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A Robotic System Method and Rebar Construction with Off-the-Shelf Robots

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ABSTRACT

The construction industry has traditionally been a labor-intensive industry. Typically, labor cost takes a significant portion of the total project cost. In spite of the good pay, there was a big gap recently between demand and supply in construction trades position. A survey shows that more than 80% of construction companies in the Midwest of U.S. are facing workforce shortage and suffering in finding enough skilled trades people to hire. This workforce shortage is also nationwide or even worldwide in many places. Construction automation provides a potential solution to mitigate this problem by seeking to replace some of the demanding, repetitive, and/or dangerous construction operations with robotic automation. Currently, robots have been used in bricklaying or heavy-lifting operations in the industry, and other uses remain to be explored. In this paper, the authors proposed a feasibility breakdown structure (FBS)-based robotic system method that can be used to test the feasibility of performing target construction operations with specific robotic systems, including a top-down work breakdown structure and a bottom-up set of feasibility analysis components based on literature search and/or simulation. The proposed method was demonstrated in testing the use of a KUKA robot and a Fetch robot to perform rebar mesh construction. Results showed that the overall workflow is feasible whereas certain limitations presented in path planning. In addition, a smooth and timely information flow from the Fetch robot sensor and computer vision-based control to the two robots for a coordinated path planning and cooperation is critical for such constructability.

INTRODUCTION

Due to the high labor costs and recent workforce shortages in the construction industry, adopting automation and robotic systems has attracted much attention, for performing demanding and/or repetitive construction operations for different types of construction projects. For example, Li et al. (2016) used a robotics-based digital fabrication method to produce and install a curved surface ceiling structure in a more efficient and cost-effective way comparing to the traditional ceiling construction method. Eversmann et al. (2017) proposed a robotic setup for timber construction that realized a complete digital workflow using additive robotic fabrication processes. Yu et al. (2018) developed a 7 degree-of-freedom (DOF) upper-limb robotic exoskeleton to assist with refractory construction operations in furnaces. Chai et al. (2019) proposed an advanced timber construction platform with a multi-robot system to support timber structures design and construction. These research efforts demonstrated great robotic application potential in the process of off-site prefabrication and on-site assembly. However, the large amount of efforts that went into the development and customization of these robotic systems may defeat the cost effectiveness of the systems and negatively affect their potential adoption in the industry. In contrast, directly adopting off-the-shelf robotic systems will have its adoption time and cost advantage because they are readily available and can potentially be directly applied. For example, Zhang et al. (2021) adopted a Kuka KR60-HA robot to build pavilion structures with tree branches/trunks collected from the trees on the construction site of Tianjin University campus. Yet, any such attempts must be based on thorough considerations of all factors related to their use. In other words, a detailed analysis of feasibility is required. In the authors' view, this feasibility analysis could come from two sources: (1) literature review, and (2) simulation study.

PROPOSED METHOD

To address the feasibility analysis needs in using off-the-shelf robotic systems (i.e., hardware and software) for performing target construction operations, the authors proposed a feasibility breakdown structure (FBS)-based robotic system method which can be used as the basis to test the feasibility of a range of robotic systems for a range of construction operations, from the simplex to the most complex (Figure 1). The proposed method includes the applications of two main parts: (1) a work breakdown structure (WBS); and (2) a set of feasibility analysis components. The WBS is similar to the conventional WBS typically used in a construction project in that it breaks down the target constructure operational task into sub-components level by level until reaching the level of detail that each component is assignable to an agent. Also, the breaking down of the activities at each level should follow reasonable rationales. The main difference, however, is that while conventional WBS breaks down a project to work packages that can be assigned to different contractors/subcontractors/crews, the WBS in the proposed method seeks to breaking down the construction operational task to sub-tasks that can be assigned to different robotic systems. The feasibility analysis components, on the other hand, have one-to-one mappings to the lowest level of sub-tasks in the WBS. Each feasibility analysis component consists of feasibility results based on literature review, simulation study, or a combination of both.

