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A NOVEL APPROACH OF BUILDING CONSTRUCTION USING ROBOTIC TECHNOLOGY

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ABSTRACT: Construction automation is yet to be improved since construction site still faces a lot of high risks and difficulties. This research focuses on applying robotic beam assembly system in place of construction workers. This system consists of CF (Construction Factory) structure to provide adequate working environment to robot automation. The CF structure not only gives automation environment for a robot but also houses the equipments to protect from outside effects. The robotic beam assembly system also consists of robotic bolting system and robot transport mechanism. It utilizes various tools to insert and join the bolts and nuts. Visual servoing helps precise robot motion by sensing bolt hole and tail of the bolt. ITA system helps non skilled workers to easily perform the assembly work with the robot system. The robot transport mechanism includes sliding rail and cross-wired lift. It carries the robot to a desired position for assembly work.

Keywords: Construction automation; Construction robot; Steel beam assembly; Robotic bolting

1. INTRODUCTION

Traditionally, robotic systems are hardly applicable to real fields without favorable environment for their usage. In such fields as the automobile industry or manufacturing industry, environment for utilizing robots is well arranged and robots usually perform very repetitive tasks with high speed and high precision. However, it has been known that construction industry where working environment is messy and a variety of tasks should be performed was not a favorable field for employing robotic technologies. As such, most construction tasks have been conducted only manually by human labors though they are dangerous and difficult to handle. However, as the society has developed, the number of skilled labors who can handle risky construction works has gradually decreased and, then the necessity of construction automation has become a hot issue.

Recently, new approaches employing robotic technologies to construction fields have been tried in several countries [1]. In 2006, a research center for application of robotic technologies to steel beam assembly for building construction was kicked off. This novel research has the title: "Robot-based construction automation system for high-rise building". It has the purpose of replacing steel beam assembly task, which is one of most labor-intensive construction works and has been totally conducted only by human labors, with a robotic automation system [2, 3]. This paper deals with an overall introduction of a robotic beam assembly system proposed in the research. This robotic steel beam assembly system consists of a robotic bolting device which perform the actual bolting task and a robotic transport mechanism which transports the robotic bolting

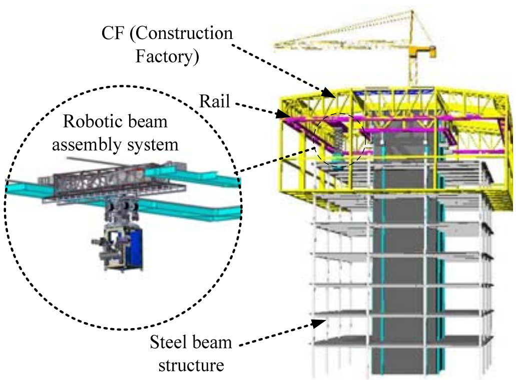


Figure 1. Robot-based construction automation system for high-rise building

device to bolting position around the building structure. And a bolting control system which administrates the robotic bolting device was developed on the visual servoing technology using a CCD camera and a laser sensor. The bolting control system includes ITA (Intelligent Teaching Agent) system which provides the operator with overall operational information and enables an efficient and safe assembly work.

In the research, a structural environment where the robotic transport mechanism can be operated was developed, which is called CF (Construction Factory). Figure 1 shows the CF which surrounds the upper part of the building. A rail system was installed on the CF around the building. The robotic transport mechanism slides on the rail and transport the robotic bolting device to the bolting positions. After the robotic beam assembly system finishes the assembly work on a floor of the building structure, CF is lifted to the next floor by a hydraulic lifting system and begins the assembly work. The robotic beam assembly system proposed in this research was actually implemented to a real building construction. The bolting task using the robotic bolting device and the robotic transport mechanism of the system were successfully experimented.

