Case Studies on Glazing Robot Technology on Construction Sites

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ABSTRACT

Glass panel (curtain-wall, glass ceiling etc.) is a type of building material for interior/exterior finishing. The demand for larger glass panel has increased along with the number of high-rise buildings and an increased interest in interior design. Typical construction machineries are, however, not adequate for installing the glass panel and most of the construction works have been still managed by a human operator. Construction processes are, therefore, fraught with a number of problems. The objective of this paper to introduce case studies on glazing robot technology for installing glass panel on construction sites. The first case is related to robot technology for installing curtain-walls in a high-rise building construction site. To satisfy curtain-walls installing needs for precise and safe work, especially, a hybrid motion typed curtain-wall glazing robot (HCGR) has been developed and applied to real construction sites. After applying HCGR to a real construction site, the second case study is directly planned to apply glazing robot technology to glass ceiling installing process. In all cases, a novel control strategy of glazing robot is proposed for installation of heavy glass panels in cooperation between a human operator and a glazing robot.

Keywords –

Case study; Glass panel; Glazing robot; Construction site

1 Introduction

Recent research has found that a lack of skilled manpower in the construction industry is rapidly becoming a serious problem. This problem of a shrinking workforce, coupled with an aging society, leads to higher wages, a drop in construction quality, project delays, increased costs and the increased likelihood of accidents occurring at construction sites. One of the solutions suggested to solve these problems is robotization or automatic installation.

The issue of applying "Automation System and Robotics in construction" has been raises as a result of the need for improvement in the safety, productivity, quality and working environment [1,2]. Sequentially, operation with automation systems and robots are widely employed at construction sites. Since the late 1980s, construction robots have helped operators perform hazardous, tedious and health-endangering tasks in heavy materials handling. Isao et al. discussed the appropriateness of automation technology for installation of curtain wall [3]. Gambao, Balaguer and Gebhart obtained the robotic systems that improve the manual block assembly tasks reducing dramatically the construction time and efforts [4]. Ostoja-Starzewski & Skibniewski designed the master-slave force-feedback hydraulic manipulator that contributes to the flexibility and productivity enhancement of related work tasks [5]. Santos et al. introduced a manipulator to assist the operators in handling and installing pre-manufactured plaster for indoor-wall construction [6]. Skibniewski & Wooldridge described an automated materials handling system concept for managing and handling construction materials within automated building construction systems [7].

Generally, almost half of construction work is said to be handling of building materials [8]. Building materials used for construction are heavy and bulky for humans. Curtain-walls are receiving much interest from the architecture sector recently, as a new form of cladding material. Even though it is composed of aluminium frames and glasses for lightweight feature, such a building cladding material is relatively heavy and thus, installation of curtain-walls by manpower can cause many problems, considering that the construction industry presently lacks skilled labor and harbors an aging workforce. Also, handling curtain-walls has been, for the most part, eliminated for outside work by cranes and other various lifting equipment. Such equipment, however, is not available for precise work.

In construction, a building is custom-made and construction robots must be reprogrammed to operate in each given condition [9]. Consequently, construction robots are defined as field robots that execute orders while operating in a dynamic environment where structures, operators, and equipment are constantly changing [10,11,12]. Therefore, during operation of remote-controlled construction robots, problems arise due to operators receiving limited accurate working information; the contact force when it carries out assembling between building materials, thus reducing the ability to respond to the constantly changing operational environments.

To satisfy curtain-walls handling needs for precise and safe work, especially, a hybrid motion typed curtain-wall glazing robot (HCGR) has been developed and applied to real construction sites. The developed robotic system overview is a macro – micro motion manipulator. A mini-excavator is considered to be the macro motion manipulator for lifting and moving of curtain-walls. The new developed 3 DOF robotic arm is considered to be a micro motion manipulator for precise handling of curtain-walls. Moreover, a human-robot cooperative construction method, in which an operator can handle building materials intuitively, is suggested as a novel control strategy. Field tests for the HCGR prototype are conducted in real construction sites. A comparative analysis between the productivity of the prototype robot and the productivity of the human based construction method is executed.

