Designing Interaction Interface for Supportive Human-Robot Collaboration: A Co-creation Study Involving Factory Employees[1]

Abstract

Considering social-technical factors during the design and implementation of collaborative robots (cobots) is important to ensure their successful integration into industrial workspaces and the well-being of the operators such as ergonomics. In this work, we present a co-creation study in developing an interaction interface for a human-robot collaboration (HRC) system involving SME factory employees in the Netherlands. Employing a qualitative research method, the co-creation activities in this study sought employees' input on preferred use cases and collaboration methods with robots. The gathered qualitative data was used to design the HRC interaction interface, aligning it with operators' needs and preferences. The developed system was fully functional, underwent technical validation, and received feedback from the factory operators. Our study emphasizes the importance of involving employees in the design of HRC interaction interfaces, which can result in HRC systems that meet their needs and preferences. Such customized systems have the potential to enhance the acceptance of robots in industrial settings. The study contributes to the field by demonstrating a participatory approach to designing an HRC interaction interface for a robot in a real industrial setting, where no use cases or interaction modalities were pre-defined.

Keywords: human-robot interaction, human-robot collaboration, co-creation, industrial settings, robot acceptance, interface design

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1. Introduction

Collaborative robots, or cobots, are becoming increasingly attractive for small and medium-sized enterprises (SMEs) as they provide flexibility in deployment for multiple uses and small batch production (Vanderborght, 2020). However, integrating robots into industrial workspaces is a complex process (Welfare et al., 2019). The successful integration of robots is affected by several social-technical factors, including occupational safety, appropriate robot configuration, fear of job loss, and the trust of operators in the robot (Kopp et al., 2021). The design of the human-robot interaction interface should consider these factors to maximize the potential of robots and minimize any negative impacts on operators' experiences (Welfare et al., 2019; Marvel et al., 2020). In other words, the social-physical interaction between operators and robots must be safe, natural, and effective, similar to the interaction between co-workers, to increase operators' acceptance of robots (Marvel et al., 2020; Sauppé and Mutlu, 2014, 2015; Elprama et al., 2016; Welfare et al., 2019). Therefore, proper consideration of these social-technical factors is crucial during the design and implementation of robots to ensure their successful integration into industrial workspaces. Some important factors are the acceptance of robots by operators, their well-being such as workload, stress, and ergonomics, and the clarity and transparency of their communication and operational states (Lagomarsino et al., 2022b,a; Omidi et al., 2023; Molino et al., 2021).

In previous studies, the social-physical interaction between operators and robots has often been pre-defined, with little input from the operators themselves, which could potentially result in a negative impact on the acceptance of robots (Neumann et al., 2021). The perception of managers and developers about how the robotic system should operate might not always align with the practical intricacies, emphasizing the significance of a bottom-up approach by involving operators at the early stages of the system development and prioritizing their well-being (Orso et al., 2022; Fletcher et al., 2020; Kaasinen et al., 2020). To address this issue, it is recommended that the design of social-physical interaction between operators and robots should involve major stakeholders, particularly the operators as end-users (Marvel et al., 2020; ISO, 2010). This can be achieved through participatory design approaches, in which operators have the opportunity to provide feedback on how robots can improve their work and contribute to their physical and mental well-being (Welfare et al., 2019). For instance, the development and implementation

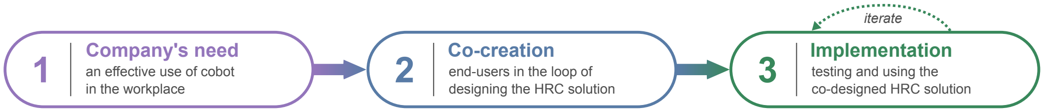

Figure 1: Our approach to developing a solution for human-robot collaboration includes identifying the company's needs, co-creating the solution with end-users, and implementing it.

of human-robot collaboration (HRC) solutions can start by addressing the company's needs, followed by a co-creation process that actively involves end-users (Figure 1). Subsequently, these solutions are implemented into practice within real-world settings. Through iterative cycles, system performance is continuously improved. By engaging operators in the design process, the resulting human-robot interface and interaction can be tailored to meet the needs and preferences of the end-users, potentially leading to increased acceptance of robots in industrial workspaces. Additionally, the incorporation of context-aware interfaces that adapt to specific work scenarios and user needs can increase efficiency and effectiveness in HRC, consequently increasing operator satisfaction and robot acceptance (Angulo et al., 2022).

In this work, we present a co-creation study involving factory employees from an SME (Hankamp Gears[2]) in the development of an interaction interface for an HRC system using a qualitative research approach. Following the Double Diamond design approach (Design Council, 2005), robot developers, social scientists, and factory employees step-by-step turned a general idea into a solution. During two co-creation workshops moderated by social scientists, factory employees determined their desired tasks (which we defined as *use cases* in the co-creation workshop 1) and preferred methods of interaction (which we defined as *interfaces* in the co-creation workshop 2) when working with a robot. This information was used by the robot developers to design the interaction interface aiming to meet the operators' requirements and preferences. The designed system was technically validated and received feedback from the factory employees. We additionally conducted an evaluation of the HRC quality and non-technological aspects of responsible robotics to better prepare for implementation across a broader range of operators in future iterations.

Our study contributes to the field of HRC by demonstrating a participa-

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[2] `https://www.hankamp.nl/en/`

tory approach to designing the social-physical interaction of robots in a real industrial setting. Specifically, we emphasize the importance of actively involving employees as key stakeholders in the design process, promoting open dialogue and collaboration to effectively tailor the human-robot interaction interface. Moreover, our study did not impose any pre-defined tasks or interaction modalities, allowing for a more organic exploration of collaborative possibilities together with future end-users.

The structure of the remaining sections of this paper is as follows. Section 2 outlines the methodology. Sections 3 and 4 provide overviews of the two co-creation workshops conducted with factory operators. Section 5 describes the design of the interaction interface. Section 6 presents the feedback from the factory operators. Section 7 asscessed the HRC quality and responsible robotics. Finally, the discussion and conclusion are provided.