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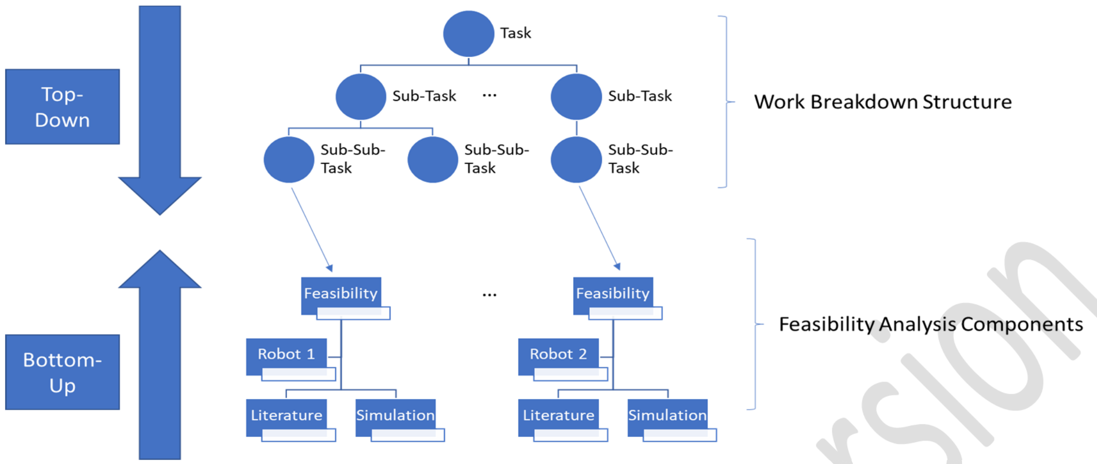

Figure 1. Proposed robotic system method.

When using the proposed method, there are two directions: (1) top down, and (2) bottom up. The top-down direction forms the WBS first and then seeks to find the feasibility analysis component for each sub-task at the lowest level of the WBS. The bottom-up direction, in contrast, integrates known feasible sub-tasks into larger tasks, level by level. The top-down and bottom-up directions could be performed in combination in a mix-and-match manner. The only constraint will be that the aggregation of sub-tasks to their parent task must follow strict logical *AND* operations. In other words, only if all sub-tasks are feasible, can their parent task be considered feasible.

EXPERIMENT

To demonstrate the use of the proposed robotic system method, the authors tested it in rebar mesh construction operation with two off-the-shelf robotic systems: KUKA KR 16 L6 and Fetch Research Robot (Figure 2). These two robotic systems were selected because they are readily available in the authors’ school labs for potential physical testing. The rebar mesh construction operation was selected because: (1) in prefabrication and off-site construction there lies the biggest opportunity in adopting robotic systems (Brissi et al. 2021), and (2) the amount of research in using robotics for concrete construction is more limited comparing to those in timber construction and steel construction (Brissi et al. 2021; Chai et al. 2019). Prefabrication is an essential topic in the robotics construction discussion, because it provides an effective construction approach in the dimensions of time, cost, quality, safety, and productivity (Gupta 2017), especially that it can be performed in a factory-like environment that is ideal for robotic systems adoption (Brissi et al. 2021). Prefabrication can also help reduce greenhouse gas emissions comparing to the conventional construction methods, indicating its benefits in the environmental sustainability dimension in addition to the above-mentioned five dimensions (Mao et al. 2013).

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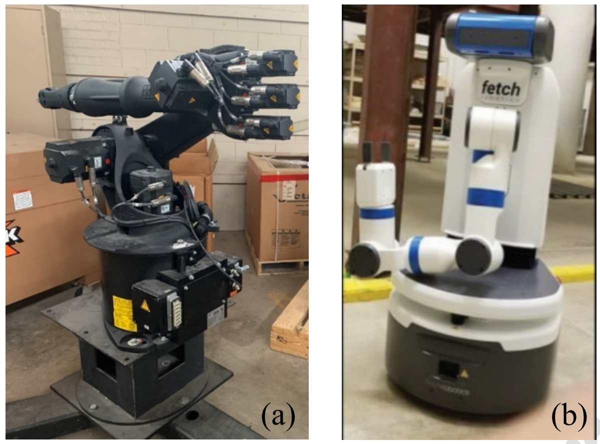

Figure 2. (a): KUKA robot, and (b): Fetch robot.

