Teleoperator-Robot-Human interaction in manufacturing: perspectives from industry, robot manufacturers, and researchers

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Occupational Applications

Industrial robots have become an important aspect in modern industry. In the context of human-robot collaboration, enabling teleoperated robots to work in close proximity to local/onsite humans can provide new opportunities to improve human engagement in a distributed workplace. Interviews with industry stakeholders highlighted several potential benefits of such *teleoperator-robot-human collaboration* (tRHC), including the application of tRHC to tasks requiring both expertise and manual dexterity (e.g., maintenance and highly skilled tasks in sectors including construction, manufacturing, and healthcare), as well as opportunities to expand job accessibility for individuals with disabilities and older individuals. However, interviewees also indicated potential challenges of tRHC, particularly related to human perception (e.g., perceiving remote environments), safety, and trust. Given these challenges, and the current limited information on practical value and implementation of tRHC, we propose several future research directions, with a focus on human factors and ergonomics, to help realize the potential benefits of tRHC.

Technical Abstract

Background: The increasing prevalence of robots in industrial environments is attributed in part to advancements in collaborative robot technologies, enabling robots to work in close proximity to humans. Simultaneously, the rise of teleoperation, involving remote robot control, poses unique opportunities and challenges for human-robot collaboration (HRC) in diverse and distributed workspaces.

Purpose: There is not yet a comprehensive understanding of HRC in teleoperation, specifically focusing on collaborations involving the teleoperator, the robot, and the local or onsite workers in industrial settings, here referred to as *teleoperator-robot-human collaboration* (tRHC). We aimed to identify opportunities, challenges, and potential applications of tRHC through insights provided from industry stakeholders, thereby supporting effective future industrial implementations.

Methods: Thirteen stakeholders in robotics, specializing in different domains (i.e., safety, robot manufacturing, aerospace/automotive manufacturing, and supply chains), completed semi-structured interviews that focused on exploring diverse aspects relevant to tRHC. The interviews were then transcribed and thematic analysis was applied to group responses into broader categories, which were further compared across stakeholder industries.

Results: We identified three main categories and 13 themes from the interviews. These categories include Benefits, Concerns, and Technical Challenges. Interviewees highlighted accessibility, ergonomics, flexibility, safety, time & cost saving, and trust as benefits of tRHC. Concerns raised encompassed safety, standards, trust, and workplace optimization. Technical challenges consisted of critical issues such as communication time delays, the need for high dexterity in robot manipulators, the importance of establishing shared situational awareness among all agents, and the potential of augmented and virtual reality in providing immersive control interfaces.

Conclusions: Despite important challenges, tRHC could offer unique benefits, facilitating seamless collaboration among the teleoperator, teleoperated robot(s), and onsite workers across physical and geographic boundaries. To realize such benefits and address the challenges, we propose several research directions to further explore and develop tRHC capabilities.

Keywords: *human-robot interaction; remote human-robot interaction;; distributed manufacturing; manufacturing performance*

1. Introduction

Robot technologies are becoming an increasingly important aspect of several industrial environments. According to the recent report from the International Federation of Robotics (Müller, 2023), for example, the mean global robot density in manufacturing was 151 robots per 10,000 employees in 2022, more than double the number in 2015. In the same year, the U.S. robot density was 120 robots per 10,000 employees. This surge in robot density can be explained by rapid advancements in robot technologies, especially collaborative robots (cobots). Since cobots can operate with humans in close proximity and within an interactive environment, this technology has enabled a new level of safety and effectiveness in human-robot collaboration (HRC) for numerous applications. Collaborative efforts between humans and robots can enhance productivity, flexibility, and safety in the workplace (Fryman & Matthias, 2012; Villani et al., 2018). Consequently, it is expected that the utilization of industrial robots will continue to grow in the foreseeable future.

Teleoperation, a type of human-robot interaction, involves active human involvement in remotely controlling a robot (Murphy & Rogers, 1996). This mode of operation offers unique benefits for HRC, particularly in unknown, challenging, and/or unstructured environments. By combining human intelligence with the advantages of robots, such as consistency and precision, teleoperated systems enable effective task execution without being restricted by physical location. The first mechanically-driven, teleoperated robot was introduced in the 1950s for nuclear waste disposal (Goertz, 1952). Since then, numerous teleoperated robots have been developed to meet specific needs and purposes. Industrial applications of teleoperation include inspection and repair in hard-to-reach or hazardous locations (Alatorre et al., 2019; Pouliot & Montambault, 2009; Saltaren et al., 2007), handling hazardous waste materials (Desbats et al., 2006; Qian et al., 2012), and operating construction equipment (Lee et al., 2022; Sato et al., 2021). Overall, these applications typically revolve around situations in which human presence is limited or constrained, often due to safety concerns.

