Introduction of Human-Robot Cooperation Technology at Construction Sites

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Abstract -

Currently, a new construction method using a robotic system is widely spreading in construction sites. This study is related to introduction of human-robot cooperation technology which can improve convenience and productivity through the efficient interaction between a worker and a robotic system while doing glass panel installation works. Based on the analysis on glass panel installation with a glazing robot, functional requirements and approaches to address these requirements that can implement human-robot cooperative manipulation at construction sites. A practical example, which is applied to a specific target construction site, is also described in this paper. After field test at a real construction site, productivity and safety of the proposed system are compared with the existing glass panel installation system.

Keywords -

Human-robot cooperation, Construction robot, Glazing robot, Glass panel, Curtain-wall

1 Introduction

Since the late 1980s, construction robots have helped operators perform hazardous, tedious, and health-endangering tasks in heavy material handling [1~10]. Iwamoto et al. stated a similar problem that reduces the need for a labor force and provides improved productivity and safety [11]. Isao et al. discussed the appropriateness of the automation technology for installation of a curtain wall [12]. Masatoshi et al. proposed the automated building interior finishing system, and a suitable structural work method is described [13].

Generally, almost half of construction work is said to be building materials handling. Building materials and components are much larger and heavier than many other industrial materials. Buildings are made of many kinds of materials and each material may be a different shape. Glass panel is one type of building materials for interior/exterior finishing. The demand for larger glass panels has been increasing along with the number of high-rise buildings and the increased interest in building design. A glass panel has been designed to pursue beautifulness and satisfy the requirements from customers. Nevertheless, the size and weight of glass panel have to be limited in consideration of feasibility on entire process from transportation to installation. Because of the lack of suitable handling/installation equipment for glass panels, the construction process is always complicated and hazardous, relying on a number of construction workers. As shown in figure 1, handling heavy construction materials (e.g. curtain-walls etc.) 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. To address curtain-walls handling needs for precise work, especially, 'TRCI (a Teleoperated Robot for Curtain-wall Installation)' has been developed and applied to the real construction site as shown in figure 2 [14]. This system comprised of two types of a robotic manipulator. One is a hydraulic actuated manipulator to implement curtain-wall handling (e.g. lifting, moving etc.) motion, the other is an electric actuated manipulator to implement precise curtain-wall installing motion with teleoperation.

A robotic system can be classified into two groups: those that can carry out work and coexist with humans in atypical environments, and those that do repeated work according to a standard program such as part assembly or welding and coating in the automobile and electronic industries. Thus, manufacturing robots are stationary and the product moves along an assembly line. In contrast, construction projects require a stationary product, that is the building, and the robots change location. Moreover, in manufacturing, robotic repetition provides identical products, whereas, in construction, the product is custom-made and robots must be reprogrammed to operate in each given condition [15]. 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. Therefore, a guidance or teleoperated (or remote-controlled) system is the natural way to implement construction robot manipulators. However, during operation of a teleoperated construction robot, problems arise due to operators receiving limited working information; the contact force when it carries out press pits between materials, thus reducing the ability to respond to the constantly changing operational environments. A human-robot cooperative method [16~18], in which an operator can handle/install glass panels intuitively, is described as improvements in this paper.

Figure 1. Glass curtain wall installation by cranes (or winches) and workers in high-rise building

Figure 2. TRCI (a Teleoperated Robot for Curtain-wall Installation)

2 Functional Requirements and Approaches

After applying TRCI to a real construction site, we analyzed that the construction methods with/without TRCI had advantages and disadvantages in glass panels installing. The construction methods with TRCI is capable of motions needed high speed or power, whereas the methods without TRCI (i.e. construction method depends on workers) is sluggish, releasing only small amounts of energy, and commits errors frequently. On the other hand, the methods without TRCI is much more flexible and adaptable in thinking, motion, and behavior. Based on the upper analysis on construction methods with/without TRCI, we deduced functional requirements to be improved that integration of advantages of both construction methods with/without TRCI, and incorporation of them into the Human-Robot Cooperative (HRC) manipulation, would improve the efficiency or quality of glass panel installation as below. First, we considered a robotic system that can correctly follow a worker (or a robot operator)'s motion intention for glass panel installation at construction sites. Second, we also examined a robotic system that can share workspace with a construction worker in safety guaranteed. Third, we designed a coordination program for efficient cooperation between a worker and a robotic system in each unit work of glass panel installation. Finally, we worked out a detailed plan for a dexterous robot control that can reflect worker's technological know-how.