In order to test the feasibility of using the KUKA and Fetch robots shown in Figure 2 in constructing rebar meshes, the proposed robotic system method was applied following a combination of top-down and bottom-up directions. Bottom-up direction was applied first, because in this way feasible sub-tasks could be quickly identified which would save efforts otherwise in investigating ways to break down the higher-level tasks.

RESULTS AND ANALYSIS

Following the bottom-up direction of the proposed method, the authors did a literature search for using KUKA and Fetch robots in related operations to steel reinforcement.

It was found that the KUKA robot was mostly used in laser welding and melting. For example, Zhang et al. (2019a) used the KUKA KR 60-3F robot to control an annular-beam cladding nozzle for the relative motion of laser spot and substrate in performing finishes work on surfaces of thin metal walls. Liu et al. (2019) used the KUKA KR 30HA robot to perform dual laser-beam bilateral synchronous welding with the laser welding head attached on its flange. Zhang et al. (2019b) employed the KUKA KR 30HA robot to perform their designed laser melting deposition of Inconel 738 (IN738) superalloy for the remanufacturing of gas turbines and aerospace engines. These served as early evidence of using KUKA robot for welding operations in the target rebar mesh construction. Eventually, a Norway startup company (Rebartek 2020) was found to produce reinforcement cages using KUKA robots. Up to this point, the experiment would have been finished/stopped if the goal was to investigate the use of two KUKA robots to build rebar meshes, because Rebartek already demonstrated its feasibility. However, the investigation was on the feasibility of using one KUKA robot and one Fetch Robot due to the availability of the robotic systems. Therefore, the evidence from Rebartek (2020) only supported the feasibility of using the one KUKA robot for either welding or mobilization (i.e., not both) of rebars. Coupled with all the other evidence (Zhang et al. 2019a,b; Liu et al. 2019) of the suitability of using KUKA

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robot for welding operations, the KUKA robot was tentatively designated for the welding operation and mobilization operation of rebars was left to the Fetch robot.

It was found that Fetch is an autonomous mobile robot that was typically used to pick/place/transport materials within distribution centers, factories, and warehouses. For example, Chen et al. (2019) used the Fetch robot to detect and pick up target small grocery objects. Zhu et al. (2019) used the Fetch robot to test an indoor navigation system with real-time robot pose and path planning and control, to navigate in indoor lab environments. Although Fetch could be expected to be able to mobilize certain types of rebars based on its 6-kg payload capacity. Because similar operations were not found in literature search, simulation was resorted to for analyzing such use of Fetch robot. To guide this simulation a WBS was developed as shown in Figure 3.

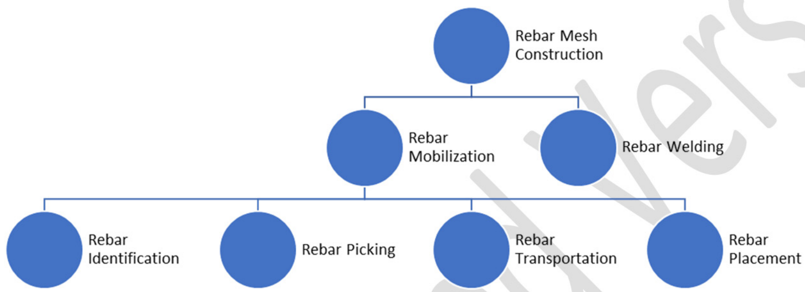

Figure 3. Rebar mesh construction work breakdown structure.

The simulation was conducted in the Gazebo simulator (Open Source Robotics Foundation 2014) with Robot Operating System (ROS) (Open Robotics 2021), which has been shown to be effective in simulating virtual environment with Fetch-like robot (Sanchez et al. 2019).

Rebar Identification. The goal of rebar identification is to correctly detect the size and position of a target rebar, using the streamed sensing data from the PrimeSense Carmine 1.09 short-range RGBD sensor attached to the head of the Fetch robot (will be called Fetch robot sensor hereafter). To test this rebar identification, two tables were set up in the virtual environment with a 1.1-meter-long rebar placed on top (Figure 4). From the point clouds generated in real-time by the Fetch robot sensor (Figure 5), it could be seen that the rebar could be picked up by the Fetch robot sensor. The real-time point cloud visualization was performed using the RViz package (Gossow et al. 2021). Given the complexity of using solely point cloud data to identify the rebar, image frame data was used in parallel. For a more robust detection and identification of the rebar, the authors further colored the end points of the rebar with distinguishing red color, which could be more easily picked up by a computer vision algorithm [e.g., filtering HSV values using the range (175,0,0) to (180,200,255) (Figure 6)] comparing to the processing of point clouds. In this simulation, OpenCV (OpenCV 2021) was used to implement the computer vision algorithm. In practical usage the color coding could be implemented by paint or mini sticker. The detected endpoints' 3D coordinates were obtained by associating them with the corresponding points in the point cloud, which helped define the position of the rebar in 3D. The length of the rebar was inferred by taking the distance between the two endpoints. It was found, however, the size (i.e., diameter) of the rebar was not easily detectable. Provided that there are only limited number of

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rebar sizes on a given construction project, this limitation could be addressed by adopting different color-coding paint or sticker for different sizes of rebars. The only constraint under such application scenarios would be sufficient lighting.

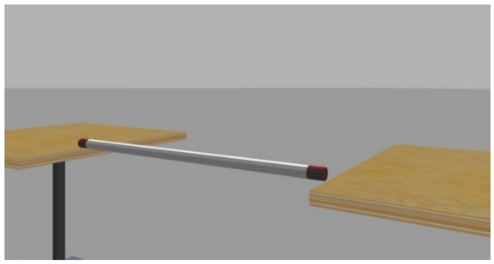

Figure 4. Rebar setup.

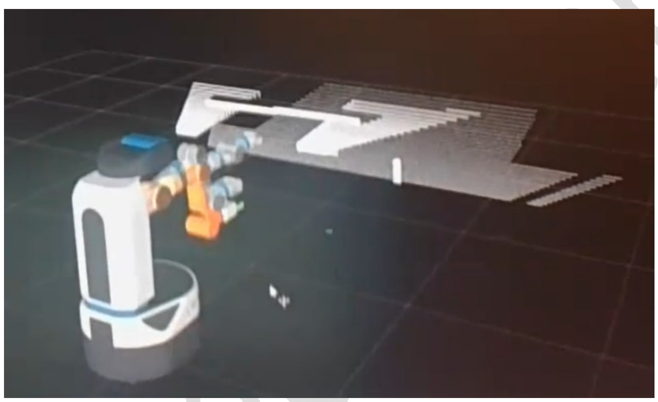

Figure 5. Real-time point clouds from Fetch robot sensor.

Rebar picking, transportation, and placement. The Fetch robot used had a torso that can raise, an arm with 7 joints, and a gripper at the end of the arm. Its arm payload capacity was 6 kg which was sufficient for the tested rebar. The reach and path were then tested in the simulation, with the objective of mobilizing the rebar from the storage tables to another table by the side of the KUKA workspace. RViz was utilized again in this process, by taking the current pose and target pose of the Fetch robotic arm and performing path planning using its built-in path planner. Two main limitations were found: (1) the path planner used could only avoid collisions of the Fetch arm with the Fetch robot itself, and therefore collisions with the rebar and occlusion of the Fetch robot sensor were occasionally observed in some paths (Figure 7); (2) the planning process for each movement took 3 to 5 seconds, which might negatively impact the productivity in its practical use. Because the purpose of this research was to test off-the-shelf robotic systems with off-the-shelf software packages to the largest extent possible, the authors did not pursue refinement of the path planner. In spite of these limitations, the feasibility of its use could be considered positive, as there were still feasible paths.

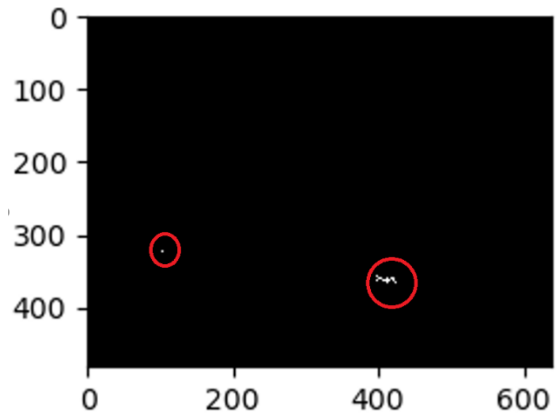

Figure 6. Color-coded end points of rebar picked up in computer vision.

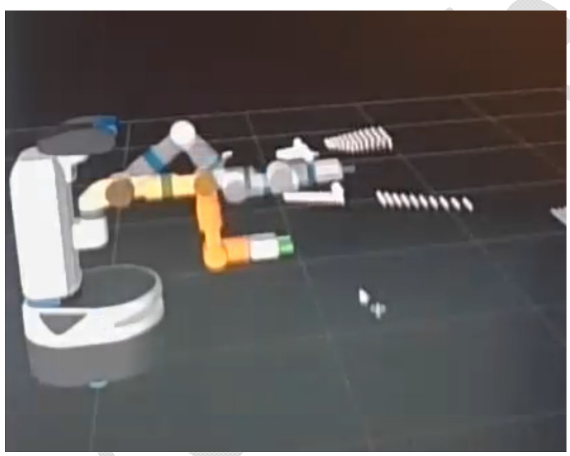

Figure 7. Collision and occlusion.

Analysis. Once the rebar is placed by the Fetch robot, the KUKA robot will move its welding gun end effector to the welding joint and weld. In this paper, the welding work was designated to the KUKA KR16 L6 robot, which has a long reach and low payload (but sufficient for holding the welding gun) robotic arm. It has six joints that can rotate. When the rebar has been placed correctly by the Fetch robot, the 3D coordinate of the welding point and the rebar's orientation is passed to KUKA for carrying out the welding. This demonstrates one iteration of the rebar mesh construction and the process repeats. In order to use the reconstructed real-time 3D point cloud, the Fetch robot sensor calibration was an important step, as any distortion could change the size and shape of objects in the image data collected. The generation of point cloud was achieved by 3D reconstruction from a set of images and short videos that Fetch robot sensor collected. However, the real-time 3D point cloud can only display the points that were visible to Fetch at that moment. To build a 3D point cloud that reflects more thoroughly the overall environment, multiple 3D point clouds taken from different angles/positions have to be combined. After the 3D point cloud of the existing rebar mesh is formed, it can be further compared with the plan for monitoring and control purpose. Due to the above stated reasons and the lack of sensing capability of the KUKA robot itself, the planner algorithm must corporate with the Fetch robot sensor data to capture the locations of all surrounding objects, and therefore a smooth and timely information flow from the Fetch robot sensor and computer vision-based control to the Fetch and KUKA robots for a coordinated path planning and cooperation is critical for such feasibility.

CONCLUSIONS

In this paper, the authors proposed a feasibility breakdown structure-based robotic system method for testing the feasibility of using off-the-shelf robotic systems in performing target construction operations. The proposed method utilizes a combination of: (1) a top-down work breakdown structure to break down the target construction operation into a set of sub-tasks, and (2) a bottom-up set of feasibility testing components to test the feasibility of using a piece of robotic equipment to perform each of the sub-tasks, through literature search and/or simulation. To demonstrate the use of the proposed method, an initial experiment was conducted to test the feasibility of rebar mesh construction using a KUKA robot and a Fetch robot. Through using the KUKA robot for welding and the Fetch robot for mobilizing rebar, the feasibility of such a system was tested positive. Through this analysis, limitations and practical considerations were also discovered, such as in the path planning and collaborative operation processes between the robots.

LIMITATIONS AND FUTURE WORK

In spite of the feasibility and practical considerations discovered in using the KUKA and Fetch robots in rebar mesh construction, its ultimate test needs to be performed physically, which was not conducted due to the COVID-19 pandemic. The authors plan to pursue it in their future work.

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