Collaborative or Simply Uncaged? Understanding Human-Cobot Interactions in Automation

Joseph E Michaelis,[1] **Amanda Siebert-Evenstone,**[2] **David Williamson Shaffer,**[2] **Bilge Mutlu**[2]
(1) University of Illinois at Chicago, Chicago, IL
(2) University of Wisconsin–Madison, Madison, WI
jmich@uic.edu, alevenstone@wisc.edu, dws@education.wisc.edu, bilge@cs.wisc.edu

ABSTRACT

Collaborative robots, or *cobots*, represent a breakthrough technology designed for high-level (*e.g.,* collaborative) interactions between workers and robots with capabilities for flexible deployment in industries such as manufacturing. Understanding how workers and companies use and integrate cobots is important to inform the future design of cobot systems and educational technologies that facilitate effective worker-cobot interaction. Yet, little is known about typical training for collaboration and the application of cobots in manufacturing. To close this gap, we interviewed nine experts in manufacturing about their experience with cobots. Our thematic analysis revealed that, contrary to the envisioned use, experts described most cobot applications as only low-level (*e.g.,* pressing start/stop buttons) interactions with little flexible deployment, and experts felt traditional robotics skills were needed for collaborative and flexible interaction with cobots. We conclude with design recommendations for improved future robots, including programming and interface designs, and educational technologies to support collaborative use.

Author Keywords

Human-robot interaction (HRI); human-robot collaboration; collaborative robots; end-user programming; educational technology; technology adoption

CCS Concepts

•**Human-centered computing** → **Empirical studies in HCI;**
•**Computer systems organization** → **Robotics;**

INTRODUCTION

Employers in modern manufacturing need workers, including those that interact with and operate manufacturing equipment, with advanced skills to meet the demands of the evolving workplace [25]. However, there is a shortage of workers equipped with these skills, giving rise to a "skills gap," that has become an increasingly critical concern in manufacturing [34]. Most

CHI '20, April 25–30, 2020, Honolulu, HI, USA.

ACM ISBN 978-1-4503-6708-0/20/04 ...$15.00.
DOI: https://doi.org/10.1145/3313831.3376547

Figure 1. An automation technology engineer demonstrates programming a cobot task using a "teach pendant" with a UR cobot.

approaches to closing the skills gap involve improving training for technology literacy and skills [3, 25]. However, we argue that a second approach, lowering the bar for entry to the technology workforce (*i.e.,* making the technology easier for novices to use and learn), can allow workers better access to higher-skill jobs. New approaches to technology design, of the core automation technology and of training technologies, can both support these needed increases in technology skills and lower the barriers to entry. This context provides HCI and design researchers with the opportunity to contribute to addressing the skills gap through the design of workplace technologies that ease worker interaction, and through new training methods, including educational technologies.

Collaborative robots, or *cobots*, (see Figure 1 for an example), are designed for safe operation around and in collaboration with human workers. Cobots may be a technological solution to reduce the skills gap by lowering the bar for entry in that they offer a greater role for human workers in programming and interacting with new these new technologies. There is a growing number of applications for human-robot collaboration (HRC) in the workplace, including in hospitals, warehouses, welding, construction, assembly, and recycling [1, 24, 32, 29, 38]. These HRC interactions are a key element in the modern wave of industrial development, often referred to as *Industry 4.0*, where flexibility and customization are emphasized [21]. Cobots are designed to be easily programmed and operate safely with and around humans, allowing them to provide flexible solutions for automation and easier training and operation. There have been several studies to illustrate the promise of cobots, particularly as alternatives to traditional robots and as augmented and collaborative supports for human manufacturing activities [13]. However, little work exists evaluating the actual implementation of cobots in automation and the ability for low-skill workers to collaborate with these technologies.

Training the modern automation workforce will require workers to learn new skills that align with the needs of Industry 4.0 and also opportunities to apply these new skills [22]. For collaboration with cobots, workers need training related to co-working with the technology in modern workplaces, including configuring and re-configuring work areas, rapid programming and reprogramming of these technologies, and attending to personal and workplace safety [25]. Engineers of cobots in automation will also need training and support on how to effectively utilize the advantages of cobots and create opportunities for workers to interact with these technologies [19]. However, designing training to increase collaboration with technology has not been adequately addressed [12].

To address these needs, in this study, we interviewed experts in cobot automation to examine how the actual use of cobots compares to the potential uses of cobots. Based on this understanding, this paper aims to propose design recommendations for future cobot technologies, including end-user programming and interface design, and educational technologies to support worker-cobot collaborative skills. These recommendations advance the field of cobot design, including the design of cobot programming environments, and of models for collaborative interactions with cobots. We also propose novel approaches to education in cobot implementation, collaboration, and operation skills. Our findings highlight a rich space of opportunities for research and design for the growing body of work on programming and authoring tools and environments and on *in situ* educational technologies that integrate learning-scientific theories and interactive technologies.

BACKGROUND

Our work is inspired by advancements in robotic technologies for manufacturing, particularly cobots, and their potential to change human-robot collaboration. Here, we review literature on the potential implications of cobots in manufacturing.

The Promise of Cobots in Manufacturing

Cobots have the *potential* to provide a technological solution for the adaptive workplaces of Industry 4.0. Cobots are designed to be distinct from traditional robots or other automation technologies, such as computer numerical control (CNC) machines, in their improved safety features, simplified programming, and flexible application that do not require an isolated work-cell and allow for simple deployment [14]. Whereas traditional robots and automation technologies are adept at repetitive and simple tasks, cobots are designed to excel at interactive activity with and around humans. These distinctions can benefit automation systems by allowing a single technology to augment human activities, across many applications, such as assembly, packaging, and organizing, in ways that utilize both human and machine strengths [4].

Traditional robots are used to automate routine and repetitive processes in manufacturing at speeds and forces that require them to be isolated from workers through the use of a physical barrier or cage. The need for isolation often implies that traditional robots are not suitable for some activities that take place within a human-occupied work-cell. These activities often include *machine tending*, where an automated machine manufactures or assembles a work-piece item that must be further handled by a human, or *pick-and-place* where items are moved from one place to another—typically packaging finished items or loading/unloading a pallet of work-pieces.

In contrast to traditional robots that require an isolated work area, the improved safety features of cobots allow them to be safely operated in and around human workers [23]. Cobots can be equipped with similar safety options as traditional robots such as automated safety stops when human proximity is detected or motion limits for areas occupied by a human [8]. Cobots improve on these systems with the inclusion of force sensors that trigger hard stops to deactivate the cobot if any collision is detected so that a cobot will rapidly stop motion when it comes into contact with humans or other objects. Cobots are also typically constrained to work at lower speeds and forces than traditional robots, to maintain safe operation around workers [39], and in some cases are designed with lighter weight materials and/or dampening padding to limit injury in the case of accidental collision [4]. These safety features are what allow cobots to work around humans without safety caging and afford more rapid and inexpensive deployment anywhere in a work environment without sacrificing worker safety.

Safer operations with cobots in HRC allow for high-level worker interactions within the programmed cobot activities. While traditional robots are programmed to operate independently, cobots can have co-located, dependant, and collaborative interactions with humans. The ability to work around humans means that cobots can perform tedious, difficult, or dangerous machine tending and pick-and-place operations near workers, and engage in higher-level collaborative activity—including dynamic communication, optimization, and program adjustments [13]. Increases in dynamic and dependant interactions and more accessible programming environments can lead to a greater role for workers in programming and interacting with cobots and can help lead to the flexible workplace of Industry 4.0 with a rise in new skilled jobs in that workplace.