Studies on the human-robot cooperation have been ceaselessly performed so far. In 1962's the Cornell Aeronautical Laboratory researched master-slave system to amplify the human operator's strength [19]. And then, further work was done by GE. GE designed Hardiman which is exoskeleton typed man-amplifier [20]. In 1980's, kazerooni approached the innovative man-amplifier, extender, which is different from a master-slave system [21~23]. Power and operational signals are directly translated from human to robot. Kosuge presented a control algorithm for the human-robot cooperation using maneuverability and amplification factor [24].

To address upper functional requirements, we deduced an approach to human-robot cooperative manipulation in process of glass panel installation at construction sites. This approach is related to design of a robotic controller that can amplify force of operator with a certain force augmentation ratio so that operator can manage a heavy glass panel with relatively scaled-down force. And, to feel reaction forces helps intuitive operation by reflection of force from environments. Figure 3 describes a schematic of conceptual design based on the approach for introducing human-robot cooperation technology at glass panel installation sites. This concept design, especially, is considered interactions among human, robot and environment, and generation of target dynamics. To implement the human-robot cooperation in constrained condition (i.e. when a glass panel is under installing to a panel frame by the robot), the impedance control method, which was proposed by Hogan [25], is applied as a basic robot force control method.

The development methods for construction robots can be classified into two categories. The first category involves developing entirely new robots that can achieve requested work. The second category involves new robots implementing with existing similar construction equipment. The first method is beneficial in optimizing specifically requested work. However, the cost and time required by this method are the major drawbacks to developing new robots. The second method is difficult to optimize for target projects, but it can achieve efficiency with limited cost and time requirements. In this study, the second method is introduced to implement the suggested robotic system.

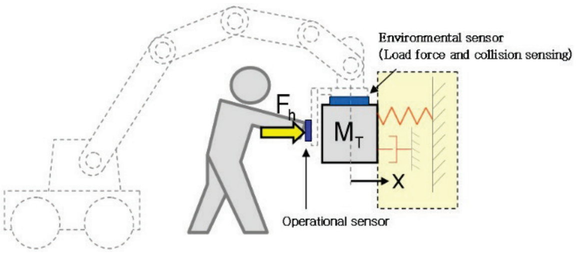

Figure 3. A schematic of conceptual design for glass panel installation based on human-robot cooperation

3 A Practical Example

The existing glass panel installation process, which is complicated and hazardous, relies on scaffolding (or aerial lift) and construction workers. This process exposes workers to falling accidents or vehicle rollovers. In addition, inappropriate working posture is a major element that increases the frequency of accidents by causing various musculo-skeletal disorders and decreasing concentration. That is to say, it becomes a direct cause of decreasing productivity and safety in building construction.

Figure 4 shows the target construction site and glass panel installation position related to the first application of human-robot cooperation at construction sites. The building size is 32m × 22m and the installation position of glass panels is 7.9m above the ground. The glass panel used for installation can be classified into two categories. The first category is a glass panel that has 3000mm × 1500mm dimensions and is 120kg. The second category is a glass panel that has 1500mm × 1500mm dimensions and is 60kg. This paper introduces the 'Module T&H-bar' installation method, which represents the 'Lay-in' to place the glass panel on frames. According to analysis of the target work, it is deduced the functional requirements for implementing a glass panel installation system based on human-robot cooperation as below. First, this system must be able to lift heavy glass panels, a worker, and the installation equipment. It requires engines, batteries, or motors to lift them. Second, this system must be able to handle heavy and fragile glass panels. It requires sophisticated force and position control based on human-robot cooperative manipulation. Third, this system must be devised to help construction workers, not to replace them. This requires a smart human-robot interfacing device to interact with a robot operator and a robotic system. The system must share the workspace with a robot operator. Fifth, this system must be able to reflect the technical operator's skills that are required to obtain homogeneous construction quality. Thus, the system must follow the operator's motion intentions in various working processes and environments at unstructured construction sites. Last, this system must belong in the task planning. This is required to prevent worker's accidents and help workers increase productivity, by reducing the recovery time from system malfunctions and decreasing the worker's duty time in dangerous works.

