Applications of Collaborative Industrial Robots in Building Construction

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The use of automation and robotics has demonstrated numerous advantages in many industries including manufacturing. Similarly, it is expected that robotic technology plays a key role in achieving a successful construction project. Industrial robots have been used widely in production in a variety of applications in the automotive or manufacturing industry. Industrial robots are large and powerful robots but because of safety concerns for humans who work around the machines, these robots are supposed to be put into a cage during their operations to address safety concerns. On the other hand, the emergence of the collaborative robots has enabled a human worker to work with the machine closely while the human worker is allowed to directly share a common workspace with the robot. Collaborative industrial robots are harmless to the human worker, affordable, and easy to use and program. More importantly, studies on human-robot collaboration have indicated that a better productivity at workplace can be achieved through the collaboration of human worker with a safe and flexible robot. However, the use of collaborative industrial robots in building construction has not been explored yet. This paper studies the features of collaborative industrial robots and investigates their applications in the construction process.

Key Words: construction, robotics, industrial robots, collaborative robots, human-robot-collaboration

Introduction

Robotics were first introduced to the construction industry in the 70s to improve the prefabrication of industrialized building components and modular housing in Japan. Later the planning for the application of robotics in construction was initiated and in the 80s the first construction robots were used on construction sites. Integrated automated construction sites were further developed in the 90s and later other applications of robotics in buildings were developed for special on-site construction tasks such as employing maintenance robots for cleaning and inspection of buildings (Bock, 2007). In many industries, the use of automation and robotics has enhanced worker productivity (Fryman and Matthias, 2012). For instance, the use of industrial robots in the manufacturing process has been very successful because it has improved product quality and economic efficiency, and it has replaced human workers in unhealthy or hazardous workspaces (Matthias et al., 2011). The deployment of industrial robots in production has grown in a variety of applications such as spot welding in the automotive manufacturing and pick-and-place operations in the packaging industry. However, because of inherent characteristics of robots such as being hazardous operating around human workers, it is required to safeguard robots against human intervention. Therefore, many efforts have been developed in robot's protective guard and safety equipment (Fryman and Matthias, 2012).

It is expected that robotic technology will be essential to achieve a successful construction project (Son et al., 2010). As the use of robotics is growing in the construction industry and on jobsites, developing safety systems for construction robots becomes critical (Saidi et al., 2016). On the other hand, to address the safety issues for human-robot collaboration in workspaces, collaborative industrial robots have been introduced to work closely with a human worker (Farish, 2017). Collaborative industrial robots provide many benefits over traditional industrial robots as safe and flexible machines (Matthias et al., 2011; Maurice et al., 2017; Hagele et al., 2004; Farish, 2017; Gambao et al., 2012). However, in the construction industry the application of collaborative industrial robots has not been widely explored. Saidi et al. (2016) have classified construction robotics to onsite and offsite robots with a further distinction between a construction robot that is intended to be used for a single task or multiple robots integrated for an automated construction site (Saidi et al., 2016). This paper intends to outline and present a new research area in construction robotics based on the application of collaborative industrial robots.

Method

The objective of this paper in to investigate the applications of a new category of industrial robots known as collaborative industrial robots that can enable human-robot collaboration in the construction process. In this paper, a mixed methods approach including qualitative and experimental studies is deployed. First, the study reviews the status of construction robotics and discusses the features of collaborative robots within the existing literature. To further investigate the features of existing collaborative robots, the study identifies and reviews examples of collaborative industrial robots that have been successfully deployed in automotive and manufacturing industry. Then, in order to study the potential application of collaborative industrial robots in construction, this research reviews and summarizes construction operations that can be performed through human-robot collaboration. Finally, the research undertakes an experimental investigation using a standard industrial collaborative robot to perform a construction task. Using a two-armed collaborative industrial robot, the study undertakes an experiment to apply the robot in a sample construction task. The study also points out future research direction and limitations of the application of existing collaborative industrial robots.

Robotics in Building Construction

Development and implementation of robotic technology in the construction industry has been a promising trend. This technology can improve productivity and efficiency of different construction tasks by simplifying the assignments, creating a safer work environment, enhancing the quality of final outcome, and making the whole process more cost effective (Son et al., 2010; Bruckmann et al., 2016). The work on construction robotics research was first initiated in 1980s in Japan by introducing single-purpose robots to address the concerns of Japanese construction labor shortage (Saidi et al., 2016). Subsequently, robotic technologies have been gradually developed and used to perform some construction tasks (Son et al., 2010). Single-task robots in construction can execute one specific construction process such as digging, concrete levelling, or concrete finishing. Since these robots can only perform in an environment isolated from construction workers, they cannot be integrated within a larger network, making most of them incompatible within the construction process. Therefore, with the development of integrated systems, the application of single task robots was transitioned to the implementation of robots working in parallel (Saidi et al., 2016).

