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Safety-Focussed Design of Collaborative Assembly Station with Large Industrial Robots

Varun Gopinath[a,*], Fredrik Ore[b,c], Sten Grahn[d], Kerstin Johansen[a]

[a] *Linköping University, Department of Management & Engineering, Linköping, Sweden*
[b] *Global Industrial Development, Scania CV AB, SE-15187 Södertälje, Sweden*
[c] *Mälardalen University, School of Innovation, Design and Engineering, Eskilstuna, Sweden*
[d] *Swerea IVF, Brinellvägen 68, 114 28 Stockholm, Sweden*

Abstract

The perceived benefits of large industrial robots for collaborative operations are characteristics such as long reach with heavy load carrying capability. Collaborative operations refers to situations where operators and robots share a workspace to complete tasks in close proximity. This mode of operation coupled with the physical characteristics of large robots represents high risks to injury and for these reasons, the safeguarding of the workspaces needs to be achieved in conjunction with the tasks to be performed within the workstation. This article will detail two workstations that was developed in a laboratory environment and are partial results of a research project titled ToMM2, whose aim was to understand safety issues associated with collaborative operations with large robots.

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Keywords: Human-Robot Collaboration; Industrial Robot Safety; Collaborative Operations; Hazards; Risks

1. Introduction

In order to be competitive, manufacturing plants needs to be more flexible and productive, and this goal is driving the development and permeation of automation technologies. Advances in control technique and sensor technology has allowed industrial robots to support this goal [1,2]. Recently, there has been an interest in employing robots in what is referred to as collaborative operations. ISO/TS 15066 [3] defines collaborative operation as *state in which a purposely-designed robot system and an operator work within a collaborative workspace*.

Earlier attempts at introducing automation devices such as cobots [4] have resulted in custom machinery that functions as ergonomic support. Recently, industrial robots specifically designed for collaboration such as UR10 [5] and KUKA iiwa [6] are available that can be characterized as having the ability to: 1. detect collisions with any part of the robot structure and 2. carry smaller load and has shorter reach compared to traditional industrial robots.

Industrial robots that does not have *Power & force limiting* (see section 3) feature, such as KUKA KR210 [6] or the ABB IRB 6600 [7] have traditionally been used within fenced workstations. However, their performance capabilities

* Corresponding author. Tel.: +46-13-28-2510.
E-mail address: varun.gopinath@liu.se

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such as long working range and higher payload, coupled with collaborative application might present new possibilities for automation. As pointed out by Marvel et. al [8], collaborative operation implies that there is a higher probability for occurrence of hazardous situations due to close proximity of humans and robots. The hazardous situations can lead to serious injury and therefore, safety needs to be guaranteed while developing collaborative applications.

The machinery safety standard [9] suggest conducting risk assessment (RA) followed by risk reduction measures to ensure the safety of the operator & other manufacturing processes. According to the machinery safety standard [9–11] risk assessment (RA) is an iterative process that concludes when all probable hazards have been identified and the risks are minimized to an acceptable level. Risk Assessment is usually carried out through a safety program and can be documented according to [12]. RA is a sequence of two separate steps: 1. Risk Analysis (comprises of Hazard Identification & Risk Estimation) and 2. Risk evaluation. Situations where risks that are evaluated to be unacceptable, the methodology details a hierarchical risk reduction strategy, which involves: 1. Inherently safe design measures, 2. Safeguarding and 3. Information for use.

The aim of this article is to present the layouts of two collaborative workstation where large industrial robots are employed. These represents partial results of a research project title ToMM2 [13] whose purpose was to improve our understanding of the requirements for safety when large robots are employed in collaborative operations. The article is structured as follows: Section 2 describes the methodology employed during the research and development phase and section 3 briefly details the theoretical background. Section 4 details the layout of two collaborative workstations followed by a short discussion (section 5) on design issues encountered during the risk assessment phase and will end with concluding remarks (section 6) on the concept of demonstrators as a viable method for manufacturing research.

2. Methodology

The results presented in section 4 were carried out as part of research project titled Collaborative Team of Man and Machine (ToMM & ToMM2 [13]) in collaboration with representatives from the Swedish automotive industry, research and academic institutions. The aim was to develop and demonstrate solutions that enables cooperation between humans and robots within an assembly cell. The objective was to understand safety requirements during collaborative operations when large industrial robots are employed. Two assembly stations were selected as case studies [14] in order to explore probable solutions that satisfies the research objectives.