The simplified programming of cobots can be an especially important part of developing jobs for workers with new skills in manufacturing as they afford increased ease of use and implementation accessible to low- to medium-skill workers [4], where, with minimal training, they can provide inputs, programming, and reprogramming of the cobot [28]. Cobot programming is generally done using a *teach pendant*, a touch screen device where programmers set waypoints and motion paths, by moving the cobot, and also integrate logic-based actions and information from sensors (see Figure 1), to simplify programming. At face value, this programming and input method is intuitive and easy to use, and improvements to this programming environment are ongoing [36], but the teach pendant can limit functionality [26], and can become a difficult intermediate device between workers and the cobot they are programming [37]. One solution to this problem is to design programming environments that allow complex but generic programs. Engineers can include simple human-robot interfaces or even manual control [37] where workers to create and deploy their own specific tasks [35]. This flexible deployment can be supported by intuitive programming for workers as end-users, such as perception-driven task planning [27], that provides functional operation and can also give feedback on the internal states and perception of the cobots [33].

With these increases to safety and ease of programming, cobots can be flexibly applied and deployed into numerous applications. This flexibility allows workplaces to train existing employees who are skilled in other aspects of manufacturing, such as welding or CNC operation, to implement cobots into their manufacturing activities. For example, a skilled welder might benefit from robotic assistance in manipulating and securing pieces for welding. If this welder were given training on cobot programming and operation, they would be able to easily supplement their activities, re-program the cobot for unique or low-volume tasks, and adjust automated routines based on environmental changes in the manufacturing process. In this way, both human and robot skills are utilized and made complimentary. This collaborative interaction with the cobot allows the worker to be more efficient and productive, reduces their exposure to repetitive and dangerous tasks, and allows them use the cobot across different parts of their job. While cobots are created with the *capacity* for collaborative work with humans, these collaborative activities require automation system designs that are different in scope than those that utilize traditional robots. That is, cobots are simply traditional robots without a cage, unless engineers deliberately design for human-robot collaboration (HRC). Therefore, it is important to compare the potential and intended uses of cobots with actual common usage of cobots in automation.

To assess levels of collaboration in a human-robot interactive system, the potential range of interactions can be summarized into a hierarchy of levels. These levels go from the robot operating completely independent of humans to fully interactive and reactive simultaneous collaboration between humans and robots [13]. Christiernen [9] describes levels of collaboration including: no collaboration (*level 0*), stop/start (*level 1*), interactive (*level 2*), and collaborative (*level 3*) types of HRC (see Figure 2). In interactions where there is no collaboration (level 0), robots perform as traditional caged or gated robots and perform activities is an isolated space where humans do not enter the work-cell. For all other levels of HRC, a cobot is required to safely operate and share the same space as human workers. In stop/start (level 1) HRC interactions, the cobot is either always idle when the human is in the work-cell area (*e.g.,* holding a work piece while the human performs manual operations), or the interaction is limited to the human controlling the beginning and ending of automation routines (*e.g.,* while the human prepares or clears a work-cell area). For HRC that is interactive, where the human acts as a guide or the human and robot are aware of each other's movements (level 2), the human is able to adapt the actions of the robot using a variety of input methods such as steering, voice, or sensor activation (*e.g.,* humans use their hands to move or relocate a cobot arm to a more precise location during assembly), and the robot is capable of adapting activity in order to avoid the human by tracking human movement (*e.g.,* a robot and human simultaneously assembling a work piece). Finally, for collaborative HRC interactions (level 3), humans and cobot cooperate in a joint task where the robot adapts to and learns through observing human actions. This level of interaction creates a dynamic and supportive collaboration, where the human and cobot are responsive to each other (*e.g.,* the robot rotates a work piece closer to the worker as the worker stands or moves to another area of a work-cell), but requires a sophisticated level of sensing and task modeling for understanding human intent and social cues. HRC interactions at levels 2 and 3 represent a more complex but intuitive type of interaction, where rather than a pre-programmed fixed sequence of robot actions, there is a variety of cobot actions that can be activated based on human and/or environmental feedback.

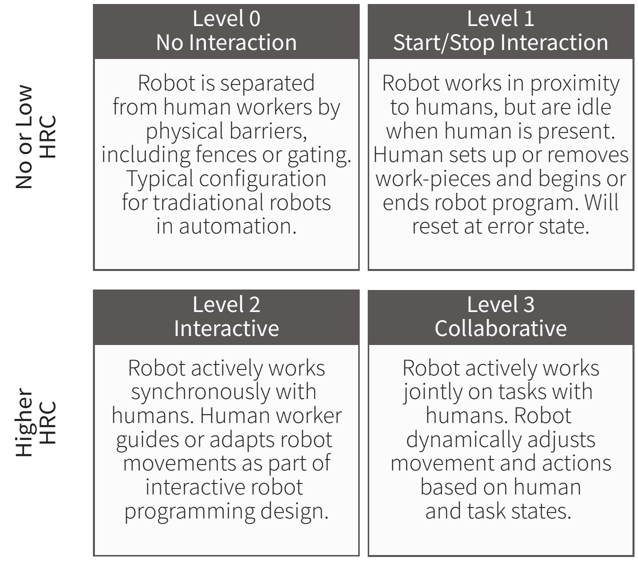

Figure 2. Four levels of human-robot collaboration (HRC) from Christiernen [9]. Levels 0 and 1 are interactions with no or low-level HRC, and levels 2 and 3 are interactions with higher-level HRC.

HRC Examples in Research

There are many examples of varying levels of HRC in research and industry (for a descriptive list, see El Zaatari et al. [13]). Examples of higher-level HRC, including interactive (level 2) and collaborative (level 3) levels, are somewhat common in research studies but are rarer in actual industry applications, where HRC with a cobot is typically a stop/start (level 1) interaction. Cobots can be programmed to respond to variations in human actions such as adjusting the cobot's weight support based on sensed human force and object mass [20] or the cobot's speed in hand-over tasks based on variations in human cycle times [17]. An example of interactive (level 2) HRC activities from research studies can be found in work by Alvarez-de-los-Mozos [1], which studied humans working with cobots to recycle electronic scrap material. In this application, many unique consumer electronic goods must be disassembled properly for recycling of valuable or hazardous materials. The human worker assessed each electronic good to be recycled and used a demonstration technique to instruct the cobot on where to cut cables or remove small components, and the cobot then independently completed a removal task. In this example, humans complete the complex task of assessing each individual recycling case and can quickly create programming instructions on what cobot actions should take place. Gabler et al. [15] provide an example of a collaborative (level 3) HRC design for co-assembling a work piece. In this example, the human and cobot jointly added Lego pieces to a board. The cobot was designed to have a wide variety of possible actions that the user can select from and dynamically chose one such action based on current and past human motions and what the system predicted as future actions of the human. In this way, the robot dynamically adapted it motions to be reactive to human activity. Workers would benefit from this type of HRC as it would allow them to choose a sequence of actions most suitable to their estimation of the overall task, rather than being bound to a pre-programmed action sequence.