On the other hand, as the construction industry is becoming more complex and it faces new challenges, the attention to robotic technology started to grow (Son et al., 2010). So far, the use of robotics in construction has been mainly focused on automating some industrially important operation thus, it can reduce the cost of operation by removing a human operator or by improving efficiency using machine control (Saidi et al., 2016). Construction Robotics and Intelligent Job-Site Management deal with issues related to the construction phase (Son et al., 2010) and existing solutions can be grouped into three categories as follows (Saidi et al., 2016):

- Teleoperated systems controlled by a remote-control machine not autonomously but under the control of a human operator.
- Software-programmable construction machines with sensors and mechanisms that augments the operation by a human operator who either chooses from a preprogrammed menu of functions or teaches the machine a new function.
- Intelligent systems in construction with unmanned robots e.g. autonomous excavation and autonomous crane operations that can operate autonomously without human intervention or with some human assistance in semiautonomous construction robot.

Currently, construction robotics has limited applications and most autonomous or semiautonomous robots are only being applied in research projects (Saidi et al., 2016) or in pre-fabrication phase such as precast concrete components (Bruckmann et al., 2016). In fact, the application of robotics in construction faces many challenges (Saidi et al., 2016; Bruckmann et al., 2016). Construction sites are difficult environments for robot operation as these sites are mostly unstructured, cluttered, congested, and dramatically change shape and form based on construction tasks (Saidi et al., 2016; Feng et al., 2015). Also, the size of a construction jobsite is mostly limited and changes project to project making the application of robots demanding (Bruckmann et al., 2016). A large number of human workers are also present on construction jobsite thus, safety becomes a major concern (Saidi et al., 2016). Existing standard industrial robots can hardly cover workspaces of more than five meters in radius while many construction processes like bricklaying require wider workspace. Therefore, the process would require relocation and recalibration of construction robots (Bruckmann et al., 2016). A construction robot needs to change workspace by either traveling to its next workface or manually being set up considering the new environment, its tolerances, and the activities in that environment. Therefore, even in repetitive tasks in construction, the need for relocating the robot places a significant mobility and cognitive burden on a robot (Feng et al., 2015) as well as the workspace and construction workers around it. The development of mobile robotic machinery requires the development and implementation of advanced feedback systems with the deployment of scanning and sensor systems to handle the significant level of uncertainty in construction jobsites. Such robotic interactions are currently avoided in construction jobsites to prevent damages to the robot and harm to human workers (Helm et al., 2014).

Intriguingly, a trend that is steadily growing in the automotive and manufacturing industry is the use of collaborative robots (Farish, 2017). A collaborative robot is a light-weight machine that is placed next to a human operator to support them in some difficult and repetitive tasks and it ensures the safety of the people who work in proximity to the collaborative robot. The goal of the construction robotics is to improve productivity, quality, and safety thus, the prospects for application of collaborative robots - as a new innovative application of robotic technology- in building construction seem promising.

Features of Collaborative Robots

Collaborative robots are gaining popularity in the automotive and manufacturing industry (Muller et al., 2014; Williamson, 2014). While these robots are not huge powerful machines for high payload operations, they have the capability to support human workers in arduous repetitive tasks in the growing field of human-robot collaboration (HRC) (Farish, 2017). Since a collaborative robot enables co-manipulation of objects with the human worker, it can provide many benefits including “strength amplification, inertia masking, and guidance via virtual surfaces and paths” as Maurice et al. discussed. (Maurice et al., 2017). Maurice et al. suggest performing an ergonomic assessment of the robot-worker system to compare the ergonomic benefits of collaborative robots and they have applied their proposed method to optimize a robot morphology in drilling activity (Maurice et al., 2017). A collaborative robot is easy to install, program, and reconfigure. It is compact and lightweight and incorporates safety capabilities thus, instead of being used only by experts, it can be used by people with no or little expertise in robotics (Farish, 2017).