Pre-Study & Data Collection: To gain a better understanding and knowledge of the case study, the following methods were employed: (a) Meetings with industry partners as well as production managers [15]. This allowed the researchers to have detailed discussion on the functioning of the workstations and challenges associated with the other normal routines such as shift changes, maintenance etc. (b) Observation of the assembly station during normal functioning allowed the researchers to conduct informal interviews with the operators as well as line managers. (c) Literature sourced from academia, books as well as documentation from various industrial equipment manufactures were reviewed.

Conceptualization of workspaces & tasks: The assembly tasks were decomposed into subtasks and these subtasks were allocated as robot, operator and collaborative tasks with the intention of improving the ergonomics and productivity of the workstation. This decomposition were carried out through Hierarchical Task Analysis [16] and the feasibility of the tasks in the corresponding workspaces were evaluated and demonstrated through virtual simulations [17–20]. Risk Assessment and risk reduction process was carried out through a series of meetings conducted in collaboration with industrial partners and supported by safety experts. The safety program was documented using standard templates such as suggested in [12].

Demonstrators to support research activities: In order to showcase solutions and progress of research activities, demonstrators in the form of virtual simulations, scaled prototypes or physical demonstrators [20,21] were employed at various stages to various stakeholders. The intention was to allow production managers, engineers, safety-experts, line- workers etc., to participate in the research process and allow them to share their knowledge from their perspective. That is, the layouts has been developed through a demonstrator-driven design approach with the purpose of supporting decision making during the evaluation phases.

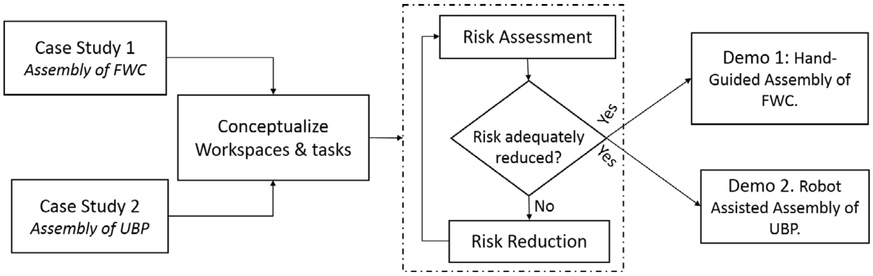

Fig. 1: Methodological Overview employed during the development of demonstrators for 1. hand- guided assembly of Flywheel Housing Cover (FWC) and 2. robot-assisted assembly of Under-Body Panels (UBP).

3. Theoretical Background

This section briefly describes relevant safety standards whose guidelines have been considered during the development of the demonstrators and then will attempt to detail problems associated with automation.

3.1. Robot Safety standards for design, integration & Industrial relevance

EN-ISO 10281-1 is a standard aimed at stipulating minimum safety requirements for robot manufacturers whereas EN-ISO 10218-2 is aimed at system integrators with the view that robotic systems are generally integrated with other systems within a manufacturing plant. These standards are published and maintained by ISO, which do not have the authority to enforce them. However, legislative bodies such as the EU through the EU Machinery Directive mandate compliance with normative standards [22] which are prefixed with an EN before their reference number. EN-ISO 10218-2 defines four types of collaborative operations that can be employed for collaborative workstation (section 5.11.5 in [11]). The four types are 1. Hand-guided 2. Speed and separation monitoring 3. Safety-rated Monitored Stop and 4. Power and force limiting by design or control. The technical report ISO/TR 15066 [3] further elaborates on the safety requirements on collaborative operations.

3.2. Design challenges associated with Human-Automation Collaboration

In the design of automation system, Norman notes that automation in itself is not the source of accidents but inappropriate feedback [23] . That is, humans who have supervisory control are not aware of the state of the system and are not able to take appropriate actions. Eberts [24] also notes that human factors needs to be taken into account when designing systems that demands humans are needed. As modern technology allows complex systems such as adaptive and adaptable automation systems[25] , it is critical to understand human abilities and design systems appropriately [26]. Academic literation points at two kinds of issues:

1. Situational Awareness: Refers to a situation where an operator loses track of the state at the machine. This can happen due to high or low levels of automation. It can also occur due to being interrupted by other factors such as noise or colleagues.