HRC Examples in Industry

Higher-level (2 and 3) HRC is less common in industry and seems to be most common in automobile assembly, such as in BMW and Audi vehicles. These applications are typically at an interactive (level 2) HRC level, where cobots, working along-side human workers, move and hold large pieces, reach to assembly parts difficult for humans to access, or complete repetitive or precise tasks. These applications reduce strain and tedium for the human work force and take advantage of the cobots' ability to work in proximity to those humans [13]. There is also some evidence of companies taking advantage of the ease of programming and re-programming for cobots to utilize agile Industry 4.0 manufacturing approaches such as automating very low-volume orders and flexibly managing a large fleet of cobots [4, 19], but these applications seem most often done as start/stop (level 1) machine-tending or pick-and-place tasks. To provide work opportunities that take advantage of human capabilities, cobots and workflows need to be designed and applied with higher-level (2 and 3) HRC in mind [19], otherwise, new technologies may only exist to replace human workers rather than to support them [31].

Training in Collaborative Robotics

Traditional robotics training for automation requires coursework in programmable logic controllers (PLCs), sensors, and process controls; advanced programming in text-based languages such as Python and C++; and operating systems such as Linux and ROS (Robot Operating System). This training can require years of work and can be a barrier to low-skill workers, such as manual laborers or machine operators, to develop the new skills needed to meet the growing demands in industry. Due to the uniquely simplified programming environments, intuitive interfaces, and opportunity for collaborative interactions, cobots represent an opportunity for these low-skill workers to have a greater role in programming and interacting with industrial technologies than traditional robots. With some additional training, workers can have direct access to collaborating with and programming cobots as a means of keeping pace with the rapidly increasing complexity of automation technologies. These newly skilled workers take advantage of the additional safety, flexibility, and ease of programming, with less technical training, to more efficiently attend to automation tools in work-cells, such as CNC machines, and reduce the need to employ engineers to program and implement automation processes [4]. Rather than requiring many years of training in traditional automation or robotics engineering, workers can complete necessary training for cobot programming in a matter of weeks, through online programs and workshops offered by cobot manufacturers and distributors or in traditional educational settings. For example, Universal Robotics offers an introductory online training followed by a series of multi-day in-person core and advanced training courses [10]. There are also possibilities for other training methods including adopting more apprenticeship-based training programs [25], consistent with modern learning theory [11], or educational programs that involve advanced learning technologies, such as virtual factories [18], to support training.

The new skills needed for workers in Industry 4.0 include the ability to interact and maintain new technologies with some knowledge of programming, automation, and mechanical systems [2]. One approach to building these skills has been demonstrated by Mourtzis et al. [22] through their *teaching factory* approach. Here, students are guided through a process of designing a new product and then manufacturing and assembling the parts for the new product. The paradigm used in this study for assembling the parts gives insight into useful skills for workers to obtain, including collaborating with a cobot and utilizing augmented reality, smart technologies, and wireless sensors in the assembly process. However, there is no definitive or detailed description of exactly what these skills are and how they should be taught. Rather than only a basic description of the advanced skills in programming and collaborating with cobots and other advanced technologies, it is crucial that a *detailed* program of the skills and expertise needed to obtain these proficiencies is outlined in future work.

The potential to provide flexible alternative solutions to traditional robots and to provide workers easier access to collaboration and programming with modern technologies would benefit modern industry and automation as well as future employees in these fields. This potential can only be met if those implementing and designing automation solutions utilize cobots effectively, workers are trained in novel ways that allow them the ability to operate and interact with cobots in sophisticated ways, and cobots and their interfaces are designed in ways that promote their collaborative use [19]. While there is potential for cobots to transform automation, there is little research done to understand how cobots are actually being applied in manufacturing and how existing workers should be trained to interact with these technologies. Robust adoption of new technologies is a continual problem in HCI [30], and a nuanced understanding of the particular issues and barriers to adoption and application of cobots in manufacturing can inform the design of these systems, including programming tools, interfaces and training focused on collaboration.

Table 1. Summary of participants and interview groups.

Participant	*Occupation*	*Company*	*Interview group*
P1	Implementer	Automation Sales	Individual
P2	Educator	Technical College	Individual
P3	Engineer	Manufacturing Enterprise	Group A
P4	Engineer	Manufacturing Enterprise	Group A
P5	Implementer	Automation Sales 2	Group B
P6	Implementer	Automation Sales 2	Group B & C
P7	Engineer	Manufacturing Enterprise 2	Group C
P8	Operator	Manufacturing Enterprise 2	Group C
P9	Implementer	Automation Sales	Individual

METHOD

To gain insight into the application of cobots and the skills experts believe are needed to successfully operate and program a cobot, we recruited participants with expertise in using cobots for automation in manufacturing. Since we are interested in understanding how cobots are applied in automation, we chose to focus our interviews on engineers and implemeters, as they represent the people that create and design real-world cobot applications. We recruited these experts using a snowball method [16], through a robotics automation guidance committee, and from email with a cobot distributor. We also included one worker, an operator, where during an interview, an expert asked this operator to join the discussion to further describe a cobot application they were working on. Our main research method and data collection approach was steeped in Constructivist Grounded Theory [7] that involved conducting open-ended interviews with participants at their workplace. We then employed Thematic Analysis as a qualitative coding method to identify patterns in the interview data [6].

Participants

A total of nine participants (all male) from five different organizations were recruited for the study, including four implementers from two different automation distribution companies, three engineers from two different manufacturing companies, one educator at a community college with automation industry experience, and one experienced worker, a CNC operator who works at the same company as one of the engineers. Both distribution companies are mid-sized regional businesses serving companies in the Midwest United States. The manufacturing companies both produce custom and small- to medium-volume fabricated parts for other companies. The community college includes a program in industrial manufacturing and automation that incorporates robotics training as a central part of the overall curriculum. All participants had first hand knowledge of Universal Robotics cobots, with various cobots from other manufacturers discussed where: all implementers and the educator mentioned Fanuc, P1 mentioned Omron, and P5 mentioned Yaskawa cobots. See Table 1 for a summary of participants, organizations and interview groups.

Data Sources and Analysis

We conducted six interviews (Mean length = 50.73 min) that occurred at participant job sites and utilized an open-ended approach to questions that allowed participants to elaborate on ideas generated during conversations. In some cases interviews were done in pairs or groups of three to foster insightful conversation about the topic (see Table 1). Two interviews included two participants: one with a pair of engineers from the same company and another with a pair of implementers from the same company. There was also one interview with three participants that included an engineer and worker from one company as well as the implementer from one of our earlier interviews who had installed and programmed the cobot at that company. In keeping with a Grounded Theory approach, the researchers reviewed and discussed each interview after visiting with the participant(s) in order to refine and inform each subsequent interview and compare potential themes from new interviews with previous interviews. After six interviews, few new insights or potential themes emerged, and the authors agreed that saturation had been reached [5].

Each interview was video recorded, transcribed and coded using a Reflexive Thematic Analysis approach [6]. After a period of familiarization with the interview data, the first two authors began generating codes with an initial round of semantic codes closely related to the data. We then utilized iterative discussions that yielded recurrent topics and themes by organizing the data around significant thematic units that were finalized into two major themes: (1) cobots are used as uncaged traditional robots and (2) experts believed worker training should focus on traditional robotics skills. The findings below are presented according to these themes.

