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"You Can Go Your Own Way, but Keep Me Informed": Taking Charge of Own Safety when Collaborating with a Robot in a Shared Space

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Abstract. Collaborative robots, designed to work alongside humans in industrial manufacturing, are becoming increasingly prevalent. These robots typically monitor their distance from workers and slow down or stop when safety thresholds are breached. However, this results in reduced task execution performance and safety-related uncertainty for the worker. To address these issues, we propose an alternative safety strategy, where the worker is responsible for their own safety, and the robot executes its task without modifying its speed except in case of imminent contact with the worker. The robot provides precise situation-awareness information to the worker using a mixed-reality display, presenting information about relative distance and movement intentions. The worker is then responsible for placing themselves with respect to the robot. A pilot user study was conducted to evaluate the efficiency of task execution, worker safety, and user experience. Preliminary results may indicate a superior user experience while maintaining worker safety.

Keywords. fenceless industrial robots, hazard warning, human-robot interaction, safety, robot autonomy, human autonomy, autonomy distribution.

1. Current Approach to Safety in Human-Robot Collaboration

Collaborative robots (aka cobots) in industry allow humans and robots to work safely in a shared space [1, 2]. The main requirement for a Human-Robot Collaboration (HRC) scenario is the safety of the human partner [3], and thus cobots are designed and built to be intrinsically safe. In designing procedures that can further improve safety in HRC scenarios, the robot is typically granted a high level of autonomy to decide how best behave safely. However, as research suggests [4], making the robot accountable for safety may affect negatively how the operator perceives safety and efficiency of collaboration with the robot.

The increase in the use of safe cobots in industry has made it necessary to remove residual hazards due to moving robot parts near the human worker. Furthermore, improving perception of safety through good situation awareness has become a priority in HRC contexts, so as to reduce user anxiety about working with robots in shared spaces.

With these goals in mind, reactive and proactive strategies are typically used:

- **Reactive strategies:** they aim at minimizing the consequences of accidental physical contact between robot and human operator. Examples include: Novel actuators and mechanisms [5]; Counterbalancing mechanisms [6].
- **Proactive strategies**: they aim at preventing collisions by developing sensor-based safety systems for the real-time monitoring. For example: definition of safety zones and speed strategies in each zone [7]; detection and tracking of 3D volumes and recalculation of the paths and speed strategies [8].

While more effective than reactive strategies, one of the main drawbacks of proactive robot behaviour techniques lies in robots slowing down or even stopping altogether in the presence of a person. This behaviour results in reduced productivity, which is undesirable. Sometimes the worker may actively try to stay far enough from the robot, not to remain safe, but to prevent triggering its slow-down safety mechanism that will affect negatively productivity. Thus, the worker may end up counteracting the safety assurance behaviour of the robot, in favour of task execution performance. Besides productivity, and even when these techniques have shown to be sufficiently safe [9], users may continue to perceive that they are still in risk when entering the area of influence of a robot. Users may have the notion that a potential danger may still exist while near a cobot, due to e.g., the possible the malfunction of a safety mechanisms. Users may also mistrust the robot's judgements under certain circumstances, such as when the robot is holding sharp tools or objects. The operator is asked to trust, but is not certain about the actions that the robot will actually take in the immediate future. This uncertainty can take a toll on the overall trust on the robot that the operator can develop [10]. For this reason, the worker is reluctant to relinquish all safety related decision-making autonomy on the robot, and both robot and worker end up keeping an eye on each other, partly spoiling the purpose of the proactive strategy to free the worker's mind with regard to safety. This can sometimes feel overwhelming and annoying to users because they feel a lack of control [11, 12]. In the long term, sustained stress caused by working in a state of permanent uncertainty due to poor situation awareness can damage health [13]. Improving situation awareness is hence necessary for workers' well-being and safety, as well as to obtain a good user experience (UX) from collaborating with robots [14].