2. Mode-error: As systems becomes complex and as tasks such as monitoring are automated, system mode can change without the operator being aware of it. When operators continue working with the assumption that state of the system has not changed is referred to as mode-error.

4. Result

This section presents two workstations in terms of workspaces and tasks and were developed to demonstrate safety solution in a laboratory environment. The current assembly stations will also be presented and compared (Table 1) in order to highlight the differences of the case studies.

4.1. Safe Hand-Guided Assembly of a Flywheel Housing Cover (FWC)

Manual Workstation Description: The task is to fasten the FWC on an engine block. Using a lifting aid, the operator lifts and moves the FWC from the storage box to a machine where automated operations are carried out. After these operations, the operator moves the FWC and carefully aligns the FWC with the engine block. Then two or more operators, with the aid of pneumatic nut-runners, fastens the FWC with bolts [20,21].

Collaborative Workstation Description: The layout of the workstation installed in a laboratory environment is shown in Fig 4 and the task sequences are detailed in Fig 2 and Table 2. The act of manipulating the FWC around the workstation is in one part carrying a heavy load and the other part is the action of moving it around. The robot taske is to carry the heavy load while the operator guides the robot, and thus the FWC to the correct location. Safeguarding the robot workspace were realized through the use of physical fences and light curtain (see Fig 4 – 4,6). Additionally, warning lamps were installed to inform the operator of the mode of operation.

The robot begins the cycle by picking up the FWC in automatic mode. When the automated motion is complete, the robot stops at the hand-over position and signals to the operator that the hand-guided operation can be started. The operator moves the robot to the assembly point where the operator can guide the FWC to the engine block. When the two parts are mated, the operator unclamp the FWC from the end-effector and proceeds to move the robot back to the hand-over position. The operator needs to communicate to the robotic system that the hand-guiding is complete and is done by the use of a three button switch. Then the operator goes out of the workstation and starts the next cycle.

4.2. Safe Robot-Assisted Collaborative Assembly of Under-Body Panels

Manual Workstation Description: The task is to fasten the UBP under the car. The operator prepares the panel by securing clips on the panel and proceeds to secure it under the car using the previously installed clips. Then the operator walks and picks up the pneumatic nut runner from the holder and moves under to the moving line, and begins to fasten the panels with bolts. A detailed description has been made by Gopinath et. al [18].

Collaborative Workstation Description: The layout of the workstation is shown in Fig 5 and the task sequences are detailed in Fig 3 and Table 3. Fences physically separate the robot and the collaborative workspace. The work process necessitates that the end-effector moves out of the fenced area in order to place the panel under the car. (Fig 3 (2)). In order to ensure that operator is not injured, the risk reduction measure suggested a hybrid safeguarding solution that is a combination of physical fences, laser scanner and light curtains (LC1 & LC2 in Fig 5). Fig 5 shows a structure (no. 14) designed to support a linear guide whose function is to simulate an unfinished vehicle moves at a constant speed of 100 mm/sec.

The cycle starts with the robot in automatic mode, where the robot picks up the panels with the aid of vacuum cups that are placed on an inventory table. When the LC1 is muted, the robot moves the panel under the car and begins following the linear motion of the assembly line. The warning lamp changes from red to green at which point the operator engages the enabling device and enters the collaborative workspace and begins fastening the panel to the moving line. When the fastening operation is complete, the operator moves out of the collaborative workspace, disengages the enabling switch, and presses the button that allows the robot to start the next cycle.

Table 1: Comparison of the two cases. Case Study 1 – Assembly of Flywheel Housing Cover. Case Study 2 – Assembly of under-body car panels

No	*Characteristic*	*Case Study 1*	*Case Study 2*
1.	Industry Vertical	Heavy Vehicle	Personal Vehicle
2.	Number of Operators	3-4	1
3.	Cycle Time	4 min (approx)	1 min (approx)
4.	Assembled part – Description	Rigid Cast Aluminium (16kg)	Flexible & Light plastic (1kg)
5.	Assembled part – Dimension	1m × 1m × 0.4m	1.5m × 0.5m × 0.1m
6.	Identified Ergonomic issue	High body forces	Upper-body work position
7.	Assembly Operation	Stop & go station	Continuously moving line