The second case of glazing robot technology is related to glass ceiling handling for interior finishing of high-rise buildings. The demand for larger glass panels has been increasing along with the number of high-rise buildings and the increased interest in interior design. Nevertheless, introducing glazing robot technology into glass ceiling handling has been more difficult than in other construction works. Robots for handling glass ceilings are receiving special attention because of the difficulties of moving to high installation position and handling fragile building materials. To address these conditions, we have proposed a 'Glass Ceiling Glazing Robot (GCGR)' based on human-robot cooperation. After analyzing a target work, we have conducted a concept design for the suggested robot. And then, detail design of the robot based on H/W and S/W is described. Lastly, the result of field test is discussed.

2 Case #1; Hybrid motioned Curtain-wall Glazing Robot (HCGR)

As the tendency changes toward larger and taller buildings and structure, it has been accompanied by advances in the study and development of new building materials. Curtain-walls, which are responsible for adiabatic function, water-tightness, and the aesthetics of a building, are of particular interest to the building construction field. But, because of the lack of suitable construction equipment for curtain-wall handling, the process is complicated and hazardous, relying on existing equipment and a large amount of manpower. In order to solve these problems, a mechanized construction involving a mini-excavator and a simple rotational mechanism was attempted in the second handling method described in Figure 1. Through use of the mini excavator system, a curtain-wall can be moved to the assembly point easily. This system also reduces the number of workers and the amount of construction time. The curtain-wall assembling, however, must still be operated by a construction worker. Therefore, we proposed the usage of 'a Hybrid motioned Curtain-wall Glazing Robot (HCGR)' as an example of a suitable robotic system for carrying out simple and safe curtain-wall handling method. The proposed system has a 3 DOF robotic manipulator. The manipulator is controlled by human force to generate robotic trajectories.

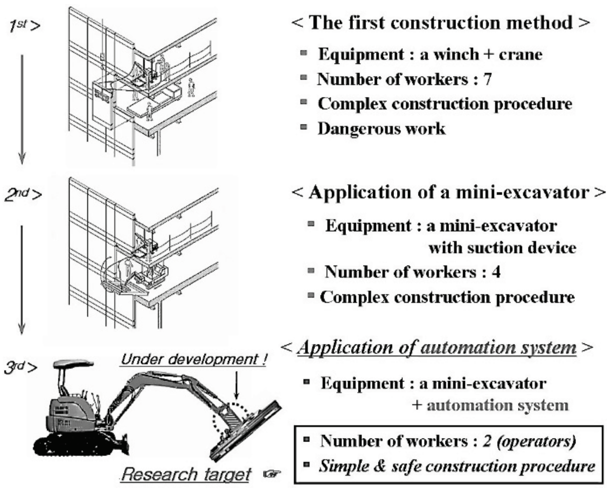

Figure 1. Development procedure of a curtain-wall glazing robot

2.1 Robot Hardware

The HCGR overview is a macro - micro motion manipulator. A mini excavator is considered to be the macro motion manipulator. The 3 DOF robotic manipulator is considered to be a micro motion manipulator as shown in Figure 2. The HCGR overview is a macro - micro motion manipulator. A mini excavator is considered to be the macro motion manipulator. The 3 DOF robotic manipulator is considered to be a micro motion manipulator as shown in Figure 2. The micro motion manipulator can be used not only in curtain-wall installation but also in other construction work. This manipulator, therefore, is modularized to add or remove DOF as target construction works as shown in Figure 3. Table 1 shows the diagram of the modularized design.