RESULTS

The thematic analysis provided insights into how cobots are used in actual manufacturing scenarios and the skills experts believed workers would need for cobot programming and operation. Figure 3 summarizes each theme.

Cobots Are Used as Uncaged Traditional Robots

We found that most cobots were used for automation applications at level 1 (start/stop) interactions that utilized their ability to work *around* humans but not in higher (levels 2 and 3) interactions that included collaboration with humans. We identified several factors related to the lack of collaborative use of cobots: (1) cobots were often chosen for simple tasks; (2) cobots were rarely used for flexible or adaptive purposes that include opportunities for workers to re-program or re-purpose cobots; and (3) the development of new, hybrid cobots to improve speed and payload capacities. Due to the consistent use of level 1 applications, we found cobots to be used for automation purposes in ways similar to traditional robots.

Low-level HRC

Most examples from our experts describe level 1 (start/stop) types of HRC. These applications typically included cobots used in machine tending and pick-and-place tasks where the cobot performs one part of a process, and the human is limited to starting, setting up, and/or ending the process. Rarely did our experts mention higher-level (2 and 3) HRC.

The applications our experts described often included cobots conducting machine tending or pick-and-place tasks, including interactions with other automation machines such as CNC

Cobots are Used as "Uncaged" Traditional Robot

Cobots were chosen for automation applications that utilize lower cost and space requirements, but it was rare for flexible or collaborative interactions to be utilized.

Training Focuses on Traditional Robotics Skills

Experts believe operators need training in traditional robotics, such as programmable logic controllers and programming, to effectively interact with cobots at higher HRC levels.

Figure 3. Two major emergent themes of the study.

machines. In these applications, interactions with workers were limited, where the robot is idle during worker activity, and the worker simply starts and stops the process for the cobot (HRC level 1). These applications seemed common because a cobot could be safely integrated into an existing shop floor without safety caging. This integration allows workers to be freed from much of the wait time of machine tending, but also be able to step into the work area to reset pallets, exchange bins, or other configuration work. In one example, we observed P8, a CNC operator, set a pallet of blank metal pieces and start the program for a cobot to load those pieces into a CNC machine for fabrication. P8 then moved to another area of the workplace while the cobot and CNC worked. P8 returned when alerted by the cobot that the process was completed and then deburred and finish each piece by hand. P8 felt that automating the CNC machine tending freed him to "do all this stuff while [the cobot] is running." In another example, P4 explained a fabrication job for a client that involved "the cobot just going to be taking the parts off the conveyor and putting them in packaging and ... where the employee comes in, or a human worker, they'll come and swap out the boxes once they're full." P6 also described a task where the cobot "loaded [an] elevator system where it loads one tray and the system automatically recycles to another empty tray and then eventually it'll say, 'Hey I have a full system, here,'" to prompt the worker to empty it. As P6 told us, commonly the worker's interaction with the cobot is "to load, unload, and start and stop." As P5 told us, their perspective was that "collaboratives work really well with simple assembly work where you have to work with a person." Using cobots made these processes more efficient than using a caged traditional robot, because the worker could step directly into the work-cell to set up, finish, or remove packaging or pieces, but still fall short of higher-levels of HRC.

Rarely, did our experts mention interactive (level 2) HRC work with cobots, and in no cases did they describe collaborative (level 3) HRC. The few examples of level 2 HRC included allowing cobots to be "alongside" workers (P2) and the cobots provide the opportunity to efficiently create processes where automated and manual work was mixed (P2). For example, the one student project that did utilize a cobot in a capstone project with our instructor, P2, involved a UR3 robot extending outside of a safety-guarded work-cell to receive a container from a worker that would be considered a level 2 HRC interaction. While P2 did say the cobot was chosen because this type of interaction was "quicker and easier" than creating a safe-guarded loading tray to pass the container to the robot, he also suggested they used it for the novelty. He said, "we had this cobot, and we decided we should use it. I mean it's just too great a resource to just let it sit and collect dust." This response suggests that engineers may be eager to find useful higher-level applications for cobots, but that these applications are not always readily apparent or available.

Simple Applications

Based on our interviews, one factor in choosing cobots for primarily level 1 HRC applications was the general focus on first automating the most repetitive and simple aspects of a manufacturing process. P5 told us, "you [automate] your easiest processes [first] to free people up to help deal with the harder issues that you're dealing with." Our experts explained that they chose a cobot, rather than a traditional robot, for cases where the limited speed, range, and payload capacity (which are typically deficient in comparison to traditional robots) were not as critical, and the lower cost of installing a cobot and the ability to place the cobot in closer proximity to workers was worth the trade-off of lower performance.

The lower speed and payload of cobots were a critical consideration for our experts. For example, P1 told us if their customers need a "fairly high throughput, we have maybe a couple of [cobots] that might work as far as reach and payload goes, but if they need the higher speeds that say a cobot might not be able to achieve, then we will talk about a traditional robot." Experts felt that high throughput or payloads would remove a cobot from consideration for an application. As P2 told us, for many of their applications "the cycle times would have been too high to try and use the collaborative robot." Cobots were therefore often found useful for applications where other parts of the overall automation process were slow, so that the cobot was not the limiting factor in the process cycle time. However, since the processes our experts often chose to automate were those that were typically simple and repetitive, it may be that these types of processes most often require the higher performance of traditional robots.

When speed and capacity limits were not prohibitive, experts saw the benefit of cobot affordability, safety, and space-saving capacity as particularly helpful for smaller companies, because cobots often cost less than traditional robots and didn't require expensive and space consuming caged work cells and other safety measures. P9 explained that most of their cobot sales were to small companies that had limited space and resources. It was also important that even though the lack of safety caging means that cobots could be installed more cheaply and quickly than traditional robots, they also did not sacrifice the safety of the work environment. P6 told us his choice of a cobot was, "really about the safety, honestly when it comes down to it," and that due to this safety, "you don't really need the guarding so it's a little bit cheaper, in the end." In sum, our experts most often chose cobots for applications to reduce costs and place the cobot near workers without reducing safety.

Flexible and Adaptive Applications Were Rare

A second factor in choosing cobots for primarily level 1 HRC applications was the rarity of using cobots flexibly. Most often a cobot was used continually for one application rather than being redeployed between multiple jobs. One of our implementers, P6, noted that "for collaborative robots, almost every robot I've seen it is set for one task and that's all it will do." Another implementer, P1, told us "that the majority of our customers leave those [cobots] for one function." He explained that this single-use perspective was related to volume, where high-volume jobs needed the cobot to be used as a dedicated single-use machine, and when companies "have more than one application for a cobot, they're going to buy another cobot." P1 did add that some low-volume customers do reapply cobots for multiple functions, and that it is "pretty simple for these guys to move the cobot from one function to another and have it up and running within a very small amount of time." This perspective is consistent with how P3 and P4 explained that their company had purchased cobots as capital investments to spread the cost across several contracts, particularly for "low-run" jobs, because cobots could be reapplied to new jobs without specialized work-cells or task-specific safety caging. P7, also explained their company has only used their cobots for single use applications that would continue the job "forever," because it was making "one of their bread and butter parts."

New Cobot Design from Traditional Robot Manufacturers

During our interviews, we found two other factors related to how cobots are implemented in the workplace, including (1) new cobot designs by traditional robot manufacturers and (2) the impact of labor cost on choosing cobot applications.