While the physical distance between an operator and a teleoperated robot confers benefits, it also creates many challenges in teleoperation. Some well documented challenges include control delays, limited perception of the remote environment, and difficulties in establishing and maintaining situational awareness (Luo, He, et al., 2020; Nielsen et al., 2007; Yanco & Drury, 2004). Extensive research efforts have sought to address these and related challenges, resulting in substantial advances in areas such as human-robot interfaces (Pacchierotti et al., 2014; Rastogi, 1997; Triantafyllidis et al., 2020), control algorithms (Kebria et al., 2020; Liu & Chopra, 2013; Polushin et al., 2007), and robot learning mechanisms (Havoutis & Calinon, 2017; Khokar et al., 2014; Luo et al., 2019).

Yet, little attention seems to have been paid to the broader context of HRC in teleoperation, which involves interactions and collaborations not only between the teleoperator and the robot but also with one or more local/onsite workers. This collaboration among the distributed team, hereafter referred to as *teleoperator-robot-human collaboration (tRHC*), remains an area that requires further exploration, especially in industrial settings. Some insights can be drawn from robotic-assisted surgery, where earlier work examined the impact of surgical robots on the entire surgical team, affecting team workflow, communication patterns, and collaborative practices (Anne-Sophie & Adélaïde, 2009; Healey & Benn, 2009). Such findings suggest that the use of teleoperated robots influences both individual team members and overall team dynamics, creating unique effects on each.

Collaboration between a teleoperator and a teleoperated robot remains a primary focus of HRC in many industrial applications of teleoperation (e.g., repair, hazardous waste handling). In this context, local workers often act simply as local supervisors or work at a distance from the teleoperated robot. However, the concept of tRHC may hold potential for enhancing and redefining how humans engage in distributed workplaces, particularly in promoting more flexible HRC through the use of *teleoperated robots as a medium*. For instance, by providing both physical and knowledge support in distributed workspaces, tRHC could facilitate collaborations between older individuals or individuals with disabilities and onsite workers. More broadly, harnessing the potential of tRHC could lead to more inclusive, diverse, and flexible work environments.

Our aim in the current study was to explore in more detail the potential of tRHC in industrial settings for the foreseeable future. For this, we completed interviews with industry stakeholders –specifically individuals who manage human-robot collaboration processes or develop teleoperating robots– to capture their perspectives on this topic. Our long-term goal was to inform and guide future research efforts on the application of tRHC across different work environments. By understanding the perspectives of industry stakeholders, we sought in particular to identify opportunities, challenges, and potential application areas associated with tRHC, and to support more effective future industrial implementations.

2. Methods

2.1. Participants

A combination of maximum variation purposive sampling (Patton, 2015) and snowball sampling (Goodman, 1961) methods was used to recruit participants, through our existing industry contacts, word-of-mouth referrals, and suggestions from participants. Eligible participants were broadly defined as experienced individuals, including those working in industries that regularly use industrial robots, individuals involved in robot development, and researchers specializing in the safety aspects of robot use. Recruitment continued until data saturation was apparent qualitatively (i.e., that limited new information would be obtained from additional interviews), which occurred after 13 interviewees (11 males and two females). The study procedures were approved by the IRB at [masked university], and interviewees provided verbal informed consent prior to their interview.

2.2. Data collection

Semi-structured interviews were conducted via the Zoom video conference system, between July and December 2022. The interviews were conducted by at least three investigators, comprising two male and one female interviewer. One primary interviewer was responsible for asking the interview questions, while the other interviewers asked additional questions for clarification when relevant. The interview script (see Appendix A in online supplemental material) was designed to cover diverse aspects that we considered relevant to tRHC, including the expected benefits of tRHC, potential tasks and industries suitable for its application, appropriate robot models, perceived technical challenges for both onsite and remote workers, and concerns regarding worker safety, health, and well-being. Each interview lasted about 40 minutes, and the sessions were recorded using the video conference system for later analysis.

2.3. Data analysis

All interview recordings were transcribed verbatim using Otter.ai (California, USA), an automated transcription service, and transcripts were then manually checked by one investigator to identify and correct any errors. Following the grounded theory method (Strauss & Corbin, 1994), two investigators repeatedly read through the corrected transcripts to gain a comprehensive understanding of the complete dataset. During this reading process, they identified common responses and converted them to codes that reflected important features relevant to the study (Hsieh & Shannon, 2005). Subsequently, they coded a subset (n=3) of the transcripts, and these codes were then reviewed by all investigators to reach consensus and to refine the list of codes. The remaining transcripts were then coded, and each transcript was reviewed by the other investigators. Throughout this coding process, emerging categories and themes were identified and further refined through collating and analyzing the assigned codes. The final set of categories grouped 13 themes into the following categories: (1) Benefits, (2) Concerns, and (3) Technical Challenges. The themes included in these categories were as follows:

- *Accessibility*: Opportunities for individuals with disabilities or limited mobility to participate in work activities.
- *Control & Capabilities*: Necessary control considerations and capabilities required by a teleoperated robot.
- *Control Interface*: Specific control interface requirements for the teleoperator.
- *Communication*: Challenges associated with communication between the teleoperator, teleoperated robot, and onsite workers.
- *Ergonomics*: Potential risks and discomfort that teleoperators and onsite workers could experience during tRHC.
- *Flexibility*: Ability to adapt to different task requirements and work scenarios.
- *Network Availability & Reliability*: Importance of a high-speed and reliable communication infrastructure for tRHC.
- *Safety*: Well-being and protection of onsite workers in the presence of a teleoperated robot.
- *Sensing*: Sensing capabilities for the teleoperated robot to perceive and interpret the remote environment.
- *Standards*: Need for established guidelines and regulations specific to tRHC.
- *Trust*: Potential benefits and challenges related to establishing and maintaining trust among all stakeholders involved in tRHC.
- *Time & Cost Savings*: Potential time and cost savings with tRHC, such as reduced travel time.
- *Workplace Optimization*: Role and integration of the teleoperator and teleoperated robot within the workplace.

3. Results

The three categories and 13 themes identified are summarized in Figure 1, which also includes several key comments/labels for certain themes to provide context and to enhance clarity. In addition, the themes are presented in terms of industry types and categories (Table 1), demonstrating that in the "Concerns" category, Security was a common theme across all interviewees regardless of their industry type. In the Technical Challenges category, Communication, Control & Capabilities, and Sensing emerged as common themes across all industry types. We subsequently present all the themes in each category, along with representative quotes. Note that when referring to workers onsite during tRHC, we use this term to encompass both the singular and plural forms.

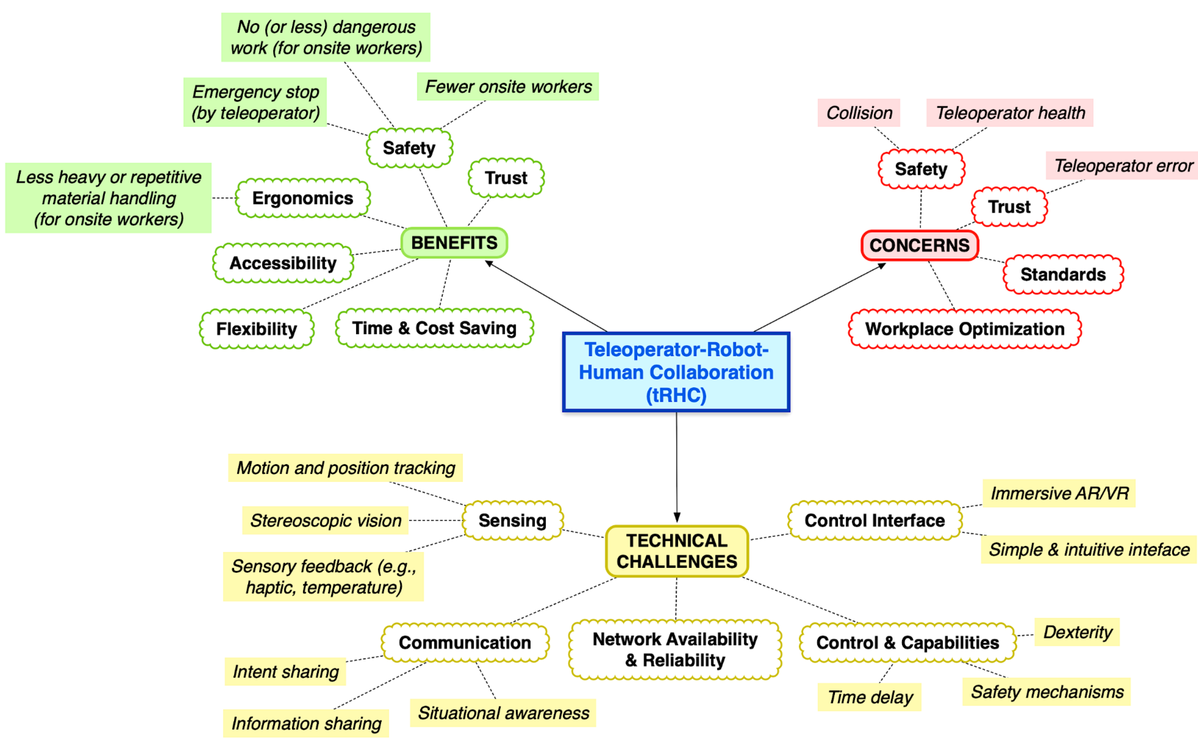

Figure 1. Illustration of three categories (round boxes), 13 themes (cloud-shaped boxes), and related comments/labels (italicized text in rectangular boxes).