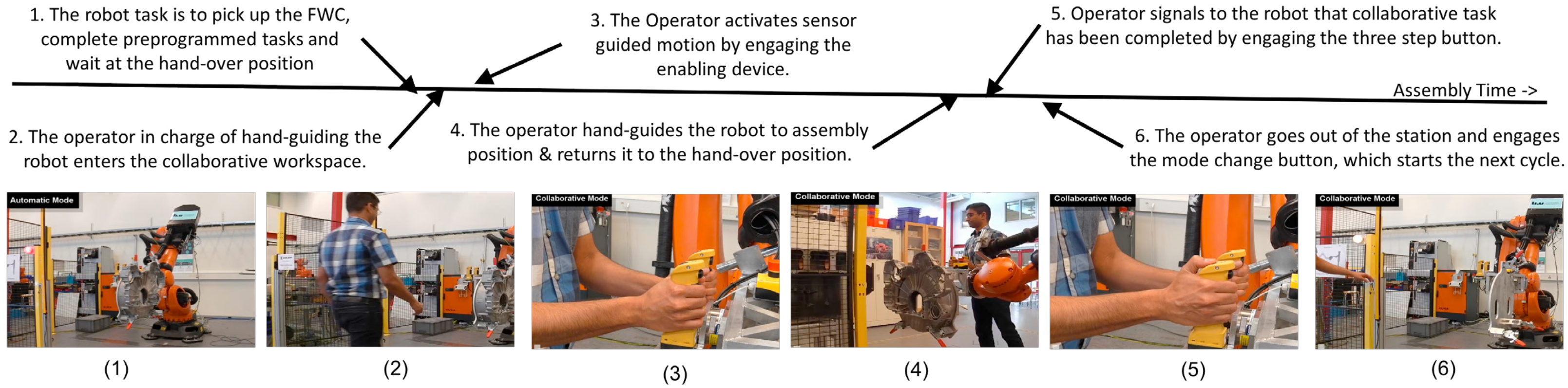

Fig. 2: The figure describes the task sequence of the collaborative assembly station where an industrial robots is used an intelligent and flexible automation machine. The tasks have been decomposed into three : Operator task, Collaborative task and robot task.

Table 2: Descriptions of the sequence of tasks in terms of robot tasks (RT), Collaborative tasks (CT) and operator tasks (OT) shown in Figure 2.

1.	Robot Task	In automatic mode, the robot tasks are 1. to pick up the FWC 2. place the part on the fixture and 3. pick up the part and wait at the hand-over position. During the automatic mode, the warning lamp is red. The hand-over position is located inside the enclosed area and is monitored by light curtains. The robot will stop if an operator accidentally enters this workspace and can be restarted by the *Auto-Continue Button* (Fig 4.A).
2.	Operator Task	Enter collaborative space: When the lamp turns from red to green, the light curtain is muted and the operator can enter the collaborative workspace. The light curtain will remain in this state till the collaborative mode is complete.
3.	Collaborative task	Engage enabling switch: The operator begins hand-guiding by engaging both the enabling switches simultaneously. This activates the sensor-guided motion & the operator can move the robot by applying force on the enabling device. If the operator releases either one or both of the enabling switch, robot motion is stopped. To reactivate sensor-guided motion, the operator simply engages both the enabling devices.
4.	Collaborative task	Hand-guide the robot: The operator moves the FWC from the hand-over position to the assembly point. The operator guides the FWC to the corresponding pins on the engine block, removes the clamp, and return the robot back to the hand-over position.
5.	Collaborative task	Engage automatic mode: Before going out of the assembly station, the operator needs to engage the three button switch. This deliberate action signals to the robot that the the collaborative task is complete. The operator goes out & engages the mode-change button.
6.	Robot task	The following sequence of events are carried out: 1. The light curtain is activated 2. Warning lamp turns from green to red & 3. The robot starts the next cycle.

