Toward Safe and Efficient HRI in Industrial Settings via Distance-Based Speed Limiting and Motion-Level Adaptation

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Abstract— **Deploying robots for human-robot interaction (HRI) in industrial settings requires specific considerations for guaranteeing the safety of collaborating humans. In this work, we present a real-time safety system capable of allowing safe HRI with a standard industrial robot at very low distances of separation without the need for robot hardware modification or replacement. In the industrial setting, it is also imperative for the interaction to be efficient and not be stressful or uncomfortable. Toward this goal, we present work on analyzing how utilizing motion-level robot adaptation affects HRI in a manufacturing task. The results indicate that motion-level adaptation results in improved team fluency, higher satisfaction, and increased perceived safety and comfort.**

I. Introduction

Within the industrial domain today, robots are deployed almost exclusively in isolation from humans, with physical barriers often separating the two to ensure no physical harm can be inflicted. While the physical separation of people and robots can be an effective strategy for guaranteeing human safety, a lack of human-robot integration prevents robots from being utilized in domains that stand to benefit from robotic assistance. The final assembly of aircraft and automobiles, for example, is still mostly a manual operation, involving minimal use of automation (SME Input, Boeing Company; SME Input, BMW). In order to allow for robots to assist humans in these types of tasks, it is necessary to develop effective and robust methods of providing safety in close-proximity human-robot interaction. This involves ensuring that neither physical harm, inflicted through unintentional contact with the robot, nor psychological harm, caused by prolonged exposure to stressful or uncomfortable interaction, takes place.

Close-proximity interaction between humans and robots, especially in industrial settings, is still a fairly new and developing interaction paradigm, and, as such, formal definitions of safety within this context are still under development. Toward the goal of establishing these definitions, the International Organization for Standardization (ISO) developed the ISO 10218 international standard [1] and is currently working on the technical specification (ISO TS 15066), which provides information and guidance on how to achieve the safety standards described in ISO 10218 specifically for collaborative robots [2]. The National Institute of Standards and Technology (NIST) has provided guidance on the two main areas of focus of the ISO TS 15066, speed and separation monitoring and power and force limiting, and is developing performance measures to test how well a robot conforms to the required standards [3].

In this work, we describe two steps taken toward developing methods that allow for safe and efficient HRI in an industrial setting. First, we discuss a low-latency, real-time safety system capable of turning a standard industrial robot into a human-safe platform without the need for specialized actuators or any other modification of the robot's hardware. Next, we describe a set of experiments designed to investigate how motion-level robot adaptation affects HRI with an industrial robot, showing that it can lead to both higher efficiency as well as improved psychological safety through higher comfort and perceived safety.

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II. Safety System for Standard Industrial Robots

As the idea of introducing HRI in industrial settings has quickly gained interest and popularity, robot manufacturers have been working on developing inherently human-safe robots. Examples of such robots include the YuMi by ABB, the Baxter and Sawyer by Rethink Robotics, and the LWR by Kuka. Purchasing new robots or retrofitting standard industrial robots with new hardware components that allow them to be inherently human-safe, however, can be cost-prohibitive or physically impossible. With an estimated 1.2 to 1.5 million industrial robots already in use worldwide [4], there is great incentive to design a solution that can turn these robots into human-safe platforms without the need for hardware modification.

Toward this goal, we developed a safety system for standard industrial robots that allows for safe close-proximity HRI without the need for physical barriers or defining large, coarse safety zones that cause the robot to stop when entered by a human worker [5]. Our system is based on accurate, real-time measurement of the separation distance between the human and any part of the robot. In our implementation, we utilize a standard ABB IRB-120 industrial robot and a PhaseSpace motion capture system along with a multi-threaded software implementation. Based on data from the robot's encoders and the motion capture system, the software generates a virtual representation of the shared workspace containing the human and robot that is updated in real time. This virtual representation is then utilized to calculate the separation distance, which is used to modulate the robot's speed such that it can gradually come to a stop as it approaches a person.

There are several key benefits to the chosen implementation method. By leveraging accurate sources of information on the position of the human and robot, the safety system supports safe interaction at very low distances of separation. By basing the speed reduction behavior of the robot on the separation distance, we do not have to define large zones of the workspace that cause the robot to stop. Furthermore, the function of separation distance used to slow down the robot can be tuned such that the slow-down behavior of the robot is perceived as comfortable and safe, which can vary based on the task or what tool the robot is holding. Critical to allowing for safe close-proximity HRI, the system has a very low latency due to the multi-threaded implementation and several key optimizations (see [5] for details). We demonstrate our system achieves latencies below 9.64 ms with 95% probability, 11.10 ms with 99% probability, and 14.08 ms with 99.99% probability, allowing for robust real-time performance.

III. Improving Safety and Efficiency through Motion-Level Adaptation

While the safety system described in the previous section serves as an effective method of preventing unwanted collisions, this type of implementation alone often would not lead to efficient or comfortable interaction. This is especially true in tasks that have a high potential for motion conflict, as the robot would need to slow and stop near the human often.

One method of alleviating this negative effect is by augmenting the safety system with human-aware motion planning. This type of motion planning attempts to predict future human workspace occupancy and then utilizes these predictions to plan robot paths that avoid the predicted regions to eliminate motion conflicts before they occur. We investigated how this type of augmentation affects team fluency, human satisfaction, and perceived safety and comfort through human-subject experiments [6].

In the experiments, participants (N=20) worked on a simple collaborative task of placing eight screws at designated locations on a table, while the robot simulated the application of a sealant to each screw. The screws were placed by the participants in a predefined order to allow us to focus on measuring the effects of the motion adaptation independent of the accuracy of action prediction. Participants worked with an adaptive robot incorporating human-aware motion planning, and with a baseline robot using shortest-path motions. In both cases, the safety system described in the previous section was deployed.

Team fluency was evaluated through a set of quantitative metrics, while human satisfaction and perceived safety and comfort were evaluated through questionnaires. In terms of team fluency metrics, when working with the adaptive robot, participants completed the task 5.57% faster, with 19.9% more concurrent motion, 2.96% less human idle time, 17.3% less robot idle time, and a 15.1% greater separation distance. Questionnaire responses indicated that participants felt safer and more comfortable when working with an adaptive robot. The participants, for example, agreed more strongly with the phrases "I felt safe when working with the robot," and "I trusted the robot would not harm me" when describing the human-aware robot and "The robot came too close to me for my comfort" when describing the robot that did not use motion-level adaptation.

Through the results of this experiment we were able to show that people learn to take advantage of human-aware motion planning when performing novel tasks, even with very limited training and no direct indication that the robot is adaptive. That human-aware motion planning leads to a higher degree of perceived safety – and thus reduced potential for stress-related health problems – while simultaneously improving team fluency is a very important result, as it makes human-aware motion planning a highly desirable tool for close-proximity human-robot interaction in industrial settings. This result also indicates that simply preventing collision from occurring is not sufficient for maintaining a perception of safety, showing the benefit of augmenting the safety system with motion-level adaptation.

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