Increasing the Adoption of Autonomous Robotic Teammates in Collaborative Manufacturing

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ABSTRACT
Advancements in robotic technology are opening up the opportunity to integrate robot workers into the labor force to increase productivity and efficiency. However, removing control from human-workers for the sake of efficiency may create resistance from the human workers, preventing this technology from being successfully integrated into the workplace. We describe our ongoing work developing an autonomous robotic teammate to work alongside human workers in a collaborative manufacturing environment. Specifically, we want to understand how to maximize team efficiency and human-worker acceptance of their robotic teammates by utilizing carefully designed human-subject experiments.

1. INTRODUCTION
In manufacturing, there is an increasing desire to integrate robots into the workforce to leverage the unique strengths of both humans and robots. To support safe and efficient human-robot co-work, this integration requires the tight choreography of human and robotic work that meets upperbound and lowerbound temporal deadlines on task completion (e.g., assigned work must be completed within one shift) and spatial restrictions on agent proximity (e.g. robots must maintain a four meter separation from human workers).

Developing human-machine systems that are able to leverage the strengths of both humans and their artificial counterparts has been the focus of much attention from both human factors engineers and researchers in artificial intelligence [3, 5, 9]. The human-robot interface has long been identified as a major bottleneck in utilizing these robotic systems to their full potential [2]. As a result, we have seen significant research efforts aimed at easing the use of these systems in the field, including careful design and validation of supervisory and control interfaces [1, 6, 8] and utilizing a human in-the-loop to improve the quality of task plans and schedules [3, 4]. In this work, we are motivated by manufacturing applications where human workers will be performing physical tasks in coordination with robotic partners.

*This work was supported by Boeing Research and Technology and by the National Science Foundation (NSF) Graduate Research Fellowship Program (GRFP) under grant number 2388357.

In prior work, we present an algorithm that enables robots to coordinate their activities in time and space for peer-to-peer collaboration with human co-workers. This algorithm gives robotic teammates the ability to adapt to disturbances in the build process (e.g., task parameters change) as well as human-induced disturbances (e.g., a human worker is proceeding faster or slower than expected). Our method handles fast re-planning of factory-sized problems in seconds, which is an order of magnitude faster than comparable work [5]. While this advancement in robot planning and scheduling is necessary to facilitate real-time, peer-to-peer human-robot collaboration, the mechanisms for coordination must be valued and appreciated by the human workers.

Human workers often find identity and security in their roles or jobs in the factory and are used to some autonomy in decision-making. A human worker that is tasked by an automated scheduling algorithm may feel devalued. Even if the algorithm increases process efficiency at first, taking control away from the human workers may alienate them and, in turn, ultimately damage overall productivity.

We hypothesize that there is a trade-off between human-robot team efficiency and the degree to which humans value working with their robotic counterparts as a function of how much control the human workers have over their own roles. In this paper, we report the results of an initial pilot study investigating control schemes for peer-to-peer human-robot work (Section 2) and we discuss design improvements for a future, full-scale experiment studying these trade-offs (Section 3). In future work, we will report the results of this full-scale experiment discussed in Section 3.

2. PRIOR INVESTIGATION
We conducted a pilot study as a first step in understanding the tradeoff between team efficiency and human-worker acceptance of robotic teammates that can autonomously schedule the team's work. In our study, the team's goal was to complete two Lego kits, each consisting of several steps. The two basic task types were *fetching* parts for the next step or *building* the next step. The team consists of two mobile manipulator robots and the human subject.

In manufacturing domains, the initial scheduling is performed offline, well in advance of the actual work. The challenge for researchers is performing dynamic re-computation of these plans in response to disturbances during runtime. Currently, this re-computation is performed by a human supervisor and the process can be costly to the manufacturer. Accordingly, we have the participant and robotic teammates begin under a nominal schedule. To create a need for an agent to re-allocate the work, we remove one of the robots during the build process in a simulated failure.

There are two options to reschedule the work. First, the human subject and remaining robot could fetch parts for and build their own Lego kits. Second, the robot fetches parts for the human, and the human finishes building both kits. If the participant is assigned to the *autonomous condition*, the remaining robot determines how to re-schedule the work. In the *manual condition*, the human subject chooses.

In our study ($n = 8$), we measured the time to complete the task objective and used subjective measures (5-point Liker scale prompts) of subjects' experiences. The time to complete the task object was higher ($p < 0.001$) in the manual condition (598.8 ± 47.5 seconds) than the autonomous condition (436 ± 19.1 seconds). When subjects were asked if "the robots were necessary to the successful completion of the tasks", subjects' responses in the autonomous condition were mixed, but every subject in the manual condition responded "strongly disagree" ($p < 0.01$). We consider these results as interesting points for further investigation.

3. FOLLOW-ON EXPERIMENT

We are preparing a full-scale, human-subject experiment to understand how to best design an autonomous robot to maximize both efficiency and the satisfaction the human teammates receive from working with their robotic counterparts. In our follow-on experiment, the team consists of two humans (the subject and a human teammate) as well as a robot teammate. The team will again build Lego kits, but we modify the experimental design to improve external and internal validity.

As before, we have both a manual and autonomous experimental condition. The manual condition requires the subject to task the human and robot teammates. For the autonomous condition, the robot will task both human workers. We now include a semi-autonomous condition to test whether there is a "sweet spot" between these two extremes that may achieve the best of efficiency and worker satisfaction. In this condition, the subject determines which tasks he or she will perform, and the robot determines how to optimally task the work of the human teammate and itself.

In manufacturing, there are significant cognitive demands required to coordinate a human-robot team. First, the teams are highly heterogeneous; humans work at different speeds, and not all team members are capable of performing the same tasks. In our case, we restrict the robot to fetching parts; further, the subject and the human teammate do not fetch or build at the same speeds. Secondly, fetching a parts kit requires that the worker inspect the kit's contents for all appropriate parts. These demands require the subject to carefully consider how to coordinate the work to elicit an efficient interleaving of the tasks and avoid agent idle time. In practice, humans would improve at efficiently tasking the team with practice. As such, we will train subjects through multiple trial runs before the final evaluation.

Lastly, Our revised post-test questionnaire includes a full suite of questions based on metrics proposed and evaluated by Hoffman [7] for human-robot teamwork.

4. CONCLUSION

The successful integration of advanced robotic technology requires algorithms that not only can efficiently coordinate human-robot teams but that also garners the support of the human workers. While researchers have considered humans in the loop to generate effective schedules, we believe it is important to understand the experience of humans working alongside robots in collaborative manufacturing tasks. We completed an initial study and are planning a follow-on experiment to understand how much control human workers should have over their robotic counterparts to maximize efficiency and the satisfaction of the human worker. Advanced robotic technology can improve productivity in manufacturing, and we aim to inform the design and implementation of this technology to realize its benefits.

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