In fact, a better productivity at workplace can be achieved through the collaboration of human worker with a safe and flexible robot (Hagele et al., 2004). However, as Hagele et al. (2004) explain, because of the limitations of conventional robots due to their technical complexity, these robots require an expert to work with them thus, collaboration of complex robots with human workers might not be cost-effective (Hagele et al., 2004). In other words, conventional robots might be able to perform complex tasks in workplace effectively and with a good result, but in many cases this application might end up being expensive (Gambao et al., 2012). In addition, for conventional robots, active safety devices should be used to monitor the interaction of workers with robot in order to achieve a safer workplace. The application of safe and cost-effective collaboration between human workers and robots can result in cost reduction and better productivity (Hagele et al., 2004). In addition to the capability of collaborative robots that can streamline the processes, these robots can help human workforce with the problems of losing vital skills through time that can be caused because of ageing (Farish, 2017). Collaborative robots have the benefits of both human experience and sophisticated robotic technical systems. For instance, Gambao et al. (2012) have demonstrated the advantages of using collaborative robots when applying in material handling tasks. They introduced a semi-automatic approach through a modular flexible collaborative robot prototype that combines robotics with human skills to undertake manual material handling (Gambao et al., 2012). Also, Guo et al (2007) have used collaborative robots for infrastructure security applications to address the need of critical facilities such as power plants, military bases, water plants, and air fields, for being protected against unauthorized intruders. In their work, a team of mobile robots are working collaboratively with human to improve effectiveness from human fatigue and boredom (Guo et al., 2007).

Safety has been a major concern in the robotic industry since the beginning. The early industrial robots were large and powerful with simple control but due to the safety concerns for humans who work around these machines, these robots were put into a cage during their operations. This concept of safety has continued to date but robotic control systems as well as safety standards has also evolved to allow human interaction with industrial robots. The ISO 10218 standard - an international standard for robot safety developed by International Organization for Standardization (ISO) Technical Committee- now enables the safe use of new industrial robots. Most importantly, the emergence of the collaborative robots has enabled the human to work with the machine closely while the human worker is allowed to directly share a common workspace with the robot (Fryman and Matthias, 2012). Collaborative industrial robots are harmless to the human worker in all situations eliminating the risk of any injuries to the human worker. The two-armed collaborative industrial robot - which is modeled after a human worker - has multiple joints in each arm for collision-free access to objects even in a constrained working environment. Each arm has a multi-tooled gripper but it has a low payload in the range of a few grams to a few hundred grams. The two-armed collaborative industrial robot ensures the safe operation of the robot at all times (Matthias et al., 2011).

Examples of Collaborative Industrial Robots

Collaborative industrial robots have grown in the recent years and are expected to grow even faster in the next few years. Some of the manufacturers of collaborative robots include ABB with YuMi IRB 1400 collaborative dual-arm robot, KUKA Robotics that has a lightweight LBR iiwa, Rethink Robotics with Sawyer and Baxter collaborative robots, FANUC from Japan that has a range of collaborative robots CR-35iA, CR-4iA, CR-7iA and CR-7iA/L, and Danish Universal Robot with UR3, UR5 and UR10 cobots. Other players in collaborative robot market are Robert Bosch GmbH (Germany), MRK-Systeme GmbH (Germany), Precise Automation, Inc. (US), Energid Technologies Corporation (US), F&P Robotics AG (Switzerland), MABI AG (Switzerland), Techman Robot for Quanta Storage Inc. (Taiwan), Franka Emika GmbH (Germany), AUBO Robotics Inc. (US), YASKAWA Electric Corporation (Japan), Comau S.p.A (Italy), and KAWADA Robotics Corp. (Japan). This section reviews some of the mostly used collaborative industrial robots and discusses their features.

Baxter

Rethink Robotics has developed the two-armed Baxter robot to collaborate with human and its safety is applied through physical compliance created by spring in between driving motors and robot joints. Although Baxter robot is not a mobile robot that can move automatically, it has a torso based on a movable pedestal that the human user can use to change the robot's location. Baxter robot has two 7 degree of freedom (DOF) arms as shown in Figure 1, with 7 rotational joints and 8 links which is installed on each arm. Each arm has an interchangeable gripper that allows the installation of different types of gripper such as electric gripper, vacuum cup or a customized gripper at the end of each arm. Baxter robot has also a screen on the top of torso as a head-pan that can rotate. Baxter robot can fulfil safe human-robot interaction since it can sense a collision at a very early time before it hits onto a subject (JU et al., 2014).