2. Methodology

2.1. Co-creation approach

Our approach followed a co-creation approach that aimed to foster active engagement of the employees in the co-creation process for the interaction interface design of HRC (Sanders et al., 2010). We used the Double Diamond model co-creation design process, which is a widely recognized framework for design thinking that involves a structured approach to problem-solving through four key phases: Discover, Define, Develop, and Deliver (Design Council, 2023). In the first diamond, the Discover phase emphasizes the importance of understanding the problem through direct engagement with end-users. These interactions provide insights that can establish the problem definition, which becomes the focus of the Define phase. Building on the defined challenge, the second diamond, the Develop phase encourages the exploration of diverse solutions, drawing inspiration from various prespectives. Finally, in the Deliver phase, the iterative process involves testing and refining potential solutions, eliminating ineffective solutions and delivering well-crafted, user-centered solutions. This user-centric design and iterative processes ensure that solutions are well-developed and refined for maximum effectiveness after being implemented and deployed.

The company that collaborated with us on this project is Hankamp Gears, an SME based in the Netherlands that specializes in producing gears for various industries. The company is equipped with several collaborative robots.

We aimed to include their employees in the co-creation process for the interaction interface design of HRC. By prioritizing ergonomics and human-centered design principles, the ultimate objective is to increase acceptance, enhance well-being, and promote a comfortable working environment for employees in the workplace.

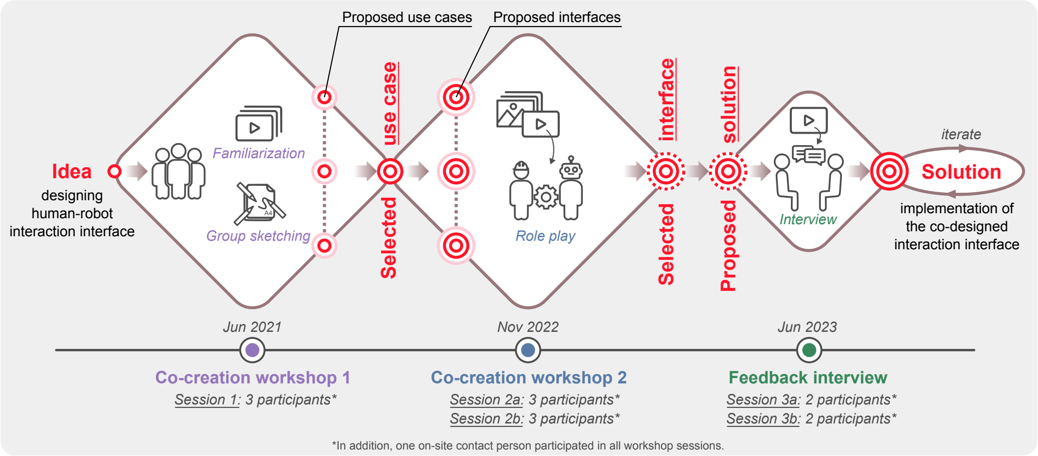


Figure 2: The co-creation design process based on the Double Diamond design approach. Two co-creation workshop sessions and a feedback interview were conducted to turn an idea into a solution. Figure inspired from Design Council (2023).

Figure 2 illustrates the data collection activities with the employees from Hankamp Gears. Two co-creation workshops were conducted. In *co-creation workshop 1*, we aimed to determine the desired *use cases*. The operators were exposed to different types of robots, such as anthropomorphic and machine-like robots. They were encouraged to share their views on working with robots. They were also asked to generate ideas for robot applications that could be implemented in their workplace through a group sketching activity. In *co-creation workshop 2*, we aimed to determine the preferred methods of *interaction interface*. Robot developers analyzed the operators' ideas from the first session. Taking into account the technological constraints of robots and the workplace, they proposed several conceptual designs that aimed to bridge the gap between human needs and robotic capabilities. The operators then further provided ideas for the development of the interaction interface in a role-play activity. During this activity, the operators took into consideration the ideas and conceptual designs proposed by robot developers. These ideas were subsequently transformed into a proposed solution developed by robot developers, which then underwent a technical validation process. In the *feedback interview*, the solution received feedback and evaluation from the factory operators, ensuring the full integration of their perspectives and practical insights into the development process.

2.2. Online data collection and data analysis

The activities within this work were organized as part of a larger scope within a European project, alongside various other activities. These activities were conducted via Microsoft Teams since the research institutes and the company are located in different countries and part of the data collection took place during the COVID-19 pandemic. This approach not only addressed the travel restriction during the pandemic but also saved travel-related costs. During these activities, a team of two or three moderators from the researchers' side worked online with a dedicated SME employee who played a crucial role in on-site preparations – the on-site contact person. The responsibilities of this contact person ranged from participant recruitment to document printing and material organization. Additionally, the contact person provided technical support and actively contributed insights during the sessions. Informed consent was obtained from the employees at the start of the workshop before the recording was started. Each session (two co-creation workshops and the feedback interview sessions) was recorded and notes were taken during each session by the moderator. After describing the participants, we describe the procedure of each workshop and summarize the findings using a thematic analysis.

2.3. Participants

We asked our contact person from the SME to recruit employees who would potentially be working with collaborative robots in the future. As the SME has limited employees, we took a qualitative approach focusing on employees with relevant job knowledge to conduct in-depth assessments instead of broad surveys with a large number of participants. All participants were male, and they were all between 18 and 60 years old at the time of their participation. The overview of all the sessions and the number of participants is summarized in Figure 2-bottom. Additionally, the contact person from the SME also participated in all workshops.

In the course of this study, we carefully considered the scheduling constraints within the SME and unanticipated circumstances in their production agenda. Consequently, we observed that certain participants were able

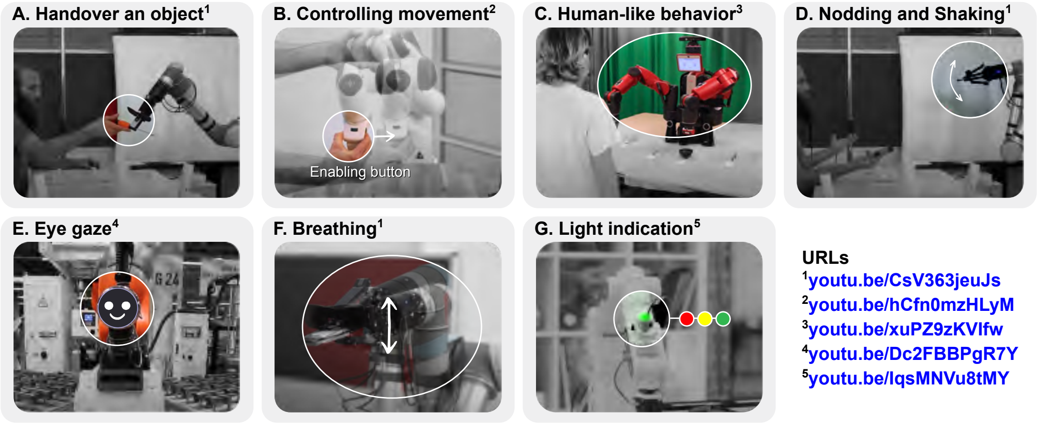


Figure 3: The operators were familiarized with robot applications by watching seven videos that demonstrated social-physical interactions between humans and robots. All videos are publicly accessible on YouTube.

to attend multiple sessions, while others engaged in just one session. It is noteworthy that, to minimize any potential disruptions to the SME's ongoing production operations, we conducted both co-creation workshop 2 and the subsequent feedback interview in two separate sessions. In each session, we used identical scripts but with different sets of participants.