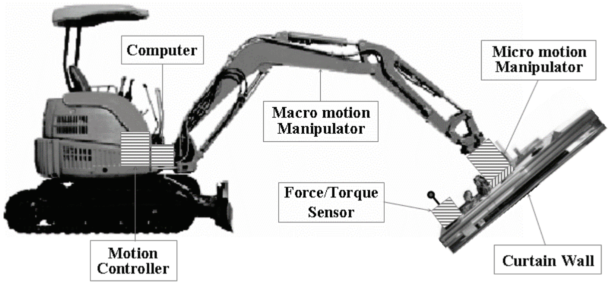

Figure 2. Hybrid (macro/micro) motioned curtain-wall glazing robot

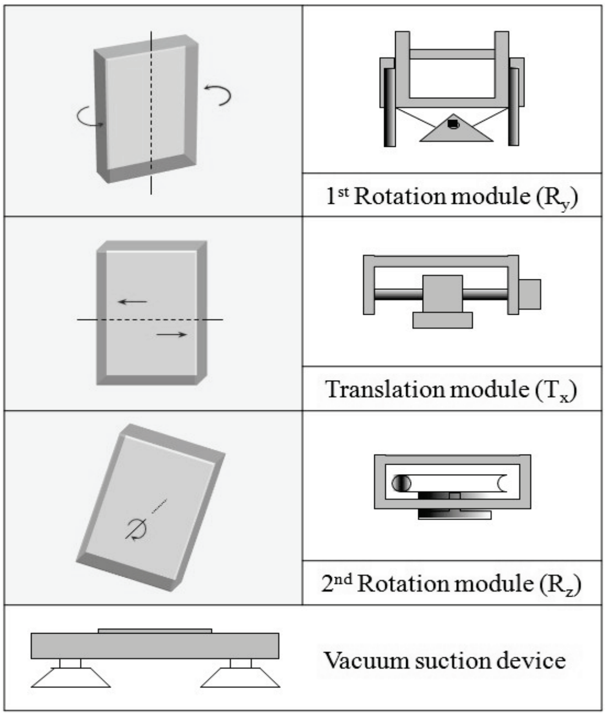

Figure 3. Modularized robotic manipulator

Table 1. Required force/torque and motion range in each module

Module	The required force, torque and motion range	
1st rotational motion module (Ry)	Motion range	20°
	Required torque	196.4 Nm
Translation module (Tx)	Motion range	0.25 m
	Required torque	20.0 N
2nd rotational motion module (Rz)	Motion range	270°
	Required torque	725.54 Nm

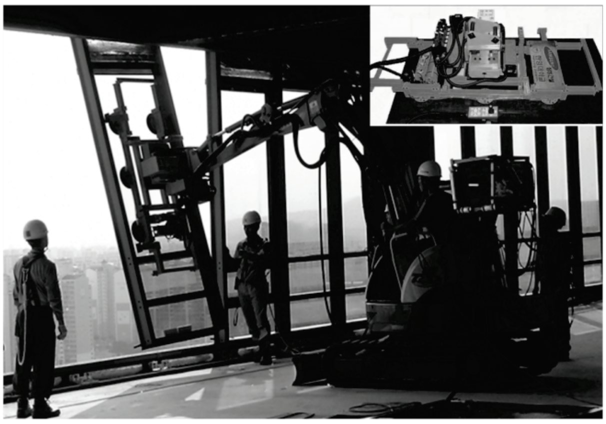

Figure 4. HCGR with a 3-DOF robotic manipulator

Figure 4 shows the shape of the completed HCGR and the 3-DOF modularized manipulator. Each module is combined with consecutive order to embody the selected DOF, and the order is then closely related to the working efficiency and safety of the system. That is, it is unreasonable for an actuator to generate beyond the necessary force and torque. This would cause the whole work capability to fall after a worker had run the manipulator with beyond-necessary power.

2.2 Control Strategy

The fully automated system is not suitable for construction work due to frequently changed construction environments. A human-robot cooperative system is, therefore, suitable for construction work [13,14]. It is an interactive system in order to cooperate with the human, as presented in Figure 5.

Generally, the robot is capable of high speed and power, whereas the human is sluggish, releasing only small amounts of energy, and commits errors frequently. On the other hand, the human is much more flexible and adaptable in thinking, motion, and behavior. As the reason, we introduce that integration of advantages of both robots and humans, and incorporation of them into the human-robot cooperative manipulation, would improve the efficiency or performance of the system from the viewpoints of human error and work efficiency.