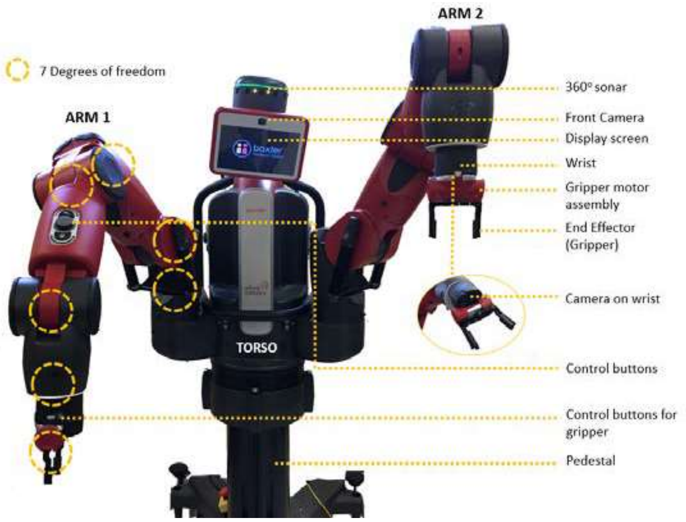

Figure 1: Baxter robot components.

YuMi

ABB's IRB 14000 YuMi robot is a two-armed robot with seven joints in each arm as shown in Figure 2, allowing for collision-free access to objects in a constrained working environment and its single controller is integrated into the torso (Matthias et al., 2011; Kirgis et al., 2016). It weighs a total of 38 kg and can reach a speed of 1.5 m/s and 0.02 mm repeatability while the payload of each arm is 0.5 kg within the reach of 559 mm (Kirgis et al., 2016). Each arm has a multi-tooled gripper that can be used in different applications (Matthias et al., 2011; Kirgis et al., 2016). YuMi enables safe assembly of affordable small robots in collaboration with human workers with sensors to see and recognize objects and interact with the environment (Kirgis et al., 2016). YuMi's arms are like a human arm with a magnesium skeleton covered by a floating plastic casing and wrapped in soft padding (Kirgis et al., 2016). YuMi's software has been built upon existing ABB controllers with new interactive teaching capabilities and to ensure safety for both human worker and the robot, the sensors will detect the force in case of a collision which will stop the robot within milliseconds (Kirgis et al., 2016).

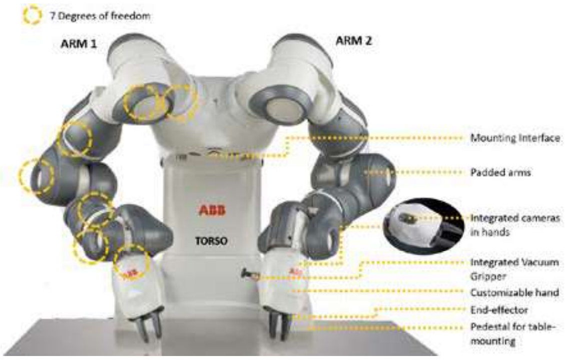

Figure 2: YuMi robot components

UR

The six-axis single-armed UR robots are developed by Universal Robots and they include UR3, UR5, and UR10 (Universal Robots, 2017). Universal Robots has developed a library called UR COM1LAPI as a C-library for development to gain access to low-level functions on the controller. This C-library allows to deploy a user supplied controller instead of the native motion controller within a frequency which enables reading the current joint angles and command joint angles, velocities and accelerations (Schrimpf et al., 2013). Three different UR collaborative robots can be integrated into existing environments and are designed to replicate the range of a human arm motion. Liu and Zhang (2015) used a UR-5 robot for a remotely-controlled welding process which can transfer human knowledge to welding robots. They accurately tracked the motion of the human welder movement by the Leap sensor and augmented a UR-5 industrial robot arm with sensors to directly observe the work-piece and reconstruct the 3D weld pool surface allowing for autonomous welding of the robot (Liu and Zhang, 2015).