Our experts told us that the concern over slow speed and payload capacity for cobots has led to the production of new hybrid robots that are capable of traditional robot speeds that are slowed and put into a "collaborative mode" when a human is detected within a certain proximity. P2 described this approach as allowing the cobot to "speed up at certain times and if you're in a guarded area away from people, why not let it do it's full motion and mute the collaborative portion of it and go faster." This insight implies that a new hybrid type of cobot could remove the limitations on using cobots for high throughput applications. P7 added that increased payload capacity would be important. He said, "if we were to buy another one for a lathe or a mill-turn machine like the one up front, we probably couldn't use this [UR5 cobot] because some of these parts are really heavy." This approach would seem to align best with level 1 (start/stop) cobot interactions, as the cobot would be expected to operate at greater speeds with the worker outside of it's safe proximity zone. Overall, the experts described newer hybrid collaborative robots as cobots that were becoming more like traditional robots.

Areas of Promise in Human-robot Collaboration

We also found evidence that with more experience with cobots, the engineers can better see how their collaborative properties can be better utilized. For example, while their company has not re-deployed any of their cobots for new applications, P7 did find this potential to be appealing. He feels that the "best part is you don't need those floor scanners or any fencing around it," because for a traditional robot these requirements "makes it more like a immovable sort of system." He told us that if they were to "buy another robot for any machine, like the one up front where we're running more parts and a higher mix, I think it'd be a collaborative." Our expert implementers also described some cases where they were asked to design interactive aspects of cobot programming. For example, P6 told us of a customer request for "a robot where we can literally let the worker change programs to speed it up, slow it down."

Another area of promise for flexible cobot programming is the implementation of templates for common (and increasingly less common) programming tasks that typically required PLC control in the past. P3 and P4 told us they can incorporate camera vision applications that used to take a "ridiculous amount of time," where they "needed a PLC in-line to send the messages to and from the camera and then back to the robot," but now "can basically run full operation just using the robot without any PLC route controls," because UR now "will build all the code internally." Our experts indicated that increases in the number of complex techniques, such as robot vision in automation, that are made as easy to access template codes will allow them to build higher levels of HRC interactions more efficiently, which may lead to their greater adoption.

Implications of Low-level HRC

Overall, it appears that engineers recognized the potential for cobots in automation, but cobots were still most often incorporated into the same simple and repetitive manufacturing applications as traditional robots. This finding suggests that the current design of cobots does not seem to adequately support engineers in creating higher-level HRC interactions. Therefore, we believe that this has significant implications for new perspectives on designing future cobots including designing for human-augmentation, and more intuitive and capable worker interfaces (see Implications Section 1).

Training Is Focused on Traditional Robotics Skills

Our second theme summarizes engineer and implementer beliefs that workers would need traditional robotics and automation skills such as programmable logic controllers and other formal programming experience to interact with and program cobots. This belief led them to see a very steep learning curve for low- to mid-skill workers in gaining these skills. Experts felt that the existing trainings designed for cobots that focus on building basic skills for simple operations, such as pick and place and machine tending, are easy to learn but inadequate for most applications in automation. They believed that this trend would continue as newer cobots began to be based on more traditional and complex robot programming. In the automation and manufacturing program at the community college, they believed that cobots will be increasingly used in industry but still see them as a niche or peripheral technology and do not include training specific to cobots. We also found a belief that it may not be worth investing in worker training for cobots, because cobots were often used in long-term applications. For example, P7 acknowledged that some workers that worked on low-volume projects might benefit from cobot programming, but "because some robots are doing the same thing day in and day out, there's no use in having the operator of that system knowing how to edit the program" Finally, we found that some of our experts, particularly the engineers, saw that improvements in worker training programs would afford increasing the capacity for workers in higher-level collaboration.

Steep Learning Curve for Learning Cobot Programming

Our experts felt that learning to use cobots in automation would be difficult, where P3 described a “steep curve” (P3) for workers without formal two and four year training, and P2 said programming is not “easy for the person off the street, there’s a learning curve that’s really steep.” P4 described this problem being due to programming in the simplified languages such as Polyscope (UR’s end-user programming interface) being easy to “pull commands in, but you still need to know how the logic works” indicating that applying basic operations is easy, but connecting them into a logical, functioning, and safe program is still very difficult. P6 felt that most companies found training in programmable logic controllers (PLCs) to be the bare minimum of training needed to even begin to work with robots, and even then, as he said, “you literally just went to school for the PLCs, and they maybe will let you touch [the cobot] a little bit,” indicating that even formal PLC training was barely enough to begin robotics work. He also noted that workplaces often employ the use of assessment to evaluate skills in PLC and robotics, including “for the PLC stuff they’ll give you a ladder logic system and they will tell you to kind of translate it.” According to P6, these tests were used as a way of establishing trust that when working with a cobot “you know enough that you’re not messing something up in the program.” Without training in PLC or robotics, P6 felt that companies would not trust a worker to do anything more than stop and start of the cobot, and “even that is literally going to be buttons on a touch screen.” P6’s statement demonstrates a belief in level 1 cobot interactions as the primary way for workers to interact with cobots, even with formal training. As a result of this steep learning curve and need for formal training, our experts felt that someone with the requisite skills to program and work with a cobot at a high level would be overqualified for a worker or operator position. P6 told us that, “if they come in with a higher skill, they’ll end up in a maintenance or automation role and so they won’t be the operator, they will be the person that the operator will call.”

Our experts felt that training a worker to become skilled at programming a simple application was feasible, but that more complex operation would require a skill set that was likely above their ability. P3 told us about a company that trained a worker, as an operator, in 45 minutes to program moving a piece from one place to another (similar to the demo we saw from P1), but added that once “you kind of [add] complexity to it, any kind of precision to it, any kind of uh other you know programming, deeper level programming to it, um, which you know typically for it to be useful, that’s what happens, though, we’re not just having operators or people who are not trained in automation doing that yet.” This perspective implies that they do not recognize the ability of a worker to be easily trained on anything more complex than a simple pick-and-place and even then were concerned about their ability to do it accurately. They explained, “because the positioning is important, as of right now, the automation trade people are still setting it up and running it,” so that workers (or operators) generally are only using “play, pause and stop buttons” and basic “navigation through the screen [interface]” that involves following explicit directions in error conditions “where the screen will point him to where to look if there is a problem.” This perspective again seems to limit workers to level 1 HRC interactions.

The persistence of training focusing on traditional robotic skills may also be influenced by choices from traditional robot manufacturers to utilize traditional programming for their cobot products. As P1 told us, “most of the traditional guys, their programming interface is the same as the older way they program their traditional robots.” P9 added that “traditional robot manufacturers that have moved into [cobots], didn’t want to abandon their their approach to programming so they’ve just kinda transitioned in that way.” P5 described the Fanuc cobot programming is “like C++ looking at it, so if you don’t know how to program a robot, [it is difficult].” The program where P2 teaches is embracing the cobots from traditional robotic manufacturers and are moving away from their UR3 robot to incorporate a Fanuc cobot. This move to a Fanuc cobot was chosen to align their training equipment and programming environments with their existing traditional robotic machines. P5 also told us that many companies will also align their choice in cobot with the type of traditional robots they already use to “keep the knowledge internally of their automation technicians and engineers up to date” that “then allows you to kind of...you’re going to have a slimmer, more lean group of people” that will also “save on the up-front costs, save on the maintenance costs.” In sum, the experts explained that the new cobot technologies from traditional manufacturers would likely continue to use more complex programming, rather than simplified languages, over time.