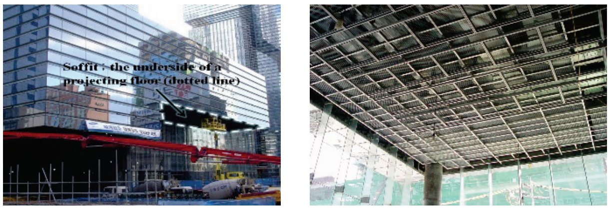

Figure 4. Target construction site

According to analysis of the functional requirements, an approach for human-robot cooperative manipulation, is generated as shown in Table 1. A hardware design in the approach can be classified into two categories: a basic system and a human-robot interfacing device. A combination between a mobile platform (e.g. aerial lift etc.) and an industrial multi-DOF manipulator is considered as the basic system. Aerial lifts are designed for enabling altitude work. In this study, the aerial lift raises the manipulator, glass panels and a robotic operator up to 7.9m. In selecting a suitable aerial lift, diverse aspects were considered including mobility, reachable distance, and payload. The aerial lift must have adjustable movement within a constantly changing work environment. Therefore, considering mobility, a wheel type of aerial lift was selected, which is mounted on the truck with a telescopic boom. Considering the reachable distance and payload, it is necessary to expand the selection criteria to include not only specific properties but also safety concerns. Figure 5 shows the selected an aerial lift that can lift payload of 2000kg. A multi-DOF manipulator is needed to install heavy glass panels, thereby replacing a large amount of construction workers, by cooperating the robotic operator and the manipulator. The manipulator is chosen to help the robotic operator, not to replace them. The manipulator has to be chosen according to the workspace and payload. The payload and the weight of any additional devices (e.g. a vacuum suction device, a human-robot interfacing device, an end-effector of a robotic manipulator, etc.) required for installation must be considered. Figure 5 shows the selected model (KUKA Industrial Robots). In order to control the motion of the manipulator, kinematic and dynamic analysis is required. As operator's safety is influenced by these types of motion, while any singularities in the hardware and software should be considered carefully. The human-robot interfacing device is involved with installing glass panels by cooperating a robot operator (In here, a robot operator is one of normal construction workers, not a robotic engineer.) with the basic system. This device plays a role in delivering the robot operator's motion intentions to the basic system's motion controller. It is positioned between the flange of the multi-DOF manipulator and the vacuum suction device, while it is composed of two types F/T sensors. If the robotic operator puts external force containing a motion intentions (i.e. operational commands) on a handle of the HRI, it is converted into a control signal to operate the manipulator from operational sensor (6 DOF force/torque sensor; ATI Industrial Automation, Inc.) and a manipulator's motion controller. Here, if the manipulator comes in contact with an external object (e.g. glass panel's frame, obstacles, etc.), information on the contact force is transmitted to the manipulator's motion controller through environmental sensor (6 DOF force/torque sensor). It is important to note that external force transmitted through environmental sensor and that transmitted to operational sensor should operate separately from each other. End-effector types of a robotic manipulator varies according to the properties of the construction materials. Since this paper aims at installing construction materials with relatively smooth surfaces, such as glass panels, a vacuum suction pad is used as the end-effector. Lastly, an outrigger to prevent a robot from tumbling, additional safety devices for a robotic operator, and an alarm device to alert neighboring workers of robot operation are

Table 1. Functional requirements and approaches

Functional requirements	Approaches to human-robot cooperation
An aerial work	Height of the workplace of 7.9m
Weights to be lift	A robot operator : approx. 80kg A glass panel : approx.120kg
A construction (installation) method	Lay-in method inserting the glass panel into frame
End-effector types of a robot manipulator	Vacuum Pad type
Control strategy; Human-robot cooperation	Intuitive manipulation Power assistance Workers' technical know-how reflection

necessary, with consideration for the operational environments and characteristics of construction sites. Figure 6 shows the field test with the proposed robotic system at the target construction site.

Figure 5. Components for installing glass panels based on human-robot cooperation

Figure 6. Loading, lifting, and installing of a glass panel

4 Results of Field Test and Conclusions

Table 2 shows the results of the field test. Comparison with manual installation process is not executed because the glass panel is too heavy to handle by construction workers. However, to prove advances in handling heavy construction materials, the existing (manual) installation process [14] of curtain-wall construction is introduced. Working time means the whole time consumed in loading the glass panel from the ground and installing (including finishing) it in the panel frame. Labor intensity means the degree of manpower strength required of workers during the glass panel installation process. Convenience indicates the degree of difficulty of the installation work, and safety shows derived degree of safety.

The resulting comparison and analysis in Table 2 can be changed according to the working environment of the target construction site. In the case of installing a glass panel on smaller buildings, the work may depend on manpower. But according to the tendency of current construction trends towards larger and more sophisticated buildings, we are looking forward to highlighting the glass panel installation method based on human-robot cooperation in the near future.

Table 2. 1 Results of field test

	Curtain-wall installation with manpower and winch [14]	Glass panel installation based on human-robot cooperation
Working time	18 min.	Avg. 26 min/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
Number of workers	3	2(deck:1, aerial lift:1)

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