2. ROBOTIC BOLTING TECHNOLOGY

The steel beam assembly work for building construction is performed by bolting beams each other. In order to accomplish this task with robotic technologies, a H/W system which physically carries out the bolting task and a S/W system which administrates the H/W system are required. In this research, the H/W system is the robotic bolting device. This device is composed of a bolting end-effector which actually tightens the bolt and nut and a robotic manipulator which moves the bolting end-effector to the bolting position within its workspace. The bolting end-effector has two different bolting tools for different functions. Efficiency of the bolting task increases considerably by harmoniously operating the two bolting tools. And, in the research, a nut feeder and a washer feeder were developed to supply nuts and washers to the bolting end-effector. As S/W technologies for beam assembly, a hole-recognition system based on visual servoing and an ITA system were developed. In order to insert bolts to bolt holes and tighten bolts and nuts, the positions of bolt holes and bolt tails should be tracked very precisely. For this purpose, the visual servoing system suggested in this research detects the bolting positions using sensor fusion technology with a CCD vision camera and a laser distance sensor. Moreover, the ITA system was appropriately operated to provide the operator with overall information about bolting process and assisted an efficient and safe assembly work.

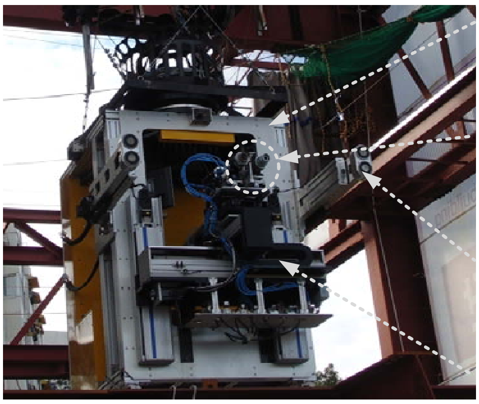


Figure 2. Overview of the robotic bolting device

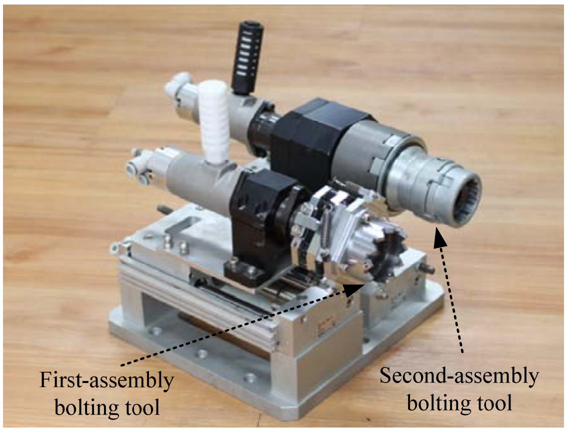


Figure 3. Bolting end-effector

2.1 Robotic Bolting Device

The robotic bolting device has the main role of performing the actual beam assembly. Figure 2 presents the overview of the robotic bolting device. It has various components, and the detailed specification and mechanism are given in [4]. The cabin of Figure 2 has the role of a control station in which the operator operates the robotic bolting device and monitors the whole system. In the cabin, there are joysticks, with which the operator manipulates this robotic system, and vision screens, which give information for monitoring the robotic beam assembly system. The vision screens are touch panels so that the operator can handle the system conveniently.

The most principle device for steel beam assembly is the bolting end-effector which actually tightens the bolt and nut. In order to improve the bolting productivity, the bolting end-effector has two different bolting tools with different specifications. In Figure 3, the bolting end-effector developed in this research is presented. This device is composed of the first-assembly bolting tool and the second-assembly bolting tool. The first-assembly bolting tool can generate a very high rotational speed but low torque. In the beginning of the bolting process, the bolting tool should generate several turns of relative rotation between bolt and nut. Since in this process a high torque is not necessary, to generate a high rotational speed and reduce the torque for tightening bolt and nut is beneficial in aspect of productivity. On the other hand, in order to perfectly assemble beams, a strong bond between plates is required. The second-assembly bolting tool finishes the tightening task with a high torque but a low speed. The two bolting tools utilize the same pneumatic