Finally, our experts found that in hiring workers it is difficult to simply find and retain reliable employees with any basic skills, let alone advanced skills. This meant that rather than replacing workers with a cobot, companies tried to improve production and reliability by using cobots to free existing workers to complete other tasks. For example, P3 told us they were, “short on people to do higher level things so typically any time we get somebody off the floor- off putting things in a box, then they can do inspections, and other testing.” They also faced problems with humans workers completing crucial tasks reliably, such as adding grease to a gearbox, and instead utilized a cobot. P5 related this to retaining workers, and said, “it is not worth the investment of training” a worker, because of the high turn over in those jobs.

Experts did find promise in emerging training resources–including accessible training videos, and freely available code samples–as potential ways to aid engineers with design and workers in interacting with cobots more effectively. P9 felt that with “collaborative robots the programming environment is much easier” for new programmers, “so you don’t have to have extensive training as you would with a traditional robot.” P4 told us the, “human interfaces are advanced enough to where you can actually have training videos right on the floor and you can train there.” Here P4 sees supports that are made readily available to aid in acclimating workers to new technologies. Some experts also told us that they have worked with companies to train workers to program their cobots. P6 told us, they "teach [workers] all the way up through the full online courses where you can do a lot with them: full-on programming, IO, IP addresses." P7 explained that they planned to do more training for their worker, P8, so that he'll be able to edit programs himself. P7 said, "because we'll probably end up adding parts to this robot, eventually it'll be nice for P8 to do some editing." In this way, P7 said, "if P8 actually knows what the error means and he knows how to reset it, then he doesn't have to call us, wait for us to come out, reset it, and it's a waste of his time and a waste of our time." These statements imply that experts see the value of workers gaining expertise in cobot programming that will ultimately allow them to interact and collaborate with cobots at a higher level.

Implications of Traditional Training Findings on HRC

The view that workers would need traditional robotics skills in order to interact and program cobots was prevalent in our interviews with experts. This view was related to both the perception that newer cobots from traditional companies would move back towards more complex programming and that the existing cobot programming interfaces provide easy programming for only simple tasks. Still, our experts were enthusiastic the positive impact that having workers capable of managing collaborative activity with cobots would have. The persistent prevalence in an emphasis for traditional training, is that low-skill workers are frequently not considered capable of programming, deploying, or collaborating with cobots. To address this issue, modern learning technologies designed to augment and support workers to build their skills in real work contexts can be developed. These technologies in conjunction with HRC training developed in real-world apprenticeships would aid workers in gaining new skills in collaborative work with cobots and engineers new perspectives on HRC that can increase higher-level interactions (see Implications Section 2).

DISCUSSION

In this study, we sought to understand how the actual use of cobots compares to the potential uses of cobots and to identify expert perspectives on worker training. We found that most uses of cobots in automation were for simple, long-term automation tasks, as level 1 HRC interactions. We also found that experts believed cobot programming and collaboration requires training similar to traditional robots, including PLC control and advanced programming. These findings are in contrast to the potential for collaboration and flexibility, without the requirement of extensive training, and represent two major barriers to robust adoption of cobots in manufacturing. We believe these two barriers are unique to cobot applications in manufacturing, and have critical implications for the future direction of cobot design and education. Specifically, applying cobots to traditional applications reduces the opportunity for high-level HRC, and insistence on traditional skills as requisite to interaction and programming prohibits worker access to high-level HRC. As a result, the combination of these two particular barriers significantly minimizes the opportunities for workers to participate in advanced HRC that represent potential future jobs in Industry 4.0 [34, 25].

The rarity of high-level HRC mentioned by our experts is a major barrier to presenting opportunities for workers to participate in advanced or new skill jobs in automation. This rarity may relate to the background of those engineers, with traditional robotics and automation training, who may be likely to perceive of cobots as special-case traditional robots and apply them in traditional—simple, independent, long-term—applications. This finding is consistent with previous findings that engineers had difficulty finding opportunities to implement cobots effectively [19]. Our experts told us they automated the simplest and most repetitive manufacturing processes first, and rarely considered complex processes. They also suggested that most applications they chose had long and sometimes indefinite runs. This approach limits the opportunity to design collaborative HRC interactions, because it is the complex and unique manufacturing processes that would benefit most from human-robot collaboration - where the strengths of both robots and humans can be utilized [4].

The second barrier to interaction with cobots was the perception that workers needed traditional robotics skills to effectively interact with cobots. A key aspect of this barrier is that the user interfaces and programming for cobots is meant to reduce the need for advanced robotics training for cobot operation, but experts felt complex programming, even in this accessible programming environment, were beyond the capability of low-skill workers to learn or engage with. For example, experts believed the teach pendant interface for the UR robots we observed were easy for simple applications, but that the teach pendant was limited in how complex the cobot programs could be. Further, the simplified programming approach may be limited to new robotics companies, such as UR and Franka Emika, that focus on cobots, where traditional robotics companies incorporate complex programming environments consistent with their traditional robot products. This programming will in turn be less accessible to novice users, and further remove opportunities for workers to engage in high-level HRC. Redesigning cobot interfaces and programming would help: 1) aid experts in finding them useful for complex programming, 2) guide experts into creating more collaborative applications for cobots, and 3) experts see the need for workers to have collaborative skills rather than advanced programming skills.

Without collaborative applications in industry, and design of cobots for easy adoption, it is likely that the interaction between worker and robot will continue to be distant. To realize the promise of collaborative HRC will require a refocused approach to designing cobots and their programming and interfaces, as well as new approaches to training both workers, and the engineers who design the cobot applications that workers engage with. We suggest these approaches in the next section as implications for cobot and learning technology design.

Implications

In this section, we address the two barriers to utilizing cobots for high-level HRC identified in this study by providing design recommendations aimed at achieving the full potential of cobots as collaborative technologies. These design recommendations represent a practical contribution to facilitate the advanced use of cobots in automation that can promote greater access to jobs in Industry 4.0.

Cobot Design Recommendations

Cobot design should foster creative applications that maximize the potential for collaborative HRC and ease of flexible implementation. In light of this need, we make two recommendations. First, we recommend re-framing the design of cobots to be viewed as *augmented supports for human worker activity* with an on-board capacity for responding to human action and intent. Currently, engineers and implementers begin by examining a manufacturing process to identify aspects that can be automated and consider whether a cobot could replace or improve one or more of those aspects. This perspective leads engineers to select simple aspects of a process to automate, or as in previous findings, struggle to find places to implement cobots at all [19]. We suggest that cobots *should be* designed to flexibly aid workers in manufacturing where the worker programs and adjusts the cobot to augment their work. This re-framing changes the paradigm to see cobot applications from a worker (end-user) first perspective rather than solely as a piece of an automation solution. For example, a worker who assembles many fabricated pieces into a finished product may utilize a "move with me" function on a cobot where the cobot will respond to the worker's activity. To do so, cobots must come equipped with task-model libraries applicable to many automation scenarios, and advanced human sensing capabilities, including monitoring human motion and inferential detection of the human's intended motions and goals. To realize this approach will also require a new perspective on designing cobot programming and interfaces.