Considerations on interactions among the operator, robot and environment are applied to design of the robot controller. That is to say, the system, to which the introduced control method is applied, allows an operator to handle building materials as if he did it by himself or herself, by exerting operational force with a certain power assist ratio. Also, this system enables an operator to perform operations more intuitively by allowing him or her to feel reaction forces from environments during

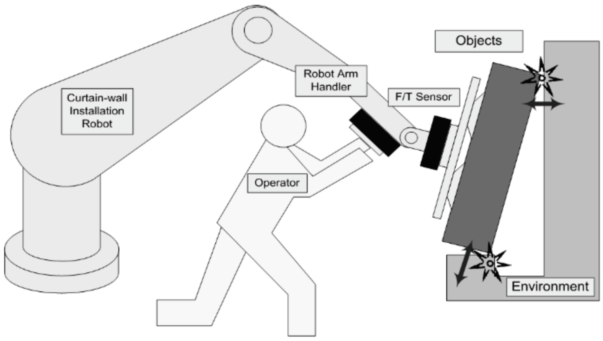

Figure 5. Concept of human-robot cooperative system

an operation. An intelligent HRI (Human-robot interface) device is introduced to implement the human-robot cooperative manipulation. As shown in Figure 6, if an operator puts external force containing an operation command on a on a handler of the robot controller, it is converted into a control signal to operate the robot with sensor A (6 DOF force/torque sensor). Here, if the robot comes in contact with an external object, information on the contact force is transmitted to the robot controller through sensor B (6 DOF force/torque sensor). It is important to note that external force transmitted through sensor B and that transmitted to sensor A should operate separately from each other.

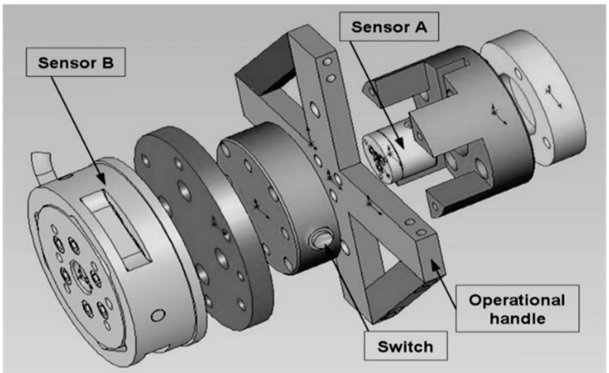

Figure 6. Human robot interface device

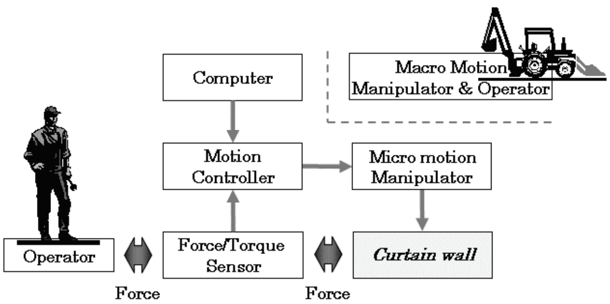

Figure 7. Control strategy of HCGR

Figure 7 shows control strategy for HCGR. The worker drives a 3-DOF robotic manipulator through the HRI device which is positioned between the manipulator and a curtain-wall. Based on the information from this controller, a control algorithm calculates a command signal which is sent to the motion controller board via a digital analog (D/A) converter. After which, the desired control is achieved after the present working information is obtained as real-time feedback from the encoder adhered to the AC servo motor.

2.3 Field test

In order to measure the productivity of the proposed robotic system, the existing handling (depends on manpower) method on a real construction site is analyzed and compared with the robotic handling method. Figure 4 indicates the handling process of the curtain-wall by applying the proposed robot to a construction site. The opinion of the operators may be of great help comparing the productivity of each handling method. We obtained the results of a questionnaire given to each curtain-wall installer. They were asked their opinion about their current curtain-wall handling method, their future demands and aspects they considered important to work well with the robot. This allowed us to identify aspects that need improvement in robot development.