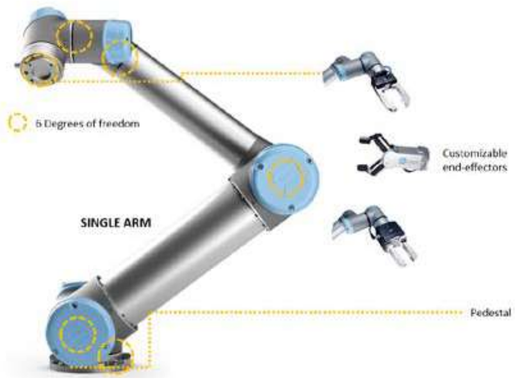

Figure 3: UR5 robot components

Construction Tasks and Collaborative Robots

Human-robot collaborative operations are limited to safety factors reducing risk when human and robots work together closely. Therefore, basic types of collaborative operation that can be combined in realistic applications according to Fryman and Matthias are (1) Safety-rated monitored stop where the robot is not permitted to move if the worker is in the collaborative work space, (2) Hand guiding where the worker directly controls the robot, (3) Speed and separation monitoring where the moving robot and the human worker are supervised to have no contacts, and (4) Power and force limiting where contact between the robot and the human worker is possible considering design measures and capabilities of the robot including sensors (Fryman and Matthias, 2012). On the other hand, construction includes a number of elementary processes that can be summarized to three main operations as (a) materials handling, (b) materials shaping, and (c) material/structural joining. Each of these tasks can be applied to multiple operands such as steel and metal work, concrete, timber, etc. (Saidi et al., 2016). There is a need to develop a framework that maps different types of collaborative operations in human-robot collaboration within building construction processes for each construction operations and operands. This framework can capture the procedure when working with collaborative robots in construction considering limited payload and reach of the robot.

Results

To evaluate the application of two-armed collaborative industrial robots in construction, a standard collaborative industrial robot i.e. a Baxter robot was deployed in an example of a construction task for material joining i.e. joining pipe fittings that includes the process of attaching and placing pipe pieces as shown in Figure 5-a and 5-b.

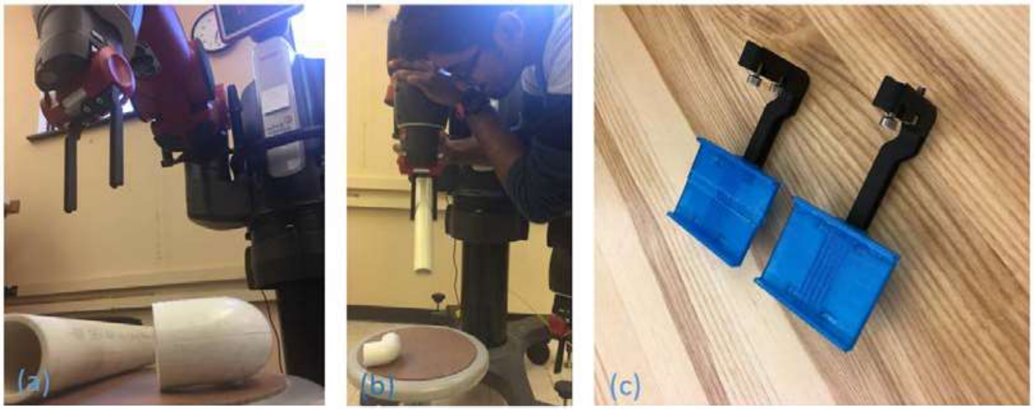

Figure 5: (a) Pipes and pipe fittings, (b) Baxter robot trained in the experiment, (c) Customized 3D printed gripper

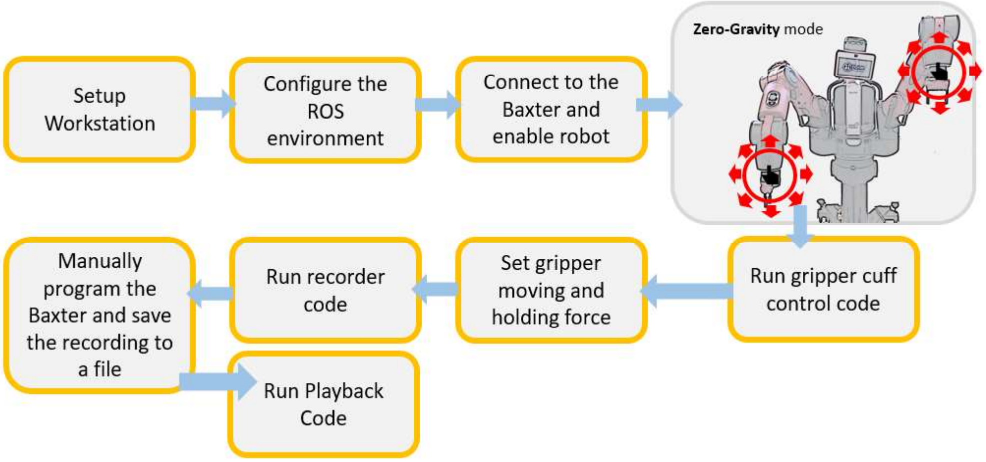

Figure 6: Methodology used in the experimental investigation.