Table 1. Themes identified in terms of industry types and categories.

Industry Type	Benefits	Concerns	Technical Challenges
Safety (*n*=2)	Ergonomics, Safety, Trust	Safety, Trust	Communication, Control & Capabilities, Sensing
Robot manufacturers (*n*=5)	Accessibility, Flexibility, Time & Cost Saving	Safety, Trust, Workplace optimization, Standards	Communication, Control & Capabilities, Control Interface, Sensing, Network Availability & Reliability
Automotive/aerospace manufacturers (*n*=4)	Ergonomics, Time & Cost Saving, Safety	Safety, Workplace optimization	Communication, Control & Capabilities, Sensing, Network Availability & Reliability
Supply chain (*n*=2)	Safety, Flexibility	Safety, Standards	Communication, Control & Capabilities, Sensing

3.1. Benefits

Six specific themes within the category of benefits were identified: Accessibility, Ergonomics, Flexibility, Safety, Time & Cost Saving, and Trust. Interviewees emphasized that teleoperation would support telepresence and physical interaction, enabling immediate and on-demand assistance from remote experts or personnel. These specific benefits could eliminate or reduce the need for travel and associated delays. Participants further suggested that telepresence could enhance accessibility, expanding the inclusion of individuals who may not have the physical ability to work on-site. As examples:

"*We have employees that are spread all around the world, many of those [are] subject matter experts themselves. It's a tremendous amount of cost, to have those individuals come into California, to work on something that could take 30 minutes…Having a system that allows them to do [teleoperation], and limit the cost of travel, … it's a tremendous benefit as a whole and allows the production to continue to move forward.*"

"*No longer have to travel because a [teleoperated] robot can be there physically.*"

Interviewees indicated that the presence of a teleoperator could have a positive impact on safety, trust, and flexibility. For example, they noted that teleoperators would be capable of making critical decisions, rather than relying solely on the robot's autonomous capabilities. They also mentioned that teleoperators could control the teleoperated robot effectively, particularly in unplanned or unforeseen situations. Some representative comments were:

"*Human workers working on site might be more willing to trust a collaborative robot that they're working alongside if they know another human is controlling it, compared to being autonomous.*"

"*If a remote teleoperator had complete control of a robot, if something went wrong, in terms of sensor/control failure, they'd be able to remotely stop it quicker, as opposed to having the onsite worker trying to figure out how to stop.*"

"*[Teleoperation can be beneficial in] highly dynamic situations, where your work isn't strictly the same and not highly repetitive.*"

Regarding safety and ergonomics, interviewees suggested that teleoperated robots could be deployed to handle tasks that are considered dangerous, dirty, or physically demanding, thereby reducing the risk to onsite workers and promoting their safety and health. Some representative comments were:

"*[Teleoperation can be beneficial in] dangerous scenarios where a human wouldn't work.*"

“*[Teleoperation can be beneficial in] dirt, dangerous [environments] and when it’s the first approaches such as deep sea, mining activities, or construction activities at large heights.*”

3.2. Concerns

This category comprises four themes: Safety, Standards, Trust, and Workplace Optimization. Safety was identified as a common concern across industries. Interviewees expressed particular concerns about collision hazards due to a lack of situational awareness, network issues leading to delays and disconnections, or the possibility of control errors by teleoperators. It was noted that the latter factor could lead to problems with trust among onsite workers.

“*If a remote worker is losing the [on-site videos] due to a problem with the network, anything could happen badly, which could make the on-site worker unsafe.*”

“*Same concerns as typical human robot interaction … While robots can reduce the common ergonomic injuries, they do present a lot of new hazards in the workplace. So, I'd be concerned about operator error, the increased risk of the onsite worker being struck by the robot … Onsite workers would be able to trust the remote workers’ control of the collaborative robot.*”

In addition, one interviewee suggested potential health concerns for teleoperators when they need to operate a teleoperated robot for an extended period, though underlying causes for such concerns were not clarified during the interview.

“*[For the teleoperator] I have some well, maybe strange ideas but what I imagined is that to teleoperate robots you have some different ways of moving. I mean, I get that the speed is limited, that the [robot] arms are not exactly the same as yours, and that you're going to to move your muscles and use them a little differently than you would do in your daily life for so long time. I don't know what could be the real impacts.*”

One interviewee raised the concern that implementing tRHC might present challenges in complying with specific Occupational Safety and Health Administration (OSHA) standards, such as the control of hazardous energy (e.g., lockout/tagout):

"*If the equipment needs to be locked out [based on the OSHA requirements], and the teleoperator needs the equipment moved, which could violate the on site regulation, how do we control this situation? How do you mitigate some of those old OSHA requirements?*"

Workplace optimization encompassed concerns regarding the ambiguity surrounding the roles and responsibilities of teleoperators and teleoperated robots within the current workplace. Two interviewees indicated concerns related to the effective integration of tRHC in their work processes, noting:

"*At the end of the day, companies are really interested in understanding human motions in order to optimize their processes, and then understand how to make robots [work] simple.*"

"*The problem with robots is that they're pretty expensive. And so it's not so easy to find a process where you get the payback.*"

3.3. Technical challenges

This category comprises five themes: Communication, Control & Capabilities, Control Interface, Network Availability & Reliability, and Sensing. The Communication, Control & Capabilities, and Control Interface themes emerged across all industry types. Interviewees emphasized challenges associated with controlling a teleoperated robot over a communication network, particularly the time delay in transmitting information between the teleoperator and the teleoperated robot. Several interviewees also noted the limited availability of high-speed and reliable networks in some of their workplaces, which could negatively impact the need for smooth and seamless control of the robot. As examples:

"*Real time data transfer does not exist, it has never existed. Never.*"

"*The latency and just kind of delay that you experience can be challenging. ... The lag would probably be there, any delay with Wi Fi conductivity, that would cause a concern for me.*"

"*We might be able to feel [the time delay] severely and something like 10 millisecond delay can create some disaster in a work environment since we are relying on the internet or network connection for this kind of operation.*"

Some interviewees indicated the importance of dexterity in a teleoperated robot gripper or hands to perform complex tasks that are currently carried out by human workers. They further suggested it might be challenging to replicate the dexterity and fine motor skills of human hands, but noted that there are active developments in this area.

"*When you start to want to do complex interactions, [robots] don't have dexterity.*"

"*We have to check like the surface finish or anything like that. We have a micron level type of specifications that we want to achieve. Maybe technology does not allow us to do that yet.*"

"*[Robots] can handle these flexible, soft parts that people currently have to deal with, and put those on the car reliably. At that point, there starts to be a real business case. ... But they're getting better. I mean, they already have robotic hands that can sense pressure and temperature.*"

Safety mechanisms were identified as additional concerns, particularly related to collision hazards. Interviewees highlighted the complexities involved in planning and executing precise and efficient motions remotely, especially in dynamic and unpredictable environments. In addition, some interviewees noted the challenge of performing tasks that require delicate manipulation or intricate movements, considering the inherent time delay in teleoperation. Several representative comments were:

"*You know, reducing delay and lag are obviously part of dealing with robotics and interacting with robots.*"

"*Build collision models and safety models for the robot. The challenge being that if you're doing complex interactions, you can't just do when the human is near. [You can] run the robot slowly, but what you actually want to do is, know where exactly are the arms and legs of a human and I move [the robot] around them.*"

"*The control has to precede the human and generate movements that keep humans safe. And then the question is, how do I generate trajectories, so that this is going to be feasible.*"

"*Our future goal, or our next project might be, more sensitive sensors on the robots like visions, or other the detecting system to detect or the recognize the environment or obstacles that the user cannot really focus on, then the robots will automatically control the system to avoid the obstacles or improve users balance and stability.*"

Regarding communication, many interviewees expressed the importance of sharing information and intention, and more generally establishing situational awareness among all agents (i.e., teleoperator, onsite workers, and a teleoperated robot). Specifically, the interviewees emphasized the need to understand and perceive various aspects such as the robot's surroundings, actions, on-site conditions, teleoperator's intentions, and on-site worker's intentions. Some example comments were:

"*Situational Awareness is more than just the visual spectrum. Multimodal interfacing is going to be new in robotics, especially in tele-robotics. Right now, the visual spectrum, we pretty much have gotten that well down. Especially when you're looking at Virtual Reality capability, you can do full immersion within the robot and see what's being seen by the robot. But again, what you lose is his proprioception, you lose the sense of mass and weight. it's going to be new territory, on how you become self-aware in this immersed environment in this robotic environment.*"

"*The problem being, I expect you to be able to see what's going on, but you can't see as much as I think you can. How do we, how do you build shared understanding of each other situational awareness to be able to work well and safely around one another*"

Interviewees discussed the need for immersive augmented reality (AR) and virtual reality (VR) to serve as essential control interfaces for effective teleoperation. They indicated that AR and VR technologies could enhance a teleoperator's perception and understanding of the robot's environment and the remote surroundings, by immersing the teleoperator in a virtual representation. However, interviewees also noted the need for improved sensing capabilities to achieve effective immersion, such as telescopic vision and real-time haptic and/or force feedback:

"*But again, what you lose is his proprioception, you lose the sense of mass and weight. it's going to be new territory, on how you become self-aware in this immersed environment in this robotic environment.*"

"*There is probably a challenge around how do you build effective, immersive virtual spaces where the human has a sufficient sense of the remote location and of their present location.*"

"*The kind of enabling technology here is immersive VR, or AR. You can absolutely be clear that you are in a remote place, and you can understand that remote place, and it becomes very easy to do some of these things. The challenge there is getting that to work well.*"