Therefore, our second recommendation suggests redesigning cobot *programming languages and interfaces to support template-based and generalized programs* that better afford workers, as end-users, to interact with and program the system for truly flexible and collaborative applications. In this paradigm, cobot programming would include a large variety of templates for engineers to incorporate into a flexible user interface for workers. The templates would allow engineers to write programs that were specific to their work environment, with built in safety and efficiency measures, as reusable functions. The programs would then allow workers to utilize the cobot interface, or as suggested by Weiss et al. [37] to use manual control options, to select from functions and modify parameters or train specific motions to meet the needs of a task at hand within a programming environment created by an engineer to limit parameters and install safety restrictions. Consistent with interface designs by Steinmetz et al. [35], engineers write the complex code as functions, and workers select and tailor these functions to augment their work.

Learning Technology Recommendations

The results of this study suggest a need for improved training for *both* workers and engineers, by supporting collaborative perspectives and skillful use of cobot programming and interaction. This approach would benefit workers–by supporting collaborative robotics skill development–and engineers–by supporting the design of high-level HRC. Learning technologies could be designed as training environments situated in the actual workplace context of engineers and workers, and provide support adapted to each learner. To take advantage of learning in context, the technologies should be designed as in-house, apprenticeship-style learning environments [25]. Apprenticeship learning allows explicit access to context relevant expert thinking and problem solving [11]. An apprenticeship approach allows engineers to learn to design collaborative activities for cobot-worker interactions with their workers and jobs in mind, and allows the workers to learn to interact with the cobot system in their actual workplace that reflects the real scope of work, tools, processes, and dynamics. Adaptive supports provide a system that can tailor trainings to meet the specific needs of learners of various backgrounds and expertise. These learning technologies, in concert with new cobot designs, would allow workers to gain expertise in utilizing their cobot to augment their own activities. Further, as Kadir et al. [19] recommend, the technologies would provide engineers with new perspectives on applications for cobots in their workplace, that also support their confidence that workers trained with the same learning technology will be skilled enough to participate in these collaborative interactions.

Limitations and Conclusion

Our findings demonstrate the difference between the potential uses of cobots and their *actual* uses in real automation scenarios, and highlight specific barriers to closing this gap beyond those typically found in technology adoption [30]. Changes to the way we design cobots and educate the workers and engineers who use them, such as those we suggest in our implications, may support a future automation workplace in which workers have an important role.

Our study is limited by a narrow representation of expertise cobots in automation due to a small sample that included only one worker and no women. We focused on engineers and implementers to gain insight into the perspectives of those who design cobot applications, but recognize the need for work that examines the worker perspective on these issues. We believe future studies should expand on this work by examining these findings through the lens of workers and women in automation, with a larger more generalizable sample to better understand their actual use. We were also limited in looking at the use of robotic arm types of cobots, that did not include other cobots, such as warehouse delivery cobots, in our study. Future work that includes a larger variety of cobots may provide insights into the specific uses and needs for cobots in these areas, and recommendations that may exist for incorporating several types of cobots into one environment.

In conclusion, we believe the insights gained from understanding how collaborative robots are used in automation have revealed several areas of improvement needed for designing these systems for increased and more effective human-robot collaboration. These improvements in learning to use and in designing cobots will require a focused effort from HCI researchers to test improved designs and evaluate their impact on real world usage. We hope our design recommendations will serve as a fertile starting point for this work.

ACKNOWLEDGEMENTS

We thank the study sites for their support, Nicole Jagemann, Isaac Siegel, and Karl Vachuska for assistance, and National Science Foundation award 1822872 for financial support.

REFERENCES

[1] Esther Alvarez-de-los Mozos and Arantxa Renteria. 2017. Collaborative Robots in e-waste Management. *Procedia Manufacturing* 11 (Jan. 2017), 55–62. DOI: http://dx.doi.org/10.1016/j.promfg.2017.07.133

[2] Andrea Benesova and Jiri Tupa. 2017. Requirements for Education and Qualification of People in Industry 4.0. *Procedia Manufacturing* 11 (Jan. 2017), 2195–2202.

[3] Thor Berger and Benedikt Frey. 2016. *Digitalisation, jobs and convergence in Europe: Strategies for closing the skills gap*. Vol. 50. Oxford Martin School.

[4] Robert Bogue. 2016. Europe continues to lead the way in the collaborative robot business. *The Industrial Robot; Bedford* 43, 1 (2016), 6–11.

[5] Glenn A. Bowen. 2008. Naturalistic inquiry and the saturation concept: a research note. *Qualitative Research* 8, 1 (Feb. 2008), 137–152. DOI: http://dx.doi.org/10.1177/1468794107085301

[6] Virginia Braun, Victoria Clarke, Nikki Hayfield, and Gareth Terry. 2018. Thematic Analysis. In *Handbook of research methods in health social sciences*, Pranee Liamputtong (Ed.). Springer, 843–860.

[7] Kathy Charmaz and Linda L. Belgrave. 2012. Qualitative interviewing and grounded theory analysis. In *The SAGE Handbook of Interview Research: The Complexity of the Craft*. Sage, Thousand Oaks, 347–366.

[8] Andrea Cherubini, Robin Passama, André Crosnier, Antoine Lasnier, and Philippe Fraisse. 2016. Collaborative manufacturing with physical human-robot interaction. *Robotics and Computer-Integrated Manufacturing* 40 (Aug. 2016), 1–13. DOI: http://dx.doi.org/10.1016/j.rcim.2015.12.007

[9] Linn Gustavsson Christiernin. 2017. How to Describe Interaction with a Collaborative Robot. In *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction (HRI '17)*. ACM, New York, NY, USA, 93–94. DOI: http://dx.doi.org/10.1145/3029798.3038325 event-place: Vienna, Austria.

[10] Universal Robots Co. 2019. Universal Robots Academy. https://www.universal-robots.com/academy. (2019).

[11] Allen Collins and Manu A. Kapur. 2014. Cognitive apprenticeship. In *The Cambridge Handbook of Learning Sciences* (2 ed.), R. K. Sawyer (Ed.). Cambridge University Press, 109–127. DOI: http://dx.doi.org/10.1017/CBO9781139519526.008

[12] Ana M. Djuric, R.J. Urbanic, and J.L. Rickli. 2016. A Framework for Collaborative Robot (CoBot) Integration in Advanced Manufacturing Systems. *SAE International Journal of Materials and Manufacturing* 9, 2 (2016), 457–464. https://www.jstor.org/stable/26267460

[13] Shirine El Zaatari, Mohamed Marei, Weidong Li, and Zahid Usman. 2019. Cobot programming for collaborative industrial tasks: An overview. *Robotics and Autonomous Systems* 116 (June 2019), 162–180. DOI:http://dx.doi.org/10.1016/j.robot.2019.03.003

[14] Maurizio Faccio, Matteo Bottin, and Giulio Rosati. 2019. Collaborative and traditional robotic assembly: a comparison model. *The International Journal of Advanced Manufacturing Technology* 102, 5 (June 2019), 1355–1372. DOI: http://dx.doi.org/10.1007/s00170-018-03247-z