AR has potential to reduce anxiety in HRC by presenting contextual information through a visual channel [15], and for example, projection-based AR has also shown to improve UX [16]. Vogel et al. developed a projection-based sensor system to monitor the robot's configuration and projected safety boundaries on the work surface [17]. However, the robot's behaviour of stopping when the worker crosses the safety boundary can lead to low efficiency and annoyance. In addition, utilizing 2D AR interfaces requires the user to shift their visual attention between the displayed information and physical scene. Furthermore, in many collaborative tasks, improved situation awareness is also needed when the task requires that the worker looks away from the robot during collaboration. XR technologies like Head-Mounted Display (HMD) devices may offer better ways to present multimodal information about the robot's position, even when it is outside the natural field of view of human vision.

Lee and See [18] state that good situation awareness requires transparency of information and trust by the operator, which can be achieved through purpose (goal), process (path to be followed), and performance (trajectory being executed).

In summary, with currently used safety mechanisms, the robot is primarily responsible for the safety of the human worker in HRC scenarios. Figure 1 shows that the robot has a high degree of autonomy for decision making related to safety, while the human worker is expected to trust that the robot will react promptly to prevent safety related incidents. Although interruptions in the collaboration due to the activation of safety mechanisms confirm that they do work to preserve safety, they can also affect the worker's UX and productivity negatively. In contrast, we propose that granting the robot freedom of movement to execute a collaborative task may be preferable, as long as the robot provides full situation awareness information for the human operator to administer.

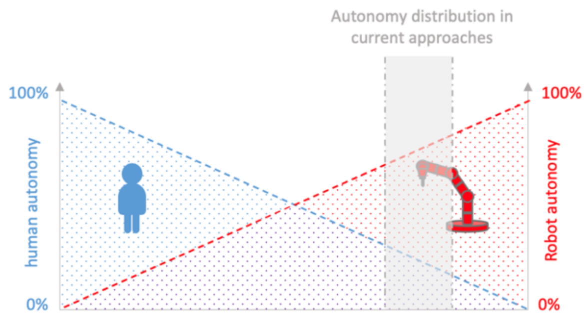

Figure 1: Decision autonomy for the mechanisms that will be implemented to keep the human worker safe in a collaborative task with a robot. In the current paradigm, most of the accountability for the operator's safety is delegated to the robot.

2. Proposed Alternative Approach to Safety in Human-Robot Collaboration

Based on the discussion above, we propose that, if the operator receives good situation awareness information from the robot, it may be a better strategy to grant to the operator most of the autonomy on safety decisions. Moreover, we hypothesize that letting the robot move freely to execute the task (while always keeping the operator well informed about position and intentions), may help improve task execution performance. Since the operator will have better control of the events, this may help the operator obtain a better sense of safety and a superior overall experience of a fluent and efficient collaboration. This proposed approach is represented in Figure 2.

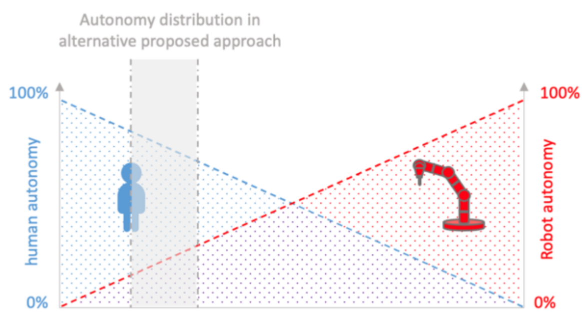

Figure 2: Decision autonomy for the mechanisms that are implemented to keep the human worker safe in a collaborative task with a robot. In the proposed new paradigm, most of the accountability for the operator's safety is on the (well informed) worker.

This alternative safety approach involves the robot monitoring distance to the operator and stopping movement if contact is imminent, but not modifying its course otherwise. In Figure 3, hypotheses are presented on how this approach could affect UX components such as actual safety, joint task performance, operator uncertainty, and sense of control. A comparison is made between the current safety paradigm (robot responsible for preventing collision) and the proposed paradigm (operator responsible for staying safe with situation awareness from robot). If confirmed, the proposed paradigm is expected to improve UX by reducing uncertainty and increasing sense of control, while maintaining comparable levels of safety and performance.