3.4. Potential industries and tasks that could benefit from tRHC

Interviewees suggested that tRHC could bring notable benefits to industries such as healthcare and diverse manufacturing sectors (Table 2). However, they mentioned that they could not provide specific tasks beyond maintenance, and they highlighted that tRHC could be valuable in general for highly skilled tasks that require human expertise. One interviewee raised concerns about the cost-effectiveness of tRHC in a work environment, considering the expenses associated with acquiring a highly dexterous teleoperated robot:

"*So, it's an economic problem if it takes 10 hours to get someone on site [to repair/fix something]. If having that person there is costing you $10,000 an hour in downtime, then $100,000 robot used once is suddenly quite a reasonable investment. I think it's essential to find the economic model that works for the problem in particular.*"

Interestingly, another interviewee pointed out that data collected during teleoperation could contribute to the development of more capable and fully automated robots, which might lead to the replacement of human labor:

"*Most of the cooperative tasks [using tRHC or teleoperation] we are doing is collecting data, and refining our machine learning algorithms will eventually transition back to autonomy. Hence, unfortunately, people may or may not, you know, lose their jobs as a result of that.*"

Table 2. Summary of potential industries and tasks that could benefit from tRHC.

Stakeholder Type	Potential Industry	Potential Task(s)
Safety (*n*=2)	Construction, Healthcare, Manufacturing/small-scale manufacturing, Mining	Highly skilled tasks (e.g., surgery), Maintenance
Robot manufacturers (*n*=5)	Aircraft manufacturing/manufacturing, Healthcare, Restaurant industry	Highly skilled tasks, Maintenance
Automotive/aerospace manufacturers (*n*=4)	Automotive manufacturing, Construction, Healthcare, Mining, Shipbuilding	Dangerous tasks, Highly skilled tasks, Maintenance
Supply chain (*n*=2)	-	Highly skilled tasks, Maintenance/Repair, Remote truck operation

4. Discussion

We sought to understand the potential of teleoperator-robot-human collaboration (tRHC) in industrial settings, by capturing the perspectives of diverse industry stakeholders. From interviews with these stakeholders, we identified three categories – Benefits, Concerns, and Technical Challenges – comprising 13 themes (Figure 1). The presence of human workers at both "ends" of tRHC appears to be a source of both benefits (e.g., flexibility, safety, and trust) and concerns (e.g., safety, trust, and workplace optimization). In addition, the presence of human worker was emphasized as posing technical challenges, particularly with respect to communication. In terms of application areas, interviewees generally noted the potential benefits of tRHC in the healthcare and manufacturing sectors and specifically identified maintenance and highly skilled tasks as areas in which tRHC could offer benefits. We subsequently discuss the potential benefits, challenges, and future research directions in more detail.

4.1. Potential benefits of tRHC

The ability of a teleoperator to make critical decisions appears to contribute to flexibility, safety, and trust in tRHC, since the teleoperator can freely control a teleoperated robot as needed and prioritize safety measures, thereby establishing a sense of trust among all involved. The teleoperator's capability to freely control the robot is particularly important in practice, as it can potentially facilitates a high level of tRHC, allowing for flexible or non-routine collaborations.

While cobots are known for their flexibility, their use is often limited to simple and repetitive tasks due to challenges (Ahmad & Bilberg, 2019; Michaelis et al., 2020; Müller-Abdelrazeq et al., 2019) in (re)programming them for new tasks and environments, and the traditional engineering perspective focusing on such tasks. With tRHC, teleoperators can use their expertise, adaptability, and decision-making abilities to guide and control teleoperated robots, enabling more complex and dynamic HRC with onsite workers and promoting trust in these interactions.

Our participants suggested that tRHC could enhance workplace accessibility for individuals with disabilities and older individuals. Teleoperated robots have been explored as a means to extend the capabilities of such individuals, allowing them to participate in activities that might otherwise be inaccessible (Balaguer et al., 2006; Mitzner et al., 2017; Zhang & Hansen, 2022). An example workshop study conducted with mobility-impaired users indicated that such users desire control options across the automation spectrum and the ability of the robot to autonomously perform tasks beyond their capabilities (Arboleda et al., 2020). The presence and proximity of onsite workers in tRHC could help address challenges that teleoperators with disabilities might not have the physical or cognitive capabilities to resolve effectively, such as detecting and resolving problematic situations that arise from the robot.

From the interviewees' perspective, tRHC holds potential benefits for tasks requiring both knowledge and manual skills, particularly sectors such as construction, manufacturing, and healthcare, including maintenance and highly skilled tasks (Table 2). However, the interviewees were not able to provide specific implementation scenarios for tRHC, which perhaps indicates some uncertainty regarding its practical application and capabilities. They also noted that teleoperated robots will do physically demanding and/or dangerous tasks instead of onsite workers, reflecting the conventional view of industrial robot use scenarios. Overall, the study highlights the promising potential of tRHC in various industrial settings, but also underscores the importance of addressing technical and implementation challenges to realize its benefits fully.