[15] Volker Gabler, Tim Stahl, Gerold Huber, Ozgur Oguz, and Dirk Wollherr. 2017. A game-theoretic approach for adaptive action selection in close proximity human-robot-collaboration. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*. 2897–2903. DOI: http://dx.doi.org/10.1109/ICRA.2017.7989336

[16] Douglas D. Heckathorn. 2011. Snowball versus respondent-driven sampling. *Sociological methodology* 41, 1 (2011), 355–366. DOI: http://dx.doi.org/10.1111/j.1467-9531.2011.01244.x

[17] Chien-Ming Huang and Bilge Mutlu. 2014. Learning-based Modeling of Multimodal Behaviors for Humanlike Robots. In *Proceedings of the 2014 ACM/IEEE International Conference on Human-robot Interaction (HRI '14)*. ACM, New York, NY, USA, 57–64. http://doi.acm.org/10.1145/2559636.2559668

[18] Eija Kaasinen, Franziska Schmalfus, Cemalettin Ozturk, Susanna Aromaa, Menouer Boubekeur, Juhani Heilala, Paivi Heikkila, Timo Kuula, Marja Liinasuo, Sebastian Mach, Rakesh Mehta, Esko Petaja, and Thomas Walter. 2019. Empowering and engaging industrial workers with Operator 4.0 solutions. *Computers & Industrial Engineering* (Jan. 2019), 105678. DOI: http://dx.doi.org/10.1016/j.cie.2019.01.052

[19] Bzhwen A. Kadir, Ole Broberg, and Carolina Souza da Conceicao. 2018. Designing human-robot collaborations in industry 4.0: explorative case studies. In *DS92: Proceedings of the DESIGN 2018 15th International Design Conference*. Design Society, 601–610. DOI: http://dx.doi.org/10.21278/idc.2018.0319

[20] Stefan Lichiardopol, Nathan van de Wouw, and Henk Nijmeijer. 2009. Control scheme for human-robot co-manipulation of uncertain, time-varying loads. In *2009 American Control Conference*. DOI: http://dx.doi.org/10.1109/ACC.2009.5160062

[21] Yang Lu. 2017. Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration* 6 (June 2017), 1–10. DOI:http://dx.doi.org/10.1016/j.jii.2017.04.005

[22] Dimitris Mourtzis. 2018. Development of Skills and Competences in Manufacturing Towards Education 4.0: A Teaching Factory Approach. In *Proceedings of 3rd International Conference on the Industry 4.0 Model for Advanced Manufacturing (Lecture Notes in Mechanical Engineering)*, Jun Ni, Vidosav D. Majstorovic, and Dragan Djurdjanovic (Eds.). Springer International Publishing, 194–210.

[23] Vladimir Murashov, Frank Hearl, and John Howard. 2016. Working Safely with Robot Workers: Recommendations for the New Workplace. *Journal of occupational and environmental hygiene* 13, 3 (March 2016), D61–D71. DOI: http://dx.doi.org/10.1080/15459624.2015.1116700

[24] Bilge Mutlu and Jodi Forlizzi. 2008. Robots in organizations: The role of workflow, social, and environmental factors in human-robot interaction. *2008 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI)* (2008), 287–294. DOI: http://dx.doi.org/10.1145/1349822.1349860

[25] National Academies of Sciences. 2017. *Building America's Skilled Technical Workforce*. The National Academies Press, Washington, DC. DOI: http://dx.doi.org/10.17226/23472

[26] Zengxi Pan, Joseph Polden, Nathan Larkin, Stephen Van Duin, and John Norrish. 2012. Recent progress on programming methods for industrial robots. *Robotics and Computer-Integrated Manufacturing* 28, 2 (April 2012), 87–94. DOI: http://dx.doi.org/10.1016/j.rcim.2011.08.004

[27] Chris Paxton, Felix Jonathan, Andrew Hundt, Bilge Mutlu, and Gregory D. Hager. 2018. Evaluating Methods for End-User Creation of Robot Task Plans. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 6086–6092. DOI: http://dx.doi.org/10.1109/IROS.2018.8594127

[28] S. Pieskä, J. Kaarela, and J. Mäkelä. 2018. Simulation and programming experiences of collaborative robots for small-scale manufacturing. In *2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)*. 1–4. DOI: http://dx.doi.org/10.1109/SIMS.2018.8355303

[29] C. Reardon, H. Tan, B. Kannan, and L. DeRose. 2015. Towards safe robot-human collaboration systems using human pose detection. In *2015 IEEE International Conference on Technologies for Practical Robot Applications (TePRA)*. 1–6. DOI: http://dx.doi.org/10.1109/TePRA.2015.7219658

[30] Everett M. Rogers. *Diffusion of Innovations, 5th Edition*. Simon and Schuster.

[31] Tamas Ruppert, Szilard Jasko, Tibor Holczinger, and Janos Abonyi. 2018. Enabling Technologies for Operator 4.0: A Survey. *Applied Sciences* 8, 9 (Sept. 2018), 1650. DOI:http://dx.doi.org/10.3390/app8091650

[32] Allison Sauppé and Bilge Mutlu. 2015. The Social Impact of a Robot Co-Worker in Industrial Settings. In *CHI'15 Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 3613–3622.

[33] Yasaman S. Sefidgar, Thomas Weng, Heather Harvey, Sarah Elliot, and Maya Cakmak. 2018. RobotIST : Interactive Situated Tangible Robot Programming. In *SUI '18: Proceedings of the Symposium on Spatial User Interaction*. ACM.

[34] Belinda P. Shipps and Robert L. Howard. 2013. Unemployment and Job Creation Programs: Is there A Skills Gap? *Review of Business* 33, 2 (2013), 103.

[35] F. Steinmetz, A. Wollschläger, and R. Weitschat. 2018. RAZER A HRI for Visual Task-Level Programming and Intuitive Skill Parameterization. *IEEE Robotics and Automation Letters* 3, 3 (July 2018), 1362–1369. DOI: http://dx.doi.org/10.1109/LRA.2018.2798300

[36] David Weintrop, Afsoon Afzal, Jean Salac, Patrick Francis, Boyang Li, David C. Shephard, and Diana Franklin. 2018. Evaluating CoBlox: A Comparative Study of Robotics Programming Environments for Adult Novices. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems Paper*. ACM, Montreal QC, Canada. https://dl.acm.org/citation.cfm?id=3173940

[37] Astrid Weiss, Andreas Huber, Jurgen Minichberger, and Markus Ikeda. 2016. First Application of Robot Teaching in an Existing Industry 4.0 Environment: Does It Really Work? *Societies* 6, 3 (2016), 20. DOI: http://dx.doi.org/10.3390/soc6030020

[38] Sangseok You, Jeong-Hwan Kim, SangHyun Lee, Vineet Kamat, and Lionel P. Robert. 2018. Enhancing perceived safety in human-robot collaborative construction using immersive virtual environments. *Automation in Construction* 96 (Dec. 2018), 161–170. DOI:http://dx.doi.org/10.1016/j.autcon.2018.09.008

[39] Andrea Maria Zanchettin, Nicola Maria Ceriani, Paolo Rocco, Hao Ding, and Björn Matthias. 2015. Safety in human-robot collaborative manufacturing environments: Metrics and control. *IEEE Transactions on Automation Science and Engineering* 13, 2 (2015), 882–893. DOI: http://dx.doi.org/10.1109/TASE.2015.2412256