Methodology used in this experimental investigation is outlined in Figure 6. In this process, after setting up the workstation and configuring Robot Operating System (ROS), the system will be connected to Baxter. Then, Baxter will be set to zero gravity mode when the human worker can freely move the arms and train the robot to perform each operand e.g. gripping. When the system and grippers are set, the recorder on robot will be run and a human worker can manually move the arms to program the Baxter robot. When all the operands are complete, running the playback code will run the experiment automatically. The two-armed Baxter robot can facilitate the operation by picking and attaching two pieces at a time. Baxter can replicate a human task by learning from a human worker as shown in Figure 5-b. The pipe fitting operation was specifically enabled by adding a customized gripper, shown in Figure 5-c. This customized gripper was designed and 3D printed based on the requirements for handling pipes and fittings. The process of picking, attaching, and placing the pipe and its fitting by the robot is shown in Figure 7. In this process, first the robot is guided by the human worker and then, it performs the operation autonomously.

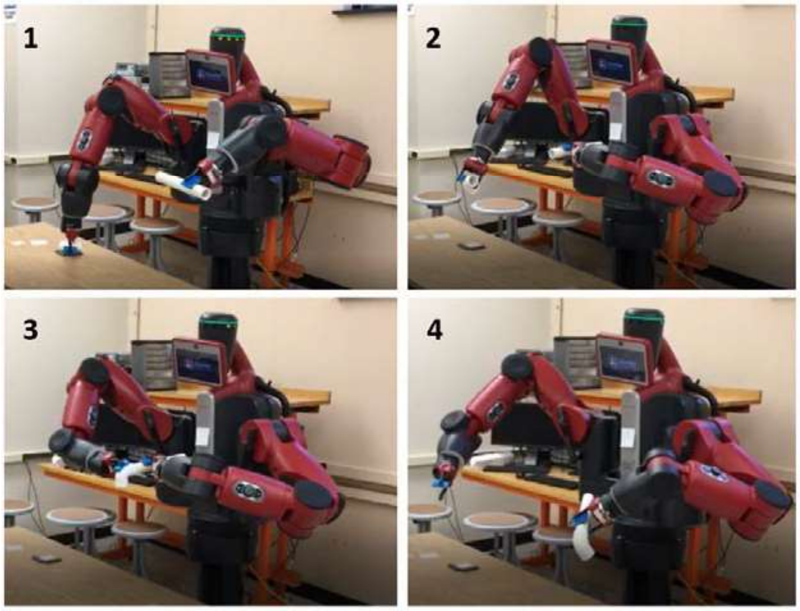

Figure 7: Attaching pipe fittings with Baxter robot; (1) picking one part, (2) picking the second part, (3) attaching the pipe and its fitting, (4) pass the assembly over to the human worker.

Discussion and Conclusion

This paper investigates the applications of collaborative industrial robots in the construction process that can enable human-robot collaboration. The experimental investigation with a Baxter robot for pipe fitting tasks shows how construction tasks can be performed by standard collaborative industrial robots. Collaborative industrial robots as depicted in this experiment are not as fast or precise as traditional industrial robots (Orcutt M. 2015; Marvel, J. 2014) and because of their limited payloads they cannot do heavy lifting. Therefore, these robots cannot undertake material handling tasks if used on their own and not augmented by other means. However, they can be employed in some material shaping and material/structural joining tasks in working with building components that are lightweight. This way, the use of collaborative industrial robots can eliminate some of the current manual and mundane construction tasks through an automated and relatively cheap operation. Currently, the application of robotics in construction is not as robust as other industries such as in automotive or manufacturing industry. To date, the application of robotics in construction has been limited to commercial teleoperated and programmable machines and autonomous or semiautonomous robots are mostly limited to research projects (Saidi et al., 2016). Because of the increasing competition in the construction industry, construction companies are in search of ways to improve productivity, quality, and safety and the use of robotics such as the application of affordable easy-to-use collaborative industrial robots seems promising. As collaborative industrial robots are safe to work with, future work will integrate collaborative industrial robots in construction education to investigate how these robots can help with the learning process of construction education. Future research can also implement and evaluate the performance of collaborative industrial robots in other construction operations such as material shaping.

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