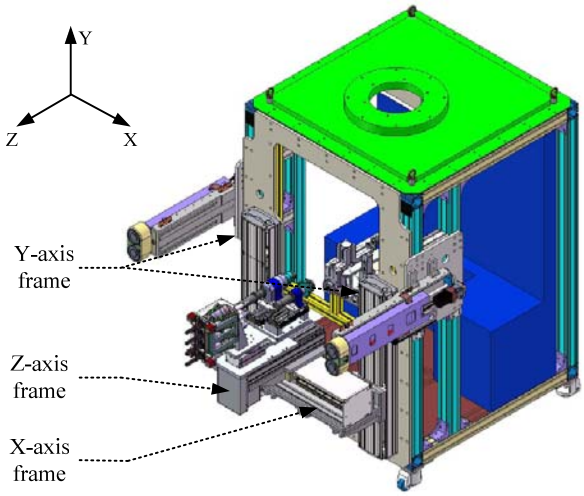


Figure 4. Coordinate system of robotic manipulator [4]

source and generate rotational motions with appropriate gear ratios. Different gear ratios of the two bolting tools make different rotational speeds and torques.

Figure 2 also shows a robotic manipulator attached on the front side of the cabin which has the function of moving the bolting end-effector to specific bolting positions. As shown in Figure 4, the robotic manipulator was designed as a gantry-type robot. The horizontal X-axis gantry frame crosses the two vertical Y-axis frames, and the Z-axis frame is placed on the X-axis frame and generates forward and backward motion. The bolting end-effector is located on the Z-axis and can be translated to any positions within the workspace of the robotic manipulator (770 Ｘ 500 Ｘ 300 mm^3). The position tracking accuracy is under dozens of micrometer, which is fine enough to perform the bolting task, considering the maximum allowable error to perform the bolting task is about a few millimeters. Also, since the gentry-type manipulator is intuitively well matched to the 3D Cartesian coordinates, a simple and reliable control algorithm can be designed [4].

2.2 Bolting Control System

The basic process for beam assembly work is to insert bolts to bolt holes and tighten the inserted bolts and nuts. For this purpose, it is necessary to place the bolting end-effector to bolt holes and bolt tails. In this research, the bolting control system is in charge of this task. The bolting control system is based on visual servoing technology which performs detecting objects of interest with information collected from a CCD vision camera and digital image processing. Since, in this research, shape recognition of circular objects like bolt holes or bolt tails is required, CHT (Circular Hough Transform) is applied to extract visual information. The distance between bolt holes and camera is measured by laser sensor, which decreases the computational complexity of digital image processing considerably. Figure 5 describes the figure used for the visual servoing process. (a) The

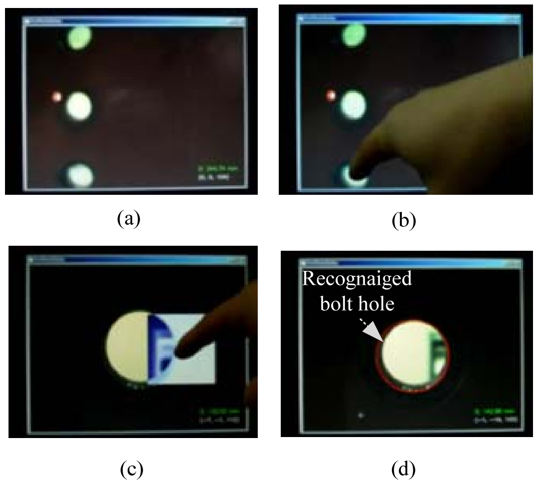


Figure 5. Visual servoing process tracking bolt holes

CCD vision camera recognizes several bolt holes on the screen. (b) The operator touches a target bolt hole among several bolt holes. (c) and (d) The visual servoing system recognizes the target bolt hole. It sends the position information of the bolt holes to the central bolting control system which controls the robotic manipulator and moves the bolting end-effector to the target holes. The visual servoing system can track the bolt tail positions as well as the bolt hole positions as shown in Figure 6.

The monitors in the cabin are not only used for visual servoing but also for ITA (Intelligent Teaching Agent) system which informs the overall state of the whole system. First, the ITA system gives the operator such information as where the robotic beam assembly system is currently located in the building and which beams the robotic bolting device is assembling, using GUI (Graphic User Interface) technology. Second, for the operator to handle the robotic system safely and efficiently, the overall assembly process, the current bolting situation, the next process, and instructions for safe operation are provided by the ITA system. Third, specific information such as the number of bolts and nuts, the distance between the robotic bolting device and beams, and so on is also given from the monitor. Figure 7 presents one of the monitor views of the ITA system.

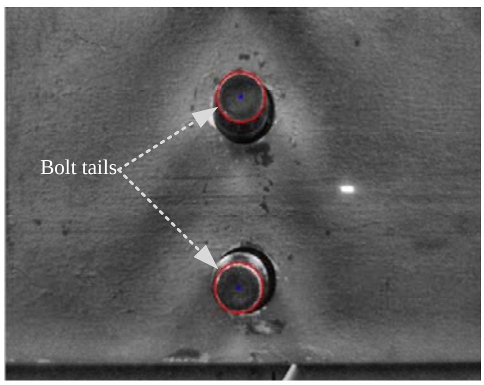


Figure 6. **V**isual servoing detecting bolt tails

Figure 7. Monitor view of the ITA system

3. ROBOTIC TRANSPORT MECHANISM

3.1 Construction Environment for the Robotic Beam Assembly System

To build even one floor of a building requires a number of steel beam assembly works. The positions where the beam assembly work should be conducted are all around the building. In this research a robotic transport mechanism that transports the robotic bolting device to bolting positions around the building was developed. In addition, in order to operate the robotic transport mechanism, a structural environment was suggested, which is called CF (Construction Factory). Figure 8 shows an actual picture of CF installed in the building. CF is a factory-like structure which gives suitable working environment for the robotic beam assembly system. CF weighs 200 tons and its operational dimension measures 28.5 X 28.5 X 11.15 m^3. Hydraulic lifting modules are used to lift CF. Figure 9 shows hydraulic lifting modules installed inside CF. One hydraulic lifting module can lift 50 tons. Total four hydraulic modules are installed on the building core to lift up CF. CF is a steel structure that surrounds one floor

Figure 8. CF installed on the building

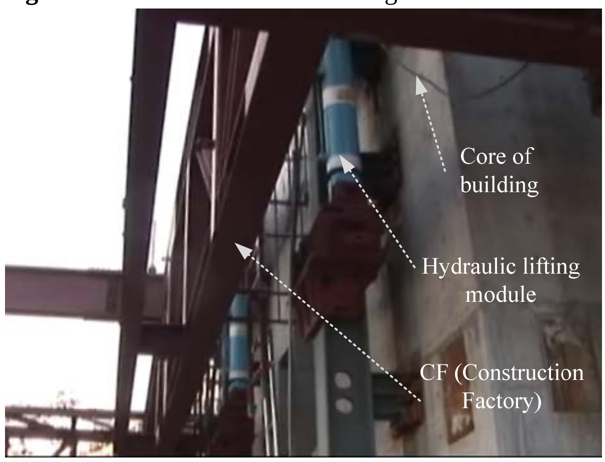


Figure 9. Hydraulic lifting modules installed inside CF

of a building and equips a rail system on which the robotic transport mechanism can slides. Figure 1 shows an overview of CF, the rail system, and the robotic beam assembly system which is installed on the rail. Figure 10 presents the real implementation of the robotic beam assembly system developed in this research. The robotic transport mechanism is composed of a cross-wired lift and a rail sliding mechanism, and the details of the system will be explained in the following sections.

3.2 Rail Sliding Mechanism

The rail sliding mechanism shown in Figure 10 slides on the rail installed in CF and transports the cross-wired lift and the robotic bolting device that are hung under it, forward and backward [5]. It consists of the body part in the middle and two electric driving modules placed at the ends of the body part. The material of the rail sliding mechanism is stiff steel since it has to support the cross-wired lift and the robotic bolting device which totally weigh 2 tons. In order to minimize the weight of the mechanism and keep the stiffness, it has a truss structure

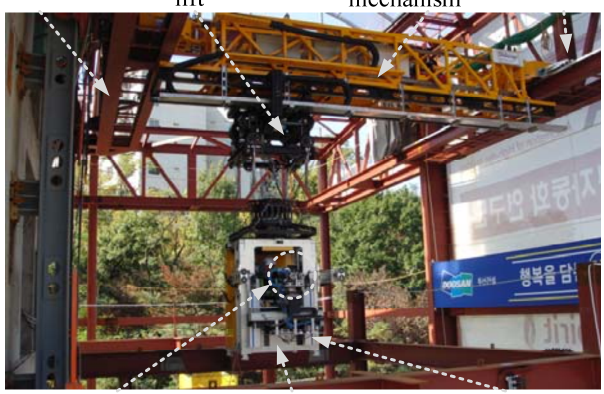


Figure 10. Real prototype of the robotic beam assembly

system

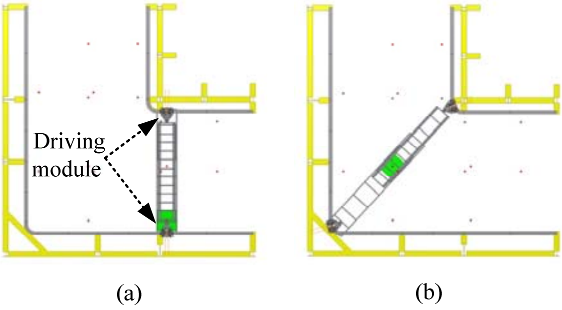


Figure 11. Rail sliding mechanism which moves around the corner

as shown in Figure 10. The weight of the mechanism is 2.5 tons and the maximum speed is 0.5 m/sec. The body part is separated to two parts, the inner part and the outer part. The inner part can slip into or out of the outer part so that the total length of the rail sliding mechanism varies from 8 m to 12 m. As shown in Figure 11, when the rail sliding mechanism moves on the corner of the building, the distance between two driving modules should increase and it is possible with the help of its variable length structure. The operator in the cabin can control each driving module independently using joystick operation.

3.3 Cross-wired Lift

The major function of the cross-wired lift is to lift the robotic bolting device attached on its lower end. The upper part of the cross-wired lift is hung on the linear guide that is installed on the bottom of the rail sliding mechanism [5]. All directional motions of the cross-wired lift can be independently controlled by operating a joystick in the cabin. A geared rack is also installed on the bottom of the rail sliding mechanism and is parallel to the linear guide. A geared pinion installed on the upper part

Figure 12. Rendering picture of building that is being constructed with the robotic system

Table 1. Description of building

Building dimension	1 story below and 7 above the ground
Use	Education and R&D
Structure	Steel frame construction
Building area	593.22 m^2
Total building floor area	4296.52 m^2
Maximum height of building	27.80 m

of the cross-wired lift is engaged in the geared rack and generates linear lateral motion by driving electric motor. Combining the lifting and lateral motion of the cross-wired lift and the forward and backward motion of the rail sliding mechanism generates a total 3D spatial motion. In addition, since the lower part of the cross-wired lift and the upper part of the cabin is connected by a rotational joint, 1DOF is additionally generated. Therefore, the robotic transport mechanism has total 4DOF and enables the robotic bolting device to approach all the bolting positions around the building. The upper and lower part of the cross-wired lift weighs 1 ton and the lifting and lateral speed is maximum 0.3 m/s [5].

Note that the lift has a cross-wired structure. In order to minimize the weight of the lift, it adopted a winching mechanism by wire. When the wires are arranged vertically, the lift can be easily disturbed by a later force. By employing the cross-wired structure as shown in Figure.10, the weight of the robotic bolting device hung under the lift, which is 1 ton, generates lateral supporting force by gravity and the cross-wired lift has a robust characteristic from lateral or twisting disturbances.

4. FIELD APPLICATION FOR BUILDING CONSTRUCTION

The robotic beam assembly system is applied to an actual building to test and evaluate its performance.

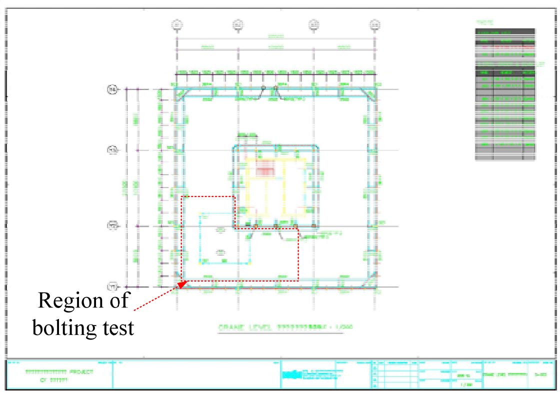


Figure 13. Plane view of the fifth floor

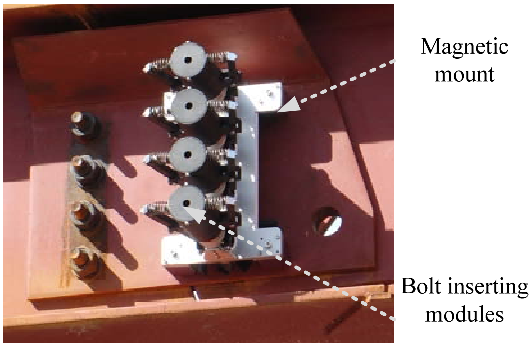
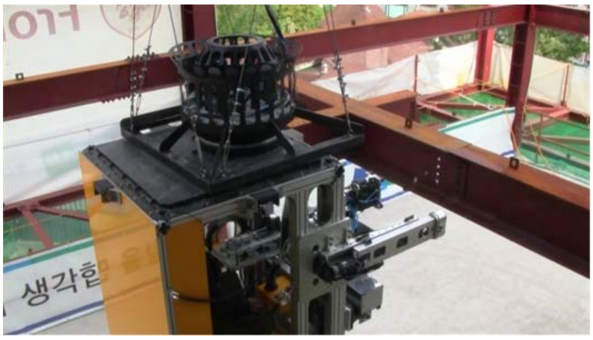


Figure 14. Bolt feeder

Figure 12 shows a rendering picture of actual building constructed with the robotic beam assembly system. The building which resides in Korea University consists of one basement and 7 floors. Table 1 shows the description of the building specification.

The robotic beam assembly system was tested on the

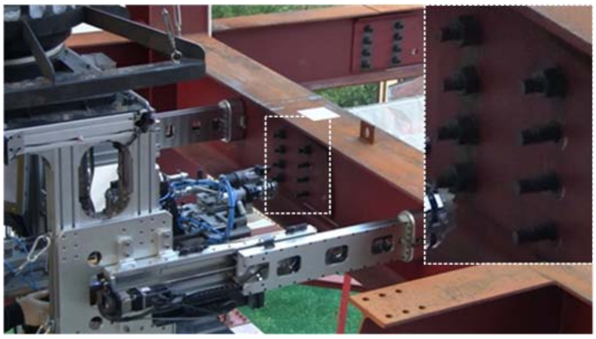


(a)

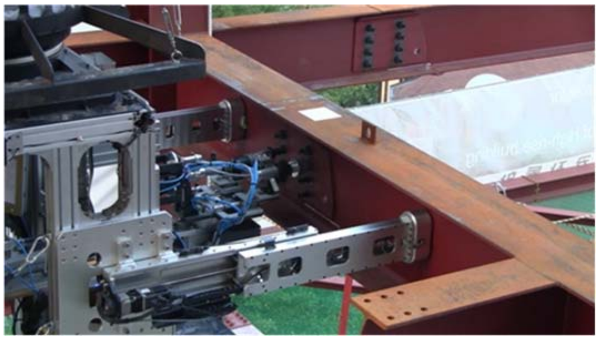
(b)

(c)

Figure 15. Bolt insertion process using bolt feeder



(a)



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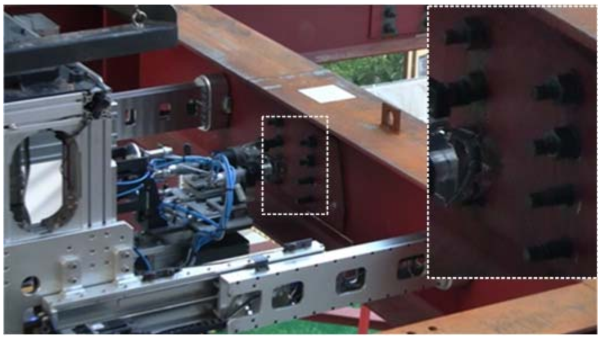


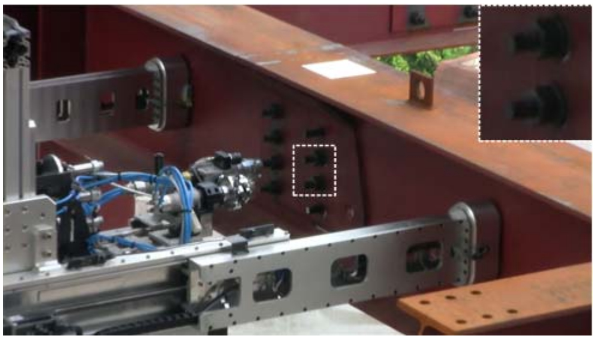
(c)

Figure 16. Assembly process using the first-assembly bolting tool

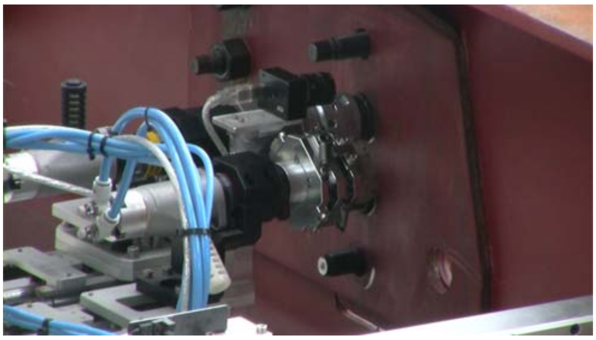
fifth floor. Figure 13 shows the plane view of the fifth floor where the robotic beam assembly system is applied. The test includes transportation of the robot, bolt insertion using a bolt feeder, and bolt assembly using bolting devices. The robotic beam assembly system was installed on the bottom left of the floor as shown in Figure 13. Rest of the building floor was constructed by human labor in order to compare efficiency, effectiveness, and safety.

4.1 Bolting Insertion Using Bolt Feeder

Figure 14 shows the bolt feeder for inserting bolts. The bolt feeder contains 4 bolt inserting modules and an attachment device. If a trigger that holds each bolt head is released, the bolt is shut by impulsive force stored in elastic springs. The attachment device uses 4 magnetic mounts to attach the bolt feeder to H-beam and prevents the bolt from falling. Figure 15 shows the bolt insertion using the bolt feeder. First, the robotic beam assembly system moves to a target position by using the rail sliding



(a)



(b)

(c)

Figure 17. Assembly process using the second-assembly bolting tool

mechanism and the cross-wired lift (Figure 15 (a)). Then, bolt holes are searched using visual servoing (Figure 15 (b)). The gantry-type manipulator precisely moves the bolt feeder to the bolt insertion point. After attaching bolt feeder by turning on the magnetic mount, air-pressure cylinder releases the trigger to insert the bolts. Figure 15 (c) shows the bolt feeder attached to the H-beam after the bolt insertion process.

4.2 Robotic Bolting Using Bolting End-effector

After bolt insertion process is completed, the robotic bolting device described in section 2.1 assembles the bolts. Figure 16 shows the assembly process using the first-assembly bolting tool. Figure 16 (a) shows transportation of the robotic beam assembly system to the bolting position. The first-assembly bolting tool is positioned after searching the bolt tail using visual servoing. Bolting manipulator is forwarded in Z-axis, and bolt, washer, and nut are engaged (Figure 16 (b)). Figure 16 (c) shows bolt, washer, and nut assembled using the first assembly bolting tool. After the first assembly is used, the second assembly bolting tool completes the entire assembly. As shown above, the visual servoing system searches the bolt tail and moves the second-assembly bolting tool close to the end point (Figure 17 (a)). When the assembly tool and nut are engaged, the second assembly tool is in motion (Figure 17 (b)). Figure 17 (c) shows the pintail of the bolt fallen off after the assembly is completed. This is the whole process of H-beam assembly [4].

5. CONCLUSIONS

In this paper, a robotic bolting assembly system was introduced, which was applied to actual building construction site. The robotic bolting technology and the robotic transport mechanism were developed to apply the system to the construction site. The robot transport mechanism that consisted of the rail sliding mechanism and the cross-wired lift was successfully tested. After recognizing bolt holes with visual servoing technique, the robot system could perform bolting process using bolt insertion feeder and other bolting tools. Repetitive test results were all satisfactory, which represents a possibility of replacing risky and difficult construction works with automated robots.

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