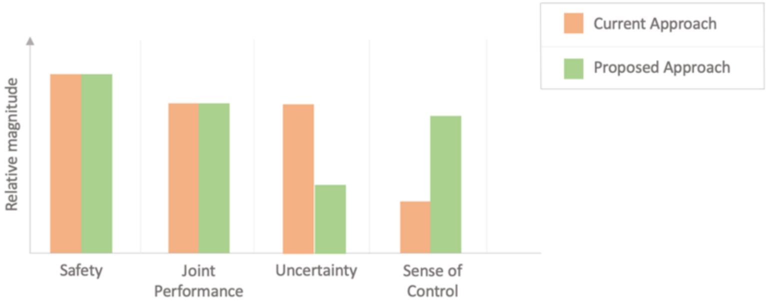

Figure 3: Key components of UX in shared workspace HRC scenarios: hypothesized relative magnitudes between current and proposed safety paradigms.

3. Early Results

We conducted a pilot study with 8 participants (4 with experience in AR and 4 with no experience) to analyse our new approach. To perform this pilot study, we designed a task to be executed collaboratively with a robot and during which we could analyse the safety perceived by participants and aspects of the UX they obtained. The task involved a user placing A4 sized paper document on specific locations of a tabletop, which were then inspected by the robot. Each participant in the study performed the task three times.

The tabletop and part of its surroundings were the workspace shared between the robot and the participant. Each time the robot needed a new document, it asked the user to bring it, which forced both agents to move inside the shared space. The participant was responsible to negotiate their relative position with respect to the robot while in the shared workspace. The participant was assisted on this by the situation awareness information that the robot provided. For that, we adapted the audio-visual display design described in San Martin *et al.* [19] for a HRC scenario (see Figure 4). The display created three nested zones of potential hazard around the robot, which were represented visually and auditorily. The robot only stopped if the participant entered its innermost red zone, which we took to mean that an imminent collision with the robot could occur.

Figure 4: Design for situation awareness and set-up for HRC task.

To assess safety, we analysed the number of times participants entered the red zone, and for how long. For UX assessment, we analysed participant feedback from post-study semi-structured interviews.

Of the 8 participants, 6 did not enter at all the red zone in any repetition of the task. For the other two participants, each entered once the red zone, in one of the task repetitions. The time spent in the red zone on those two cases was 0.4s and 1.1s.

Regarding the interviews, participants' comments described the level of safety that they perceived while collaborating with the robot during task execution: *"I feel safe"* (P1), *"You have a good safety feedback all time"* (P1), *"Good safety feedback*" (P2), *"I felt very safe*" (P7). In their responses and comments, participants shared insights into the main strengths of the situation awareness display: *"It provides complete information around danger state"* (P4), *"You cannot ignore the danger"* (P5), *"It helps to react fast to the danger"* (P6). Similarly, participants also shared hints about what aspects of the displays appeared to them to be weaker: *"It gives too much information"* (P8), *"Too much information"* (P4).

4. Discussion and Future Work

The results of the pilot study suggest that the new HRC safety paradigm leads to a safe collaborative context that delivers a positive UX. When the human user in the HRC scenario bears the full responsibility for maintaining a safe distance with the cobot, the results obtained from the user pilot study suggest that both actual and perceived safety may remain high for the user. During the study, in almost every case, participants never positioned themselves next to the cobot. In the very few instances that they did so (2 out of 24 trials), they left that position after a maximum of 1 second (in both cases, the robot had stopped itself to avoid any possible contact with a moving part).

The pilot study also produced encouraging results regarding the UX that might be obtained from this new safety paradigm. Participants reported feeling safe, which is a deciding factor for a good UX in HRC. According to their descriptions, the situation awareness information received from the multimodal mixed reality display was comprehensive, easily noticeable, and helpful to understand and monitor the moving area of influence of the robot, and how to avoid it. The only aspect for improvement in the information display was that, for some, there might have been an excess of information. This might be negative for UX over a longer period of use.

Future steps in this line of research should investigate how to optimise the amount of information conveyed without compromising the awareness. This might be achieved by considering single modality displays (auditory or visual) in addition to the combined audio-visual used in the present pilot study. In addition, future work should include user studies with larger cohorts of participants, in which with different information display designs are analysed and clearer results can be obtained that lead to design recommendations.

We conclude that this alternative new paradigm should be considered as a subject of research, for its potential to provide a superior UX without compromising safety.

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