Table 2. Comparison of the existing (depends on manpower) handling method and the robotic handling method

	The existing handling	The robotic handling
Working time	18 min.	15 min.
Labor intensity	High momentary labor intensity	Generally low labor intensity
Convenience	Profoundly dangerous work under obstacle interference	Generally convenient work
Safety	Generally dangerous; scattered accidents	Reduction in danger; fewer accidents
Laborer	3	2

3 Case #2; Glass Ceiling Glazing Robot (GCGR)

Existing glass ceiling glazing process is complicated and hazardous, relying on a scaffold (or aerial lift) and a human labor. This process exposes operators to accidents of falls or vehicle rollover, and so on. Moreover, inappropriate working postures are major elements in increasing the frequency of accidents by causing various musculo-skeletal disorders and decreasing concentration on work [15]. That is to say, it becomes causes of decreasing productivity and safety in construction. Since Ramazzini mentioned the harmful consequences for violent and irregular motions and unnatural postures of the body, poor working postures have been considered as one of the major causes of musculoskeletal disorders in industrial sites by many ergonomists and practitioners of health and safety.

Figure 8 shows the construction site and glass ceilings glazing position (soffit of building). The building size is 32m × 22m, and the glazing positions of glass ceilings are 7.9m and 15m above the ground. Glass ceilings for handling can be classified into three categories. The first category includes the glass ceiling 750mm×1500mm and 40kg. The second category includes the glass ceiling with 1500mm×1500mm and 80kg. The last category includes the glass ceiling with 3000mm×1500mm and 150kg. We introduced 'Module T&H-bar' as installation method that is represented 'Lay-in' to put up glass ceilings on ceiling fames as shown in Figure 9.

Figure 8. Glazing position

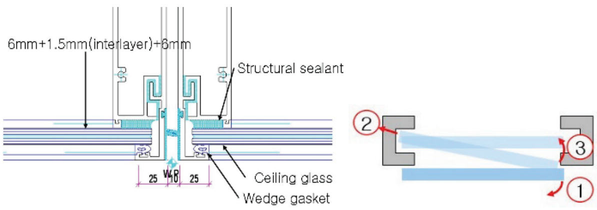

Figure 9. Module T&H bar and Lay-in

3.1 Robot Hardware

The essential function of the glass ceiling glazing robot is drawn through spot analysis and existing methods, as shown in Table 3. First, exclusive equipment that can transition through many operators is required to install large-sized ceiling glass safely. Also, the modus that is necessary for the worker's technology can be reflected as is during installation, in order to achieve

Table 3. Essential function

Requirements	Details
High–rise work	Working height : Approx. 15m
Support for high-rise work	Operator (Approx. 70kg) + Glass ceiling (Approx. 150kg ×3EA) + Installation equipment (dependant)
Working range	32m × 22m
6-DOF manipulation	Lay-in operation after grip glass ceiling
Handling heavy materials	available weight : approx. 150kg
Grip for glass ceiling	Optimization for handling glass ceiling
Intuitive control	Directly teaching by operator
Force augmentation	Handling heavy materials by relatively scaled down force
Force reflection	Feeling environmental force

consistent construction quality. The most suitable installation plan design for increased productivity and a countermeasure to prevent accidents with simulations and spot tests is required. According to the essential functions determined by work analysis, the concept design of a GCGR is as follows.

1. An aerial lift is needed that can support an operator and the installation equipment with enough working range to reach about 15m height from the ground.
2. A multi-DOF manipulator is needed to install the heavy glass ceiling alternating through many operators. The robot has to be chosen according to the working space and payload.
3. This system is in semi-automation, in order to cope in a changing work environment. One operator gets into the deck of the aerial lift to operate a multi-DOF manipulator. The worker's judgment becomes the upper robot controller.
4. In order to reflect the worker's ability, external force information is used as the input signal for the robot exercise. The force information that uses the input signal needs to regulate freely according to the desired robot exercise and operator's age.
5. A vacuum suction device is used as an end-effect device to handle the glass ceiling. In preparation for variation of glass ceiling form, an end-effector is designed by modulation.
6. The deck of the aerial lift supports both the worker and robot. The design of the deck and work process must consider the worker's safety and productivity.

The essential functions found by work analysis are classified by hardware and software. Table 4 shows each requirement and approach method.