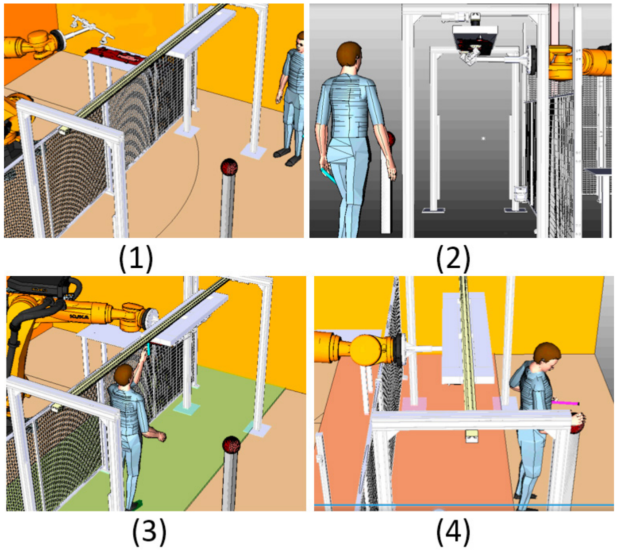

Fig. 3: Simulations of a collaborative assembly workstation where the robot picks and places the panel under a simulated car while the operator fasten bolts to secure the panels on a continuously moving line..

Table 3: Description of the sequence of tasks that form a complete work cycle, beginning with the robot picking up the panel and ending with the operator starting the next work cycle. The tasks are specified in terms of robot task (RT), Collaborative task (CT) & operator task (OT) as visualized in Figure 3.

1. RT	In automatic mode, the robot moves from the starting position to pick up the panel and uses vacuum to reliably grip the panel. When the robot exits the workspace to place the panel under the car, LC1 (Fig 5 (5)) is muted.
2. OT	When the robot and the moving line is synchronized, the red light turns to green. Now the operator activates the collaborative mode by engaging the enabling switch attached to the nut-runner which mutes the laser scanner. The operator can now enter the collaborative workspace (CW).
3. CT	The operator enters the CW and positions themselves under the simulated car. Then, they can begin fastening bolts to firmly secure the panels.
4. OT	When the bolts are fastened, the operator goes out and engages the button which tells the robot that the collaborative mode is now complete. When the operator disengages the enabling device, the laser scanner is activated.
5. RT	The robot moves out of the CW and when it has passed the fence, LC1 is activated. This is the beginning of the next work cycle.

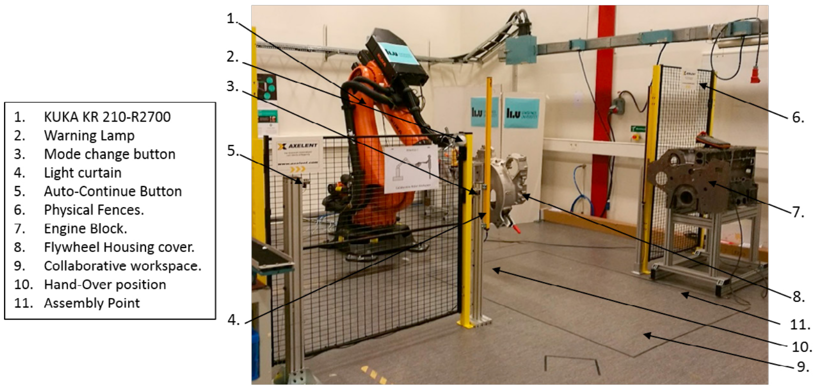

Fig. 4: Picture of a demonstrator developed in a laboratory environment intended to showcase safety of hand-guided collaborative operations (See [27].

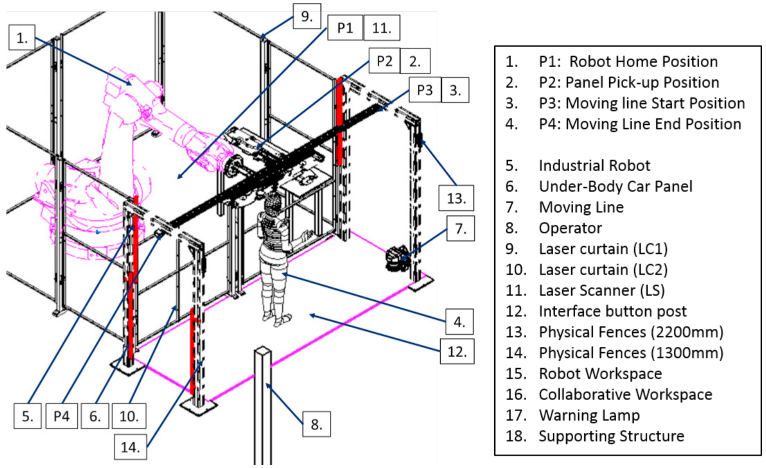

Fig. 5: Fig depicts the layout of a collaborative workstation where the assembly task is the installation of panels under the car.

