24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

DESIGN OF A CEILING GLASS INSTALLATION ROBOT

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ABSTRACT

Building materials and components are much larger and heavier than many industrial materials. Ceiling glass is a type of building material for interior finishing. The demand for larger ceiling glass has increased along with the number of high-rise buildings and an increased interest in interior design. The objective of the study is to introduce robotic technology for installing ceiling glass on construction site. Robotically installed ceiling glass is receiving special attention because of the difficulties in moving