4.2. Challenges in tRHC implementation

Human perception and safety seem to be fundamental factors contributing to technical challenges in tRHC. Teleoperator face inherent challenges in perceiving the remote environment due to the physical distance between them and the robot. These challenges can limit sensory modalities (Almeida et al., 2020; Hirche & Buss, 2012), such as force perception, vision, hearing, haptics, and spatial awareness. However, recent evidence suggests that AR/VR platforms can help address such perceptual challenges (Bejczy et al., 2020; Jankowski & Grabowski, 2015; Theofilis et al., 2016; Vaz et al., 2022), offering an immersive experience that enhances the teleoperator's perception and understanding of the remote workspace. Integrating AR/VR platforms with sensors and feedback mechanisms can provide a realistic and interactive environment, improving task performance and the teleoperator's sense of presence in the remote workspace.

Using head-mounted or head-worn displays for AR/VR platforms, however, can lead to adverse physiological symptoms such as nausea, dizziness, disorientation, fatigue, and/or postural instability (Hughes et al., 2020; Palmisano et al., 2017; Sharples et al., 2008; Vovk et al., 2018), though the severity of these symptoms is lower and less common with AR exposure. Regardless, symptom severity can be exacerbated by the time delay inherent in teleoperation (Yang & Dorneich, 2017). VR-induced symptoms can also temporarily decrease cognitive performance, affecting decision making and hand-eye coordination (Champney et al., 2007; Nalivaiko et al., 2015; Szpak et al., 2019). However, there is limited information on the long-term effects of prolonged or frequent use of immersive virtual interfaces on the well-being and health of workers.

Worker safety and trust were important concerns in tRHC highlighted by the interviewees, particularly related to the possibility of collisions between the teleoperated robot and onsite workers. These concerns align with existing reports, which consistently highlight safety and trust as a major challenge in cobot systems (Chemweno et al., 2020; Robla-Gómez et al., 2017; Villani et al., 2018). There are four normative methods to ensure safe HRC, as described in ISO 10218:2011 and ISO/TS 15066:2016 – safety-rated monitored stop; speed and separation monitoring; hand guiding; and power and force limiting. However, implementing these and other safety measures – while concurrently meeting efficiency, flexibility and productivity requirements – can be challenging in practice (Guiochet et al., 2017; Hanna et al., 2022). Several approaches have been proposed to address this, including a framework based on ISO 31000 to design safeguards for collaborative robots (Chemweno et al., 2020) and a flexible approach to implement safety measures based on the specific needs and intentions of both humans and robots in the system (Hanna et al., 2022).

In tRHC scenarios, various types of interactions may occur, including human-human and human-robot interactions, as well as joint teleoperated robot manipulations. These interactions present distinct safety and trust challenges related to multi-agent goal negotiation and the physical and cognitive coordination among the closely integrated human-robot team members. The complexity of tRHC highlights the need for further advances in safety and trust concerning human-robot interaction (HRI) in tRHC scenarios.

4.3. Future research directions

Our stakeholder interviews revealed several potential benefits and challenges of HRC between the teleoperated robot and the onsite workers. Some of the benefits include the application of tRHC to tasks requiring both expertise and manual dexterity, as well as expanding job accessibility for individuals with disabilities. On the other hand, challenges encompass aspects regarding human perception, along with safety and trust. To fully realize the potential benefits and address the associated challenges of tRHC, we propose several future research directions, with a focus on human factors and ergonomics.

- *Develop case studies to explore the potential of tRHC in realistic industrial scenarios with diverse stakeholders (e.g., human operators, production and safety engineers from different industries and companies of varying sizes)*. Although the interviewees suggested some tasks and industries that may benefit from tRHC, their suggestions were rather general. This lack of specificity might be because they considered potential implementation of tRHC within existing work environments that are optimized for current work systems. Developing specific case studies will provide actionable insights into specific tasks, processes, or industries where tRHC can have the greatest impacts. This will also help in developing metrics to assess the quality of interactions among tRHC agents (Panagou et al., 2023).
- *Improve our understanding of the long-term effects of using virtual teleoperation interfaces on teleoperator well-being and safety.* While such interfaces have been developed to support several goals, such as remote perception (Bejczy et al., 2020; Pacchierotti et al., 2014; Theofilis et al., 2016), remote highly dexterous manipulation (Graham et al., 2011; Tunstel et al., 2013), and effective control with varying time delays (Kebria et al., 2020; Polushin et al., 2007; Várkonyi et al., 2014), there is still a lack of research on the potential long-term implications using immersive virtual interfaces. Note that while less immersive virtual teleoperation interfaces such as desktop- or mobile-

based VR may have lesser VR-related adverse effects, there is still a lack of research on the long-term impact of frequent or prolonged use of such interfaces on the user.