5. Discussion

The two case studies presented in section 4 are different in terms of assembled part (heavy & rigid versus light & flexible), assembly stations (stop & go operation versus continuously moving line) etc. (compared in Table 1) and consequently the hazards associated with the introduction of a robot are unique. However, several parallels between the two can be identified and discussed.

The workspaces are well defined in terms of robot, operator and collaborative workspace (CW). Within the robot workspace, the robot can be programmed to move at high speed to meet production demands. Strategically placed fences and safety sensors are used to reduce the risks of a hazardous event from occurring. However, when the task sequence requires collaboration (see No.3 in Table 2 or No. 3 in Table 3), the system needs to change its state so that the operator can safely enter the collaborative workspace and this mode is referred to as collaborative mode. In this mode, the speed of the robot is reduced to a value determined during RA and safety sensors are selectively muted. For example, in case 2 (see section 4.1), the light curtain (LC – see No.4 in fig. 4) is muted when the operator has to enter the collaborative workspace and in case 2 (see section 4.2), Light curtain (LC1 – see No.9 in fig. 5)) and laser scanner (LS – see No.11 in fig. 5) are muted during collaborative mode.

In addition, physical and visual interfaces such as warning lamps, enabling devices, floor markings etc., are designed as part of the system that functions as a communication channel between the operator and the robotic system. They ensure that operators are: 1. aware of the state of the system, 2. aware of the boundaries of the workspaces, 3. knows when and how to start the collaborative mode and 4. when to exit the collaborative workspace and start the next cycle.

The function of safety sensors is to detect intrusion and bring the system to a safe state. The definition of a safe state for the two workstations is to stop all robot motion. However, this may vary depending on the application and needs to be addressed during the risk assessment phase. The interfaces discussed above are meant to avoid unintended stoppage of production activities.

For example, in the case of UBP assembly, though the line is moving at a relatively slow speed, when the robot enters the collaborative workspace, it needs to synchronise with the line, which may take time and might require speeds faster than 100 mm/sec. Therefore, the collaborative mode is activated after the robot has synchronised with the moving line. In order to avoid a hazardous situation where the operator intentionally/unintentionally enters the collaborative workspace as soon as they see the end-effector under the moving line, a laser scanner is used to detect entry and stop all motion. In addition, to avoid unintentional entry, a red warning lamp communicates that the system is not in collaborative mode and that the operator should not enter the clearly marked collaborative workspace, thereby strengthening the situational awareness of the operator.

During collaborative mode, the operator is in CW and the laser scanner is muted. In order to avoid hazardous events from taking place, an enabling switch mounted on the nut runner was specified. The operator must intentionally engage the enabling switch before entering the CW and can only disengage after completing all tasks. In the event that the operator disengages the switch while in the CW, the laser scanner will activate and stop all motion. When the task is complete, the operator must exist the CW, engage the Interface button (see fig 5 (8)) and then disengage the enabling switch, which will start the next cycle. That is, the enabling switch 1. enables the operator to be in charge , 2. the operator can decide when the next cycle can begin and that external actors does not influence proper functioning of the cell and 3. allows for a safe work environment.

6. Conclusion

This article presented two workstations that was developed as part of a research project aimed at understanding industry relevant safety solutions for collaborative operations. The two cases have been demonstrated publicly in a laboratory environment – the hand-guided robot application (2017-02-15) and the Under-Body assembly (2018-04-26). The experience from the first public event has set a benchmark and the knowledge from it has contributed to organize the next iteration of the human-robot collaboration (HRC) demonstrator, in a manner that improves the knowledge for both industry and academia.

One observation during this period is that the industry has increased their internal work aiming for evaluating and implementing HRC in production lines. The demonstrator has facilitated a dialogue between engineers, operators, researchers and management, who have contributed with their perspective and needs in the continuous development and testing of solutions. It can be concluded that the research complemented by demonstrating solutions in different forms (physically or virtually) has contributed to a broader knowledge base and can facilitate introduction of emerging technologies in the manufacturing industry.

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