3. Co-creation workshop 1: Identifying the desired HRC use case

3.1. Procedure

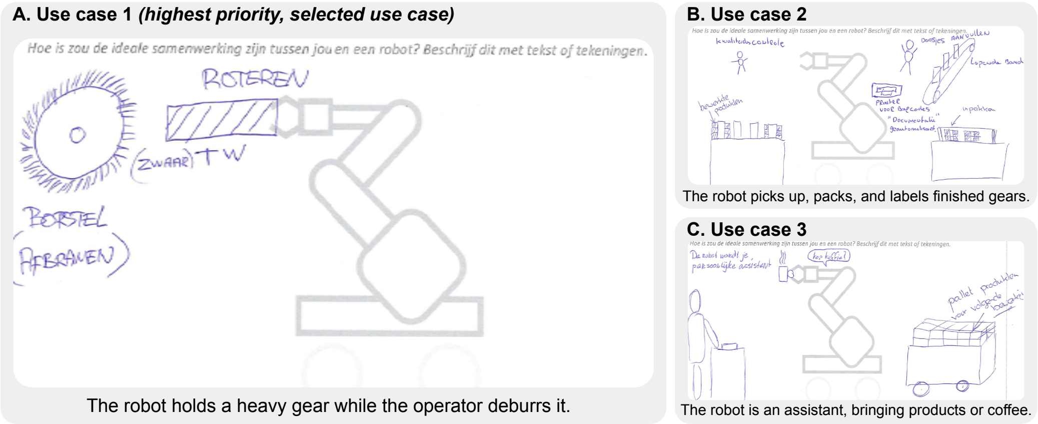
In the first co-creation workshop (Session 1), we identified which task (use case) is the most important for their current job. First, a short association and a drawing exercise were performed to make the operators more comfortable in speaking and drawing during the workshop. Next, short fragments of seven videos with different robots were shown and discussed with the operators (see Figure 3). We carefully selected videos that covered a wide range of human-robot collaboration and interaction. This familiarized the operators with robot applications. Then, the operators were asked to do a group sketching activity consisting of two assignments (relay method).

In the first assignment, each operator was asked to freely describe with drawings or text a place at their work where they would like to use a robot or where they were already using a robot. Upon completing the initial assignment, the group engaged in a thorough discussion of all ideas presented. For the second assignment, each participant received an idea from a colleague's initial submission, with the task of enhancing, elaborating, or refining it further. Upon completing the second assignment, all modifications were discussed in a group. After that, each idea was handed to another operator. During the last exercise, they were asked to describe these ideas in as much detail as possible. Finally, among the generated ideas, they were also asked to identify the idea that was most important to them, which served as the selected use case for the following activities of the co-design process. This session lasted around two hours.

3.2. Results

The desired use cases created by the factory operators during the workshop are shown in Figure 4. Based on the three drawings that depict the desired use cases, it can be inferred that the operators envision robots as suitable for performing heavy, dangerous, and repetitive tasks. Specifically, the operators identified the following tasks as suitable for robots: (1) holding heavy gears with sharp edges for deburring – given the highest priority; (2) picking up finished gears, packing them, and labeling them; and (3) assisting in the transportation of other parts, products, and even beverages. The operators' focus on these use cases suggests their awareness of the importance of occupational health and safety and highlights the potential of robots in reducing risks associated with such use cases (Welfare et al., 2019). This collaborative approach between humans and robots may result in a more productive and satisfying work environment.

Regarding the collaborative dynamic, the operators expressed their preference for a robot that would support some of the workloads, allowing them to maintain a leading role in the process. In this arrangement, the robot would act as a supportive assistant, closely following the operator's established steps and guidelines. This mode of co-working can be classified as "supportive human-robot collaboration," as depicted in Figure 5D, wherein a human operator and a robot collaborate simultaneously on the same task with the same object (Helms et al., 2002; Marvel et al., 2020). The desired used cases were based on the practical situations at the workplace. Regarding physical interaction, the operators preferred to control the robot's position, such as the position of its end-effector and the rotation of the gear. For social interaction, they expected a certain level of mutual understanding between the operators and the robot. They would like to give verbal commands to the robot if it is technologically possible, and the robot should indicate its


A. Use case 1 *(highest priority, selected use case)*

The robot holds a heavy gear while the operator deburrs it.

B. Use case 2

The robot picks up, packs, and labels finished gears.

C. Use case 3

The robot is an assistant, bringing products or coffee.

Figure 4: The factory operators created three desired use cases and interactions during the first co-creation session, with the use cases of heavy gear deburring given the highest priority.

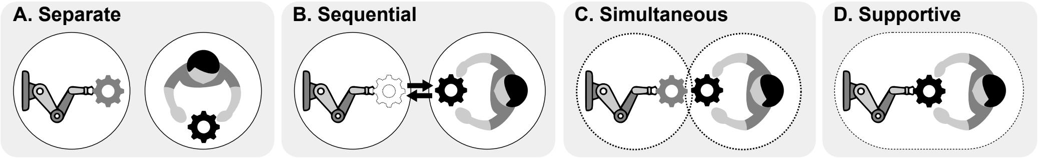


Figure 5: Four types of human-robot collaboration: separate, sequential, simultaneous, and supportive (Helms et al., 2002).

internal state and the task progress through light signals or displayed icons. However, it was still challenging for them to decide which special signals were suitable despite a range of different videos being presented and discussed.

4. Co-creation workshop 2: Co-creating the interaction interface

4.1. Procedure

In the second co-creation workshop (Sessions 2a and 2b), we decided to continue working on the heavy gear deburring task, see Figure 6A. This decision was based on the fact that this use case received the highest priority in the previous session, indicating its importance to the participants. From the selected use case, robot developers proposed various conceptual designs of the HRC interaction interface, see Figure 6B-D. The proposed designs included ergonomically adapting the robot's position based on the user's height and posture, different methods for sending commands to the robot (e.g. gesture, touch, buttons, foot pedal switches, speech), and different communication modalities for the robot to express its internal states (e.g. sound, light, displays) to enhance mutual understanding between the operator and robot.

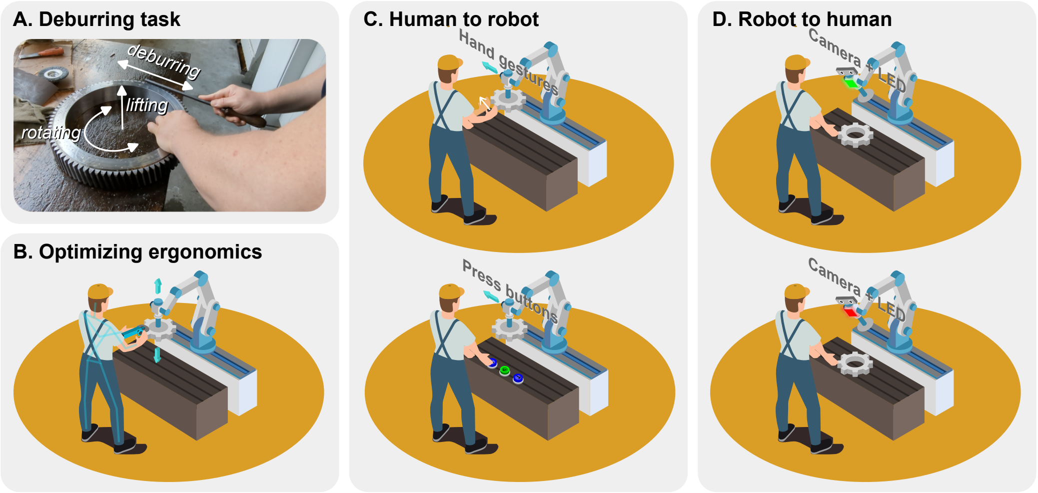


Figure 6: The heavy gear deburring task and examples of conceptual designs proposed by robot developers. (A) An operator is deburring heavy gear. (B) The robot moves to the most ergonomic robot position based on user's height and posture. (B) Two of several proposed methods for sending commands to the robot: gestures and buttons. (D) A proposed method for the robot to communicate its internal states through light signals: green indicating a positive status and red indicating a negative status.

From the proposed interfaces, an interactive role-play activity was conducted to determine which interface is the most suitable for the selected use case, see Figure 7A. More specifically, one participant was asked to play the robot and another participant was asked to play the operator, taking into account the conceptual designs. We chose this activity to make the interaction and the workflow more specific and practical because it was acted out by the participants. Therefore, we also asked them to think out loud and explain why they did an action. During the role-play activity, the scenario was refined and replayed through questioning and discussion between the moderators and participants. Each role-play scenario only lasted a couple of minutes and went through several iterations. Through this activity, we gained insights into the workflow and the preferred interface and interaction. The session lasted for approximately two hours.

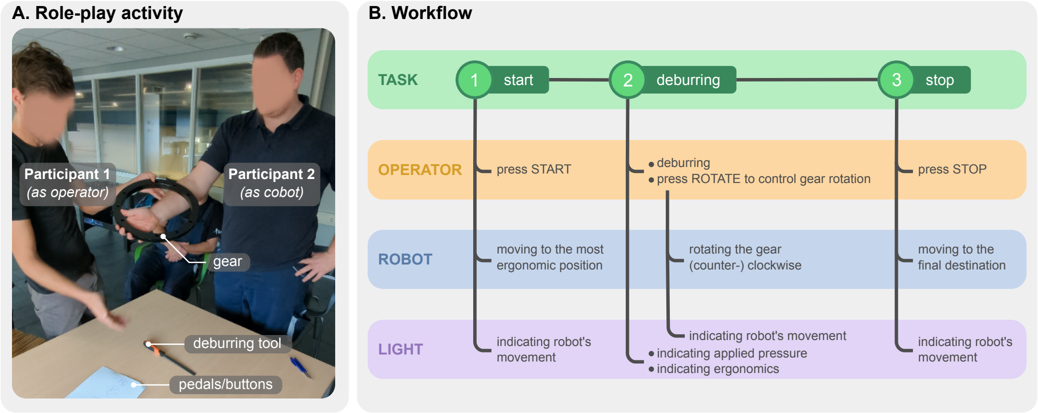


Figure 7: The role-play activity. (A) One participant acted as an operator while the other one acted as a robot. (B) The heavy gear deburring workflow with corresponding actions of the operator, the robot, and the light feedback.

4.2. Results

The workflow of the heavy gear deburring use case developed through the role-play activity is shown in Figure 7B. Initially, the operator requested the robot to move to the most ergonomic position according to their body's height. During the deburring process, they preferred to have active control over the robot position and gear rotation. They indicated their preference for using foot pedal switches (or buttons) to instruct the robot to start and finish the deburring process and to rotate the gear in their desired direction. They especially mentioned that foot pedals were a familiar interaction interface with their currently available manufacturing machines. This interface also enables them to control the robot's operation when both of their hands are occupied during deburring. To indicate its internal states, the robot's preferred modality was light signals (e.g. LEDs). These signals included notifications about the operator's unergonomic posture, which can lead to musculoskeletal disorders. Additionally, the operators wanted to know the state of the robot and an indication of how much force they were applying on the gear - too much force can lead to fast fatigue. It is worth mentioning that the fatigue caused by excessive force application was not fully understood by the robot developers, which resulted in a minor correction being made in the subsequent step of the co-design process. Other modalities such as sound signals, control using gestures, or tapping the robot were not preferred by the operators due to noise, an unfamiliar interface, or the inability to provide

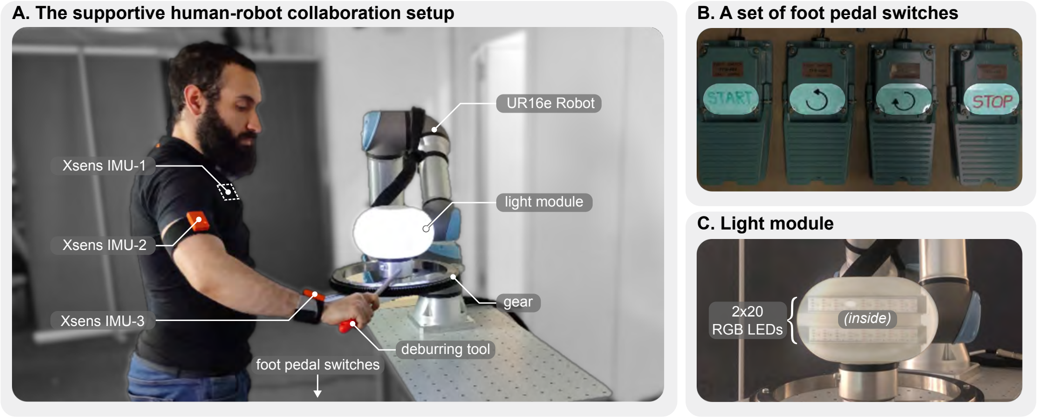


Figure 8: The supportive human-robot collaboration setup for the heavy gear deburring task. (A) Real-time monitoring of operator ergonomics and applied force, with light feedback. (B) Foot pedal switches for hands-free control of the task. (C) Light module for robot-to-human communication through color patterns.

a hands-free operation.

5. The proposed design of the interaction interface for supportive HRC

Based on the results from the two co-creation workshops, the robot developers designed the interaction interface aiming to meet the operators' requirements and preferences. The supportive HRC setup for the heavy gear deburring task includes a UR16e collaborative industrial robot, an Xsens full-body motion capture suit for assessing ergonomics, a set of foot pedal switches for human-to-robot communication, and a light module for robot-to-human communication (see Figure 8). The system is controlled via ROS[3] and aims to improve safety, ergonomics, and efficiency in the workplace.

5.1. The UR16e collaborative industrial robot

The UR16e[4] collaborative industrial robot was selected for the heavy gear deburring task since it is designed to handle heavy-duty tasks such as machine tending, material handling, packaging, material removal, and screw

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[3] https://www.ros.org/

[4] https://www.universal-robots.com/products/ur16-robot/

and nut driving applications (see Figure 8A). With a payload capacity of 16 kg, it is suitable for lifting heavy gears. The internal force torque sensors can help detect how much force is applied on the gear, which is communicated to the operators through the light module. The I/O terminals and ROS support enable robot developers to connect external devices (e.g. foot pedal switches, motion capture systems, and LEDs) and to control the HRC system via ROS.

5.2. The motion capture suit for accessing ergonomics

The Xsens MVN Link full-body motion capture suit[5] was selected to assess the ergonomics of operators while collaborating with robots (see Figure 8A). The suit captures the operator's body motion in real-time using high-precision inertial measurement unit sensors (IMUs) and provides accurate data on their movements and postures. Three IMUs were used because the deburring use case was executed by one hand. The captured data is used to assess ergonomics using the Rapid entire body assessment (REBA) (Hignett and McAtamney, 2000) which is then used to optimize the robot's end-effector position for ergonomics. Additionally, it can provide real-time feedback to the operator on their ergonomics via the light module.

5.3. The foot pedal switches for human-to-robot communication

A set of four TFS-402 foot pedal switches[6] was used to provide operators with intuitive and efficient control over the robot's movements during the deburring process (see Figure 8B). Four foot pedal switches are assigned to *Start*, *Rotate Counter-clockwise*, *Rotate Clockwise*, and *Stop* functions. These foot pedal switches are used to initiate and stop the deburring process, as well as to rotate the gear in the desired direction. Each foot pedal switch is assigned to a specific function, ensuring that operators can easily and quickly communicate their instructions to the robot. The use of foot pedal switches provides a hands-free interface, reducing the risk of operator fatigue and improving ergonomics.

5.4. The light module for robot-to-human communication

A light module was designed and installed near the robot's end-effector to facilitate a variety of robot-to-human communication through color patterns

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[5] `https://www.movella.com/products/motion-capture/xsens-mvn-link`

[6] `http://www.tend.com.tw/eng/product/tbf-11.htm`

(see Figure 8C). The design consists of two RGB LED strips[7] (2x20 single LEDs) placed under a translucent light diffuser allowing 180-degree visibility, based on previous work (**?**).

We followed color codes specified in the international standard IEC 60073:2002 (British Standards Institute, 2002), which are commonly used in the industry's tower lights. Firstly, it is used to communicate the robot's internal state while it is in motion i.e. breathing white while moving, spinning blue while rotating, and static green when reaching the final destination. This helps to improve safety in the workspace by allowing the operators to better understand the robot's planned actions. Secondly, the light module is used to provide feedback on ergonomics, indicating bad posture with a flashing red light. This allowed operators to quickly and easily assess their posture and movements while working with the robot, helping to prevent repetitive strain injuries and other ergonomic issues. Finally, the light module is used to indicate the amount of force being applied to the gear, with the color changing to purple and the intensity increasing linearly with the applied force. This allowed operators to avoid damaging the gear while still achieving optimal performance.

5.5. Controlling the HRC interaction interface

All components of the system were integrated and controlled in ROS, see Figure 9. The robot trajectories are planned and controlled following the heavy gear deburring workflow (Figure 7B). Data gathered from Xsens motion capture suit and the internal force torque sensors are converted into corresponding color patterns and sent to the light module to communicate with the operator (arrows 4, 9, and 11).

The optimal starting position of the robot is determined by postural optimization using the body joint angles, based on our previous studies. The angles are captured by the IMUs (Xsens, arrow 1) and converts into a REBA score (arrow 2). The REBA score is used as input of the postural optimization algorithm (arrow 5) to accordingly control the position of the robot's end-effector (arrows 6 and 7), which aimes to reduce the risk of musculoskeletal disorders. Regarding the ergonomics feedback, while the REBA score may fluctuate depending on the individual, our observations indicated that it generally fell within the range of 1 to 4. When the score reaches 3 or higher,

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[7] `https://www.adafruit.com/product/2329`

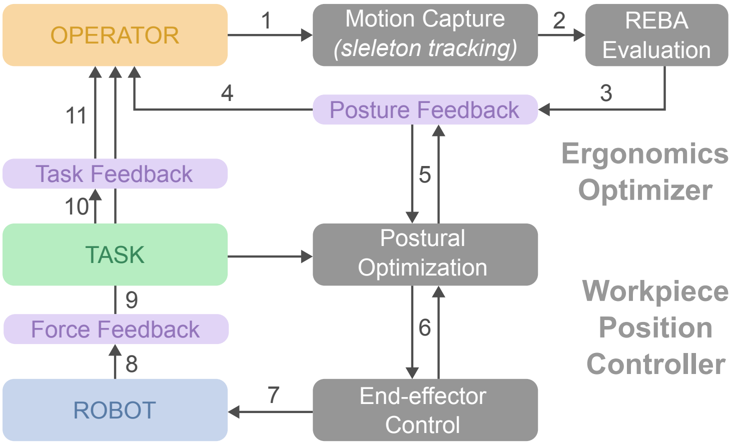

Figure 9: System architecture. Components are integrated for ergonomics optimization, workpiece position control, and light feedback.

it signifies an increased risk, necessitating a change in posture (Joshi and Deshpande, 2020; Omidi et al., 2023; **?**).

The proposed HRC interaction interface was tested to assess its technical performance proposed by the operators during the co-creation workshop. All functionalities of the system were summarized in Figure 10 and a demonstration video[8], providing an overview of the system's design and capabilities.

6. Feedback on the HRC interaction interface from factory employees

6.1. Procedure

As part of the co-creation process, we conducted two semi-structured feedback interviews with four employees to gather their insights on the developed HRC interaction interface compared to the manual process currently being used. During the feedback interviews, the demonstration video was shown, followed by discussions of individual short scenes from the video to elicit feedback on the interaction interface. During the interviews, participants were asked a series of questions to gain insights into their perspectives

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[8] Demonstration of the proposed interaction interface: `https://youtu.be/SmHhE4YQ8nQ`

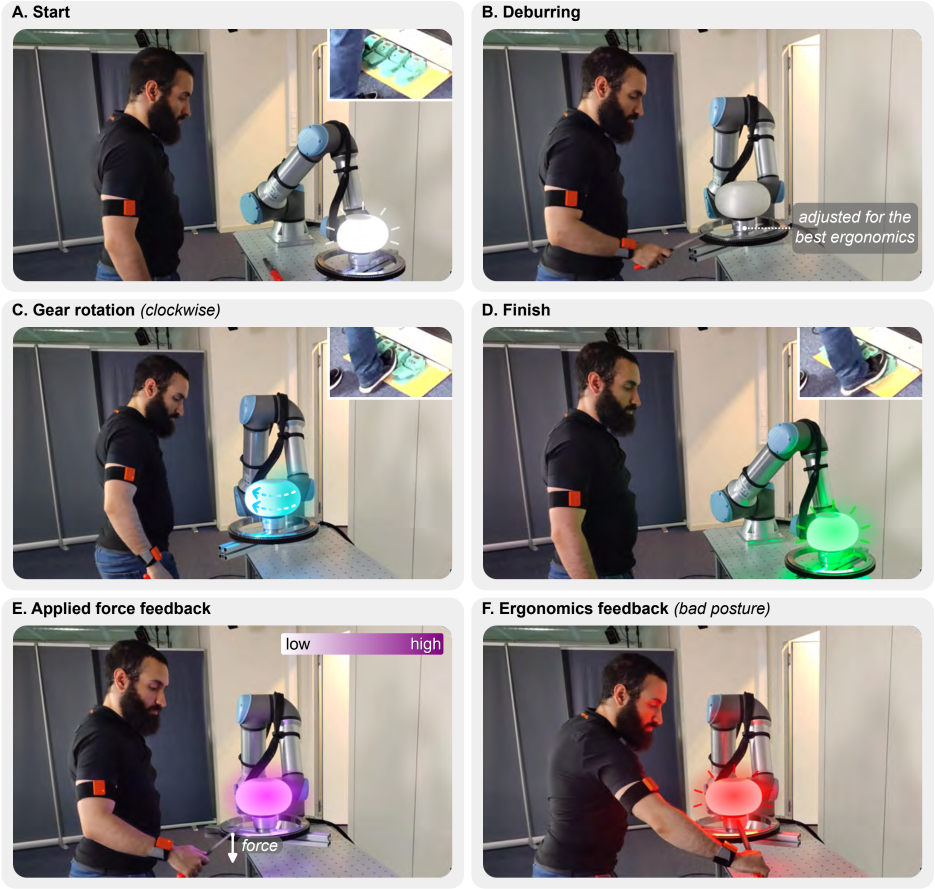

Figure 10: The proposed human-robot collaboration interaction interface is being tested to assess the technical performance.

on: *the co-creation process*, *the interaction interface*, and *suggestions for improvements* to make it more practical for their work environment. These inquiries aimed to assess the alignment between the system and the operators' needs and preferences and their willingness to integrate the system into their factory.

6.2. Results

In general, the feedback from the factory employees who participated in the design process was positive and provided insights for improving the HRC interaction interface. We structured the feedback according to the Technology Acceptance Model (TAM) (Davis, 1989). In general, the operators felt that the interface met their needs and preferences and that they would be willing to work with it in a factory setting. They appreciated their involvement in the co-design process. They also provided suggestions for improving the interface's usability and functionality, which will be considered in future iterations.

6.2.1. Perceived Usefulness

The participants found the proposed HRC interaction interface to be useful in addressing their health concerns compared to the manual process. They particularly appreciated the ergonomic feedback provided by the system. The foot pedal switches and robot rotation allowed them to use both hands for deburring, then more sensors should be added for the other hand. The light module provided robot-to-human communication, which was not present in their current robots, and they found it helpful in understanding the robot's actions. However, they suggested removing the feedback on the excessive applied force at the moment as it was difficult to use in practice. As mentioned earlier, this functionality was not fully understood by the robot developers. After more discussion about this issue, the team concluded that some operators might prefer to use higher force to finish the task faster and therefore it is difficult to standardize the maximum applied forces.

6.2.2. Perceived Ease of Use

While some operators felt comfortable wearing the IMUs, others did not since they had prior experience using IMUs in other robot applications. Their main concern was the possibility of losing, accidentally breaking, or getting dirty. They suggested incorporating a simpler ergonomic optimization process based on their height for future iterations, which could be configured through a graphical user interface (GUI). The GUI could also be used to determine whether the operator is wearing IMUs and select the corresponding ergonomic optimization. The foot pedal switches were easy to use, and the sequence followed the workflow. However, the operators suggested adding a protection cover for the pedal switches to prevent damage if heavy objects fall onto them. For safety reasons, they recommended moving the UR robot's emergency button closer to the operator. They also found the light module colors easy to understand but suggested synchronizing the rotation speed of the light module with the gear's rotation speed. Although we focused on designing the interaction interface, we also received feedback on how to improve the robot hardware e.g., a better gripper with continuous rotation, and wireless communication with the light module.

6.2.3. Intention to Use

The operators expressed a willingness to work with the proposed HRC interaction interface, and some were interested in participating in future iterations to further improve the system. One of the participants even repeated multiple times during the interview that he already wanted to have the robot "tomorrow" to replace the manual process. This level of engagement and commitment from the operators is crucial for the actual usage of the system.

6.3. The HRC interaction interface in the next iteration

We attempted to sketch how the HRC interaction interface would look like in the next iteration taking into account recommendations from the factory employees, see Figure 11. The next iteration of the HRC interaction interface should feature a simplified ergonomic optimization process configured through a GUI, a protection cover for the foot pedal switches, and relocation of the UR robot's emergency button closer to the operator for improved safety. The light module should be synchronized with the gear's rotation speed, the gripper should be enhanced, and wireless communication with the light module should be implemented. Additionally, the force feedback feature should be removed, and more sensors should be added for the other hand. These enhancements would provide operators with an even more user-friendly and ergonomic HRC system that improves their health and safety while increasing productivity and efficiency.

7. Assessing Human-Robot Collaboration for the Next Iterations

Following the first iteration with operators engaged in the co-design process, we conducted a quantitative assessment of the *HRC quality* and *responsible robotics*. The purpose of this evaluation is to prepare for the implementation with a broader scope of operators in the next iterations. The aim is to investigate not only the technological suitability of the co-designed interaction interface but also its ethical and social responsibility.

7.1. Quantification of human-robot collaboration quality

We applied the proposed Human-Robot Collaboration - Quality Index (HRC-QI) to quantify the HRC quality of the proposed interaction interface (Kokotinis et al., 2023). This quantification tool provides a comprehensive

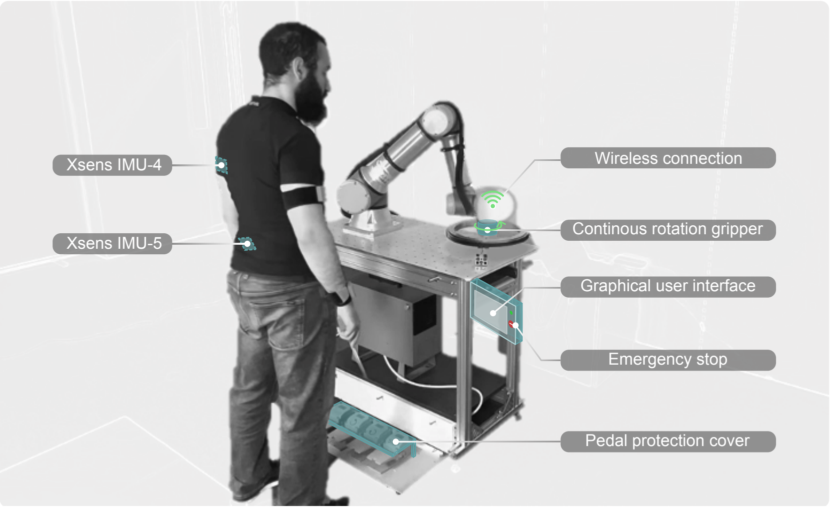

Figure 11: The human-robot collaboration interaction interface in the next iteration, taking into account suggestions from the operators in the feedback interview.

evaluation framework to assess the flexibility, performance, cost, and quality of HRC applications. The cumulative HRC-QI score Q_t for a specific application is calculated as follows.

$$Q_t = \frac{\sum_{m=1}^{M} \left(\frac{v_m - v_{\min_m}}{v_{\max_m} - v_{\min_m}} \right)}{M} \tag{1}$$

where M is the total number of the metrics, v_m is the evaluated value of each metric, $v_{\min_m}$, $v_{\max_m}$ are the minimum and the maximum values of v_m. The evaluation of each metric and justification is summarized in Table 1. The value of Q_t we obtained is 0.67/1, indicating a moderate to high level of HRC quality.

7.2. Responsible Robotics

We adopted the Responsible Robotics Compass to further assess the non-technological aspects of responsible robotics[9]. This evaluation tool provides a detailed analysis of risks, mitigation strategies, and recommendations for the factors that impact a robot's acceptance, such as human experience, socio-economics, environment, legal, and data. Ideally, a system should obtain

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[9] Responsible Robotics Compass: `robocompass.aiod.eu`

a high global score, with each individual factor having a mitigation score higher than its corresponding risk score, reflecting robust risk management practices across all aspects. With a Technology Readiness Level of 7 (TRL-7: Prototype refinement and operational validation), we obtained a global score of 60% at this stage of development and there is still room for improvement. Details of the five factors and recommendations for the next iteration are summarized in Table 2. For example, the *Data* factor recommends a Data Management Plan. The *Environment* factor suggests prioritizing recyclable materials and considering transportation impact. The *Human experience* factor emphasizes ethical guidelines and safety standards. The *Legal* factor advises compliance with third-party licenses. The *Socio-economics* factor suggests assessing job impacts at a broader scope and ensuring compliance with labor laws.

Table 1: HRC – QI results for the proposed interaction interface and justification. Notes: Robot Autonomy (RA), Robot Manipulation ability (RM), Mobility (M), Cognition and Knowledge acquisition ability (CK), Cost (C), Performance for Human Safety (HS), Ergonomics benefits (E), User eXperience (UX), Interaction ability (I), Workspace sharing (WSs), Time Sharing (Ts), Workpiece sharing (WPs).

Metrics	**HRC – QI**	**Comments**
RA	2/5	The robot automatically adapts the end-effector position while the human operator manually deburrs the gear and controls the workflow with pedals.
RM	3/5	The robots is equipped with a dedicated end-effector for holding heavy gears, which can be customized according to the gear's dimension.
M	1/3	The robot is stationary.
CK	5/6	The robot 'observes' human motions, by using data from Xsens motion capture suit and internal force torque sensors.
C	2/3	Medium cost with a light module and sensors. Note that the company has purchased several robots.
HS	5/5	The robot is equipped with sensors for collision detection.
E	5/5	The robot adapts the end-effector for ergonomics optimization.
UX	3/3	The human operator works with a collaborative robot under full trust.
I	5/6	The human operators can control the workflow through pedals, and information on the workflow and warning messages are displayed via the light module.
WSs	5/5	The human and the robot work in the same workplace without restriction.
Ts	2/3	The human and the robot co-manipulate at the same time while deburring. In other steps, the robot handles the heavy gear alone.
WPs	3/4	The human and the robot co-manipulate the same workpiece while deburring. In other steps, the robot handles the heavy gear alone.
Qt	***0.67/1***	***Moderate to high***

Table 2: Responsible Robotics Compass results for the proposed interaction interface and relevant recommendations.

Factors	Scores	Evaluation and Relevant recommendations
Data	**68%**	**Risk score (1%): Extremely low. Mitigation score (15%): Low.**
Collection	73%	Consider implementing a Data Management Plan governing the collection, storage, and use of data.
External data	60%	Consider relevant issues if external data will be used in the next iterations.
Storage	64%	Consider encrypting sensitive robot data, using secure protocols, assessing data leak risks, including cybersecurity in training, setting legal data deletion timelines, and regularly assessing for vulnerabilities.
Usage	65%	Monitor access to personal data with mandatory authentication. If possible, data processes and practices should be controlled by an external audit.
Environment	**64%**	**Risk score (26%): Slightly low. Mitigation score (37%): Moderate.**
End-of-life	30%	Prioritize recyclable materials in robot design and consider obtaining the EPEAT ecolabel. Further prepare for maintenance and repair solutions.
Logistics	72%	Consider the impact of transportation in the assessment of environmental impact.
Operation	67%	Train operators on environmental risks and mitigation measures, including documentation.
Production	69%	Prioritize renewable and recyclable materials.
Human experience	**68%**	**Risk score (36%): Moderate. Mitigation score (57%): Slightly high.**
Life	72%	Establish ethical guidelines and engage with stakeholders to address concerns and build trust.
Work	65%	Implement strict safety standards and protocols for human-robot collaboration.
Legal	**64%**	**Risk score (23%): Slightly low. Mitigation score (38%): Moderate.**
Governance	65%	Comply with third-party solution licenses, including open-source software or hardware, used in robot development.
Regulatory Readiness	73%	Consider complying with the machinery directive and receiving the CE marking.
Socio-economics	**34%**	**Risk score (33%): Moderate. Mitigation score (17%): Low.**
Development economics	26%	Assess the robot's job impact and comply with ethical employment standards and labor laws
Equality	31%	Include diverse groups in validating and testing design choices.
Labor market impact	64%	Consider operators' skills in designing and training for robot maintenance to enable them to work with minimal additional training.

8. Discussion

In this work, our co-creation study contributes to the field of HRC by demonstrating the benefits of involving operators as key stakeholders in the design process through a qualitative research method. The participatory design approach adopted in this study allowed for a more organic exploration of the possibilities for human-robot interaction, resulting in a customized HRC interaction interface that aimed to meet the operators' requirements and preferences.

Reflecting on our experience conducting online co-creation workshops, we encountered both successes and difficulties. While the overall process proceeded smoothly, moderating discussions remotely occasionally posed difficulties. Conducting online co-creation workshops without physically visiting participants' work environments might lead to limited contextual information about the use cases. To overcome these challenges, two of the authors, with experience in design ethnographic research, took proactive steps to address these difficulties. We asked for further explanations when participants used industry-specific jargon and requested supplementary materials, such as video recordings, additional images, or post-workshop clarifications. These measures enhanced our understanding of the participants' work context, contributing to the depth of our insights and mitigating the constraints caused by the online medium.

Regarding the co-creation process, a significant challenge was the alignment of the operators' preferences and requirements with the technical capabilities and limitations of the robot system. While the design team aimed to balance these factors, there were features that the operators desired but were not technically feasible or optimal for the robot system. This issue highlights the importance of clear communication and expectations between the design team and the operators, ensuring that both parties understand the technical capabilities and limitations of the system.

Another challenge observed during the co-creation workshop came from the incomplete understanding of a preferred feature by the robot developers (e.g. applied force feedback), resulting in an implemented feature that was not entirely usable at the moment. The impact of this challenge on the project in terms of time and effort depends on the magnitude and timing of the misunderstanding between the design team and the operators. Specifically, the larger the misunderstanding and the later it occurs in the design process, the more time and effort might be required to address it. To minimize this unavoidable issue and improve the design process, it is crucial to develop more effective strategies for ensuring that the developers fully comprehend the operators' preferences. While one strategy was employed (i.e. sharing a summary of the findings with our contact person), there is room for improvement through the exploration of more effective strategies.

Working with an SME faced challenges in obtaining a high number of participants for the co-creation sessions. Therefore, it is proper to employ a qualitative research approach to gain better insights. However, it was still challenging to ensure consistent participation from the same operators throughout all co-creation sessions due to their availability and production schedules. This issue suggests the need for flexible scheduling options such as splitting one session into several sub-sessions with different operators.

Finally, our study focused on the design of the human-robot interaction interface and has not yet investigated the long-term impact of the designed system on operator satisfaction or productivity. While the feedback from the operators was positive, future studies should investigate the long-term effects of the designed system on operator satisfaction, productivity, and wellbeing. In terms of developing the system, efforts should be made to enhance the HRC quality and to consider implementing recommendations related to responsible robotics.

9. Conclusion

In this paper, we presented a co-creation approach for designing a supportive human-robot collaboration system using the Double Diamond design process. By involving operators in the design process through two co-creation sessions and a feedback interview, we gained insights into their needs and preferences regarding the HRC interaction interface. This resulted in a customized interface that aimed to best meet their needs and preferences for the desired task, functionalities (such as active control, heavy load support, and ergonomics), and modalities of human-to-robot and robot-to-human interaction. The HRC interaction interface was well-received by operators. This suggests that involving operators in the design process can lead to higher acceptance and adoption of HRC systems in industrial settings. Further research is needed to test the system in the long term with more iterations, focusing on improving the quality of human-robot collaboration (HRC) and implementing recommendations related to responsible robotics. This will help the team gain a deeper understanding of the system's impact on the workplace and explore its potential benefits, such as increased productivity and reduced ergonomic-related health issues. Taking a broader view, further investigation is needed to assess the impact of the co-designed system on the broader context of the enterprise's operations and business models.

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