- *Enable functional exchanges of information across distributed agents involved in tRHC to improve safety and trust.* Functional exchanges can include communication exchanges, cross-checks, and automation mode acknowledgement, which support developing and maintaining situational awareness. Adriaensen and colleagues (2022; 2022) discussed the need for a socio-technical perspective on cobot safety to facilitate more complex cobot applications, which emphasizes the need for a broader understanding of safety issues beyond hardware-related safeguards and generic collision-avoidance strategies. These authors adopted the principle of distributed cognition or distributed situational awareness (Salmon et al., 2018), as well as a joint cognitive system perspective (Hollnagel & Woods, 2005), such that the focus is on the functional exchanges and interactions of task-relevant information between multiple agents, rather than treating them as separate entities. In this regard, it becomes important to investigate effective mechanisms and strategies for facilitating communication and functional exchanges across the agents.
- *Facilitate an adaptable autonomy level of a teleoperated robot to promote safety, trust, and better performance in tRHC*. Earlier studies on cobots have highlighted the importance of adaptation – the cobot's ability to intelligently adapt its level of autonomy – especially in dynamic environments and diverse task scenarios, to foster human trust in robot and improve human-robot performance (El Zaatari et al., 2019; Selvaggio et al., 2021). Such adaptation is often referred to as shared autonomy (Selvaggio et al., 2021), which requires inferring user goals and the evolving states of a task and a remote work environment. Though current teleoperation research focuses mainly on sensing the teleoperator's intentions (Luo, Lin, et al., 2020; Tanwani & Calinon, 2017) and modeling the remote environment for the teleoperator (Chen et al., 2020; Milgram & Ballantyne, 1997), effective tRHC will require a teleoperated robot to have comprehensive context awareness or higher cognitive abilities – inferring the goals of both the teleoperator and onsite workers, while understanding the task

and remote environment. Further, as suggested by Panagou et al. (2023), there is a need to assess the robot's intention-sharing capabilities on human worker's psychosocial states, safety, and comfort, to support effective human-robot system implementation in the workplace.

- *Develop guidelines to promote privacy-preserving tRHC technology and the implementation of such technology in the workplace.* Though interviewees did not raise concerns regarding ethics and privacy with tRHC, it is important to consider the implication of the implementation of such technology. The nature of tRHC enabling technologies (e.g., motion, biometric, and vision sensors) can allow for extensive monitoring or surveillance of workers to ensure a safe and optimal collaboration, yet this level of monitoring also can introduce ethical questions including privacy protection (Bhave et al., 2020) and a shift from human to algorithmic decision making (Mittelstadt et al., 2016). There are several laws and regulations on data protection and privacy, such as the European Union's General Data Protection Regulation (GDPR) and the U.S. Electronic Communications Privacy Act (ECPA). However, privacy at work is still an important concern for employees and employers (Bhave et al., 2020). Future attention should be made to guide and promote privacy-by-design approaches, so that developers and organizations can proactively incorporate privacy considerations into their design and implementation of tRHC systems.

In summary, through stakeholder interviews we identified three key areas regarding tRHC dynamics that consisted of 15 themes. The dual presence of human workers in tRHC emerges as providing both advantages and difficulties, offering flexibility, safety, and trust, while also raising concerns and technical challenges, particularly in communication. While tRHC shows promise in healthcare and manufacturing, its practical application needs more exploration, especially in replacing demanding or hazardous tasks. Addressing technical issues is critical, such as teleoperation perception and ensuring safety. *It is important to acknowledge that these findings are based on a relatively small sample size, potentially limiting their generalizability. Caution should thus be used when extending these findings to broader contexts.* Future research directions include case studies in industrial settings, understanding long-term effects of virtual interfaces, enhancing distributed agent coordination, and focusing on privacy and ethics in tRHC deployment.

As we enter the era of the next industrial revolution, referred to as Industry 5.0, which prioritizes the well-being of workers and envisions symbiotic human-robot collaboration (Leng et al., 2022), tRHC can play an important role. Realizing the full potential of tRHC, though, will require substantial advancements in teleoperation interfaces, robot cognitive abilities, communication capabilities, and socio-technical perspectives on safety and trust. However, the evolving nature of HRC presents its own set of uncertainties, making it challenging to predict both future technological advancements and how these advancements will redefine collaborative processes and roles. As robotics and artificial intelligence technologies continue to advance, teleoperation may act as a transitional phase on the path toward fully autonomous robots, offering unique benefits in facilitating seamless and safe interactions between multiple distributed agents. Such benefits could help in creating more inclusive and efficient workplaces, transforming work processes and resource allocation, while removing constraints imposed by workers' physical capabilities or geographical limitations.

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