Figure 10 shows a hardware design of GCGR, and Table 5 indicates a specification of GCGR. The hardware of the proposed system is classified into two parts: the basic system and a HRI device (Figure 11). An aerial lift and an industrial multi-DOF manipulator are suggested for use in the basic system. The HRI device is involved with installing glass ceiling by correlating the operator with a manipulator. This device plays a role in delivering the operator's intentions to the robot controller. It is positioned between the flange of the multi-DOF manipulator and the vacuum suction device, as shown in Figure 11, while it is composed of two 6-axis F/T sensors.

Table 4. Approach for requirements

Requirements	Section	Solution
High-rise work	H/W	Aerial lift
Support for high-rise work	H/W	Aerial lift
Movement covering working range	H/W	Wheel-typed aerial lift
Deck	H/W	Aerial lift reconstruction
Multi-DOF manipulation	H/W	Multi-DOF manipulator
Gripper for glass ceiling	H/W	Suction device
Force augmentation	H/W	Multi-DOF manipulator
	H/W	HRI device
	S/W	Human-Robot Cooperative control algorithm
Intuitive operation	S/W	Human-Robot Cooperative control algorithm
Force reflection		Human-Robot Cooperative control algorithm

Table 5. Specification of GCGR

Functions	Descriptions
Aerial work	Height of the workplace of 15m
Allowable weight	Laborer: approx. 70kg Glass ceiling: approx.150kg
Construction method	Lay-in method inserting the glass ceiling into frame
Installation Gripper	Vacuum Pad type handler
Control strategy; Human-Robot Cooperation	Intuitive manipulation Power assistance Force reflection

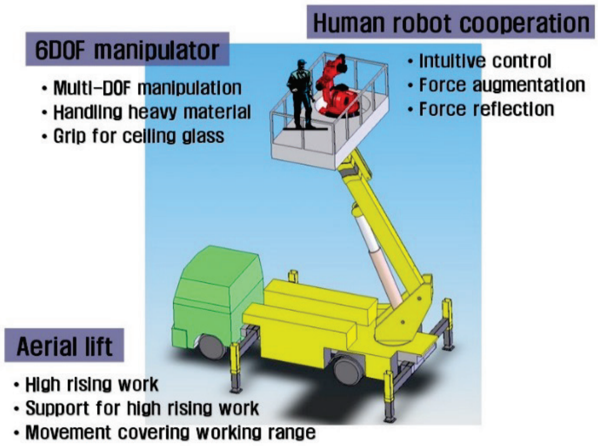

Figure 10. Design of GCGR

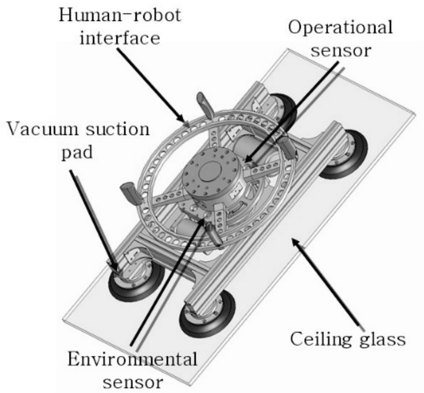

Figure 11. A vacuum suction device and a HRI device

3.2 Robot Control

Free space motion (motion under non-contact conditions between glass ceilings and glazing frames) needs rapid movement with relatively low precision while motion under contact conditions needs precise motion with relatively slow robotic motion. According to modeling of the interactions among the operator, robot and environment, we designed an impedance controller for the human-robot cooperation (Figure 12). When an operator judges that the position (X) to which a robot carries glass ceilings fails to agree with the position (X_d) to which he or she wants to carry them, his or her force is transmitted to sensor A. In particular, external human force (F_h) measured by sensor A can be used by operators from various age groups through the force augmentation ratio (α). That is, all people, regardless of muscular strength, can operate a robot by the force augmentation ratio. In terms of an operator's inputted force and the contact force (F_e) with environments inputted from sensor B, the target dynamics needed for operation are determined by the following equation (1) for impedance. Of the dynamics values, the deviation between the target position (X_d) and the present position (X) decreases as feedback is received through the encoder of a position/direction controller, resulting in 0. In other words, the current deviation is inputted into a servo controller, which causes a manipulator to pursue the target position value. In addition, it is possible to adapt the operation properties of a robot's motion characteristics by controlling the impedance parameters (M_t, B_t) in equation (1). Relatively rapid and precise motions can be implemented by controlling these parameters.

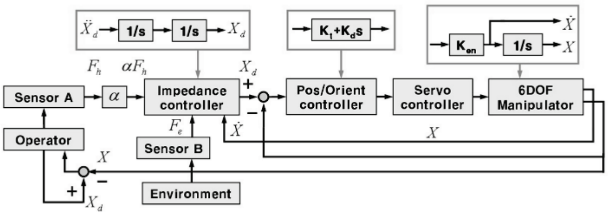

Figure 12. Block diagram for GCGR control

$$\ddot{X}_d = (M_t)^{-1}\{(\alpha F_h - F_e) - B_t \dot{X}_d\} \quad (1)$$

Where, $\ddot{X}_d$: Acceleration related target dynamics
$\dot{X}_d$: Velocity related target dynamics
M_t : Inertia related impedance parameter in the virtual system
B_t : Damping related impedance parameter in the virtual system

3.3 Field Test

The proposed robotic system is developed to construct the soffit, an exterior (a glass ceiling) as shown in Figure 13. The installation positions of glass ceilings are 15m, and the size and weight of glass ceilings are 3000mm×1500mm and 150kg. Based on the task planning, the proposed handling process can be described as below:

1. The deployment of an aerial work platform on which the proposed robotic system is mounted.
2. Loading the glass ceiling on the deck.
3. Lift the glass ceiling near the frame in which the glass ceiling is laid.
4. Install the glass ceiling and finish the work.

Before lifting the deck, one piece of glass ceiling is loaded on the deck. Then, according to the deployment plan, the robot approaches to the installation position.

Figure 13. Field test of GCGR

Then, the installation begins according to the planned process shown in Figure 13. The procedure of handling cannot be defined systematically because it depends on the workmanship of workers and the construction environment which is unconstrained or not repetitive.

Table 6 shows the comparison and analysis of the two glazing methods. Working time means the whole time consumed in moving the glass ceiling from the ground and fixing it on the building soffit, and labor intensity means the degree of manpower strength required of workers during the glass ceiling handling process. Convenience indicates the degree of difficulty of the handling work, and safety shows derived degree of safety.

Table 6. Comparison and analysis of existing (depends on manpower) glazing method and robotic glazing method (The size and weight of glass ceilings are 3000mm×1500mm and 150kg.)

	The existing handling method	The HRC handling method
Working time	Avg. 28min/piece(including finishing and break time)	Avg. 26min/piece(including finishing)
Labor intensity	High momentary labor intensity	Generally low labor intensity
Convenience	Profoundly dangerous work under obstacle interference	Generally convenient work
Safety	Generally dangerous; scattered accidents	Reduction in danger; fewer accidents
Laborer	13(deck:12(2groups), aerial lift:1)	3(deck:2, aerial lift:1)

The resulting comparison and analysis in Table 6 can be changed according to the working environment of the applied construction site. In the case of handling building materials on smaller buildings, the work may depend on manpower. But according to the tendency of current construction trends towards larger and taller buildings, the presented expectations of the GCGR here provide a bright outlook.

4 Conclusion

Until now, we discussed introduction to human-robot cooperative system on glazing process in high-rise building. To apply human-robot cooperative manipulation at real construction sites, we must execute additional work required for application. Firstly, according to analysis of job definition and working condition, it is deduced that the conceptual design of a construction robot for handling building materials. And then, detail design of the robot based on the field robot design is described. Finally, after field test at a real construction site, productivity and safety of the developed system are compared with the existing glazing equipment. A robotic manipulator and a mobile platform of the HCGR and GCGR, are combined to suit various working conditions and building materials as module type. Therefore it is possible to handle a variety of building materials in various construction sites. To improve technology of human-robot cooperative manipulation, lightweight robot link, robust robot force control, flexible robot arm and teleoperation based on force feedback will be developed in the future.

Acknowledgment

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