechanical part of the workstation can already be easily reconfigured to react quickly to product variability, the automatic management of product change from the robot side has not been addressed yet. As future development, the robot will be provided with a vision system and workstation top with markers, so that by means of vision tasks the robot can automatically recognize a new product and adapt its operations.
- *Physical ergonomics.* Even if a great improvement of the working postures has been obtained, the final RULA score is slightly over the optimal zone (i.e., the green one). To further improve the operator's physical ergonomics, other methodologies that allow for a more detailed assessment (and hence a better identification) of the biomechanical risks will be adopted, for example the OCRA check list analysis [30].
- *Safety.* The risk assessment was performed only for mechanical risks related to the operators working with the robot. However, it must be extended to all the workers interacting with the system (e.g., maintainers). The final, industrial version of the product will be manufactured in compliance with all the essential health and safety requirements specified by the Machinery Directive [31].

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References

1. Trommnau, J.; Kühnle, J.; Siegert, J.; Inderka, R.; Bauernhansl, T. Overview of the State of the Art in the Production Process of Automotive Wire Harnesses, Current Research and Future Trends. *Procedia CIRP* **2019**, *81*, 387–392. [CrossRef]
2. Trommnau, J.; Frommknecht, A.; Siegert, J.; Wößner, J.; Bauernhansl, T. Design for Automatic Assembly: A new Approach to Classify Limp Components. *Procedia CIRP* **2020**, *91*, 49–54. [CrossRef]
3. Shi, G.M.; Jian, W. Wiring harness assembly detection system based on image processing technology. In Proceedings of the 2011 International Conference on Electronics, Communications and Control, ICECC 2011, Ningbo, China, 9–11 September 2011; pp. 2397–2400. [CrossRef]
4. Yumbla, F.; Abeyabas, M.; Luong, T.; Yi, J.S.; Moon, H. Preliminary Connector Recognition System Based on Image Processing for Wire Harness Assembly Tasks. In Proceedings of the 2020 20th International Conference on Control, Automation and Systems (ICCAS), Busan, Korea, 13–16 October 2020; pp. 1146–1150. [CrossRef]
5. Tamada, T.; Yamakawa, Y.; Senoo, T.; Ishikawa, M. High-speed manipulation of cable connector using a high-speed robot hand. In Proceedings of the 2013 IEEE International Conference on Robotics and Biomimetics, ROBIO 2013, Shenzhen, China, 12–14 December 2013; pp. 1598–1604. [CrossRef]
6. Song, H.C.; Kim, Y.L.; Lee, D.H.; Song, J.B. Electric connector assembly based on vision and impedance control using cable connector-feeding system. *J. Mech. Sci. Technol.* **2017**, *31*, 5997–6003. [CrossRef]
7. Jiang, X.; Nagaoka, Y.; Ishii, K.; Abiko, S.; Tsujita, T.; Uchiyama, M. Robotized recognition of a wire harness utilizing tracing operation. *Robot. Comput. Integr. Manuf.* **2015**, *34*, 52–61. [CrossRef]
8. Koo, K.; Jiang, X.; Konno, A.; Uchiyama, M. Development of a wire harness assembly motion planner for redundant multiple manipulators. *J. Robot. Mechatron.* **2011**, *23*, 907–918. [CrossRef]
9. Guo, J.; Zhang, J.; Wu, D.; Gai, Y.; Chen, K. An algorithm based on bidirectional searching and geometric constrained sampling for automatic manipulation planning in aircraft cable assembly. *J. Manuf. Syst.* **2020**, *57*, 158–168. [CrossRef]
10. Koo, K.M.; Jiang, X.; Kikuchi, K.; Konno, A.; Uchiyama, M. Development of a robot car wiring system. In Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM, Xi'an, China, 2–5 July 2008; pp. 862–867. [CrossRef]
11. Jiang, X.; Koo, K.; Kikuchi, K.; Konno, A.; Uchiyama, M. Robotized assembly of a wire harness in car production line. In Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010; pp. 490–495. [CrossRef]
12. Company Elvez d.o.o. Available online: https://elvez.si/en/ (accessed on 21 December 2020).
13. Wire Cobots. Available online: https://www.wirecobots.com/en/ (accessed on 21 December 2020).
14. ESMERA. European SMEs Robotic Applications. Available online: http://www.esmera-project.eu (accessed on 21 December 2020).
15. Company Carretta s.r.l. Available online: http://www.carrettaautomazioni.it/en/ (accessed on 21 December 2020).
16. Gualtieri, L.; Rojas, R.; Carabin, G.; Palomba, I.; Rauch, E.; Vidoni, R.; Matt, D. Advanced Automation for SMEs in the I4.0 Revolution: Engineering Education and Employees Training in the Smart Mini Factory Laboratory. In Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, Bangkok, Thailand, 16–19 December 2019; pp. 1111–1115. [CrossRef]
17. McAtamney, L.; Corlett, N. R.U.L.A.—A Rapid Upper Limb Assessment tool. In Proceedings of the Contemporary Ergonomics 1984–2008: Selected Papers and an Overview of the Ergonomics Society Annual Conference, San Antonio, TX, USA, 19–23 October 2009; pp. 316–321.
18. ISO/TR 14121-2:2012. *Safety of Machinery—Risk Assessment—Part 2: Practical Guidance and Examples of Methods*; International Organization for Standardization: Geneva, Switzerland, 2012.
19. Gualtieri, L.; Palomba, I.; Merati, F.; Rauch, E.; Vidoni, R. Design of Human-Centered Collaborative Assembly Workstations for the Improvement of Operators' Physical Ergonomics and Production Efficiency: A Case Study. *Sustainability* **2020**, *12*, 3606. [CrossRef]
20. EN ISO 14738:2008. *Safety of Machinery—Anthropometric Requirements for the Design of Workstations at Machinery*; International Organization for Standardization: Geneva, Switzerland, 2008.
21. Faccio, M.; Minto, R.; Rosati, G.; Bottin, M. The influence of the product characteristics on human-robot collaboration: a model for the performance of collaborative robotic assembly. *Int. J. Adv. Manuf. Technol.* **2020**, *106*, 2317–2331. [CrossRef]
22. Gualtieri, L.; Palomba, I.; Wehrle, E.; Vidoni, R. The Opportunities and Challenges of SME Manufacturing Automation: Safety and Ergonomics in Human–Robot Collaboration. In *Industry 4.0 for SMEs Challenges, Opportunities and Requirements*; Matt, D., Modrak, V., Zsifkovits, H., Eds.; Palgrave Macmillan: London, UK, 2020; pp. 105–144. [CrossRef]
23. Universal Robot. *User Manual UR3/CB3 Original Instructions (Version 3.1)*; Universal Robot: Odense, Denmark, 2009.

24. Rojas, R.A.; Garcia, M.A.R.; Gualtieri, L.; Wehrle, E.; Rauch, E.; Vidoni, R. Automatic Planning of Psychologically Less-Stressful Trajectories in Collaborative Workstations: An Integrated Toolbox for Unskilled Users. In *Symposium on Robot Design, Dynamics and Control*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 118–126.
25. Gualtieri, L.; Rauch, E.; Vidoni, R. Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review. *Robot. Comput. Integr. Manuf.* **2021**, *67*. [CrossRef]
26. Murashov, V.; Hearl, F.; Howard, J. Working safely with robot workers: Recommendations for the new workplace. *J. Occup. Environ. Hyg.* **2016**, *13*, D61–D71. [CrossRef] [PubMed]
27. Matthias, B.; Reisinger, T. Example application of ISO/TS 15066 to a collaborative assembly scenario. In Proceedings of the 47th International Symposium on Robotics, ISR 2016, Frankfurt am Main, Germany, 21–22 June 2016; pp. 88–92.
28. ISO/TS 15066:2016. *Robots and Robotic Devices—Collaborative Robots*; International Organization for Standardization: Geneva, Switzerland, 2016.
29. EN ISO 10218-2:2011. *Robots and Robotic Devices—Safety Requirements for Industrial Robots—Part 2: Robot Systems and Integration*; International Organization for Standardization: Geneva, Switzerland, 2011.
30. Colombini, D. *Risk Assessment and Management of Repetitive Movements and Exertions of Upper Limbs: Job Analysis, Ocra Risk Indices, Prevention Strategies, and Design Principles*; Elsevier Ergonomics Book Series; Elsevier: Amsterdam, The Netherlands, 2002; Volume 2.
31. European Union. *Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006*; Machinery Directive, Official Journal of the European Union; European Union: Brussels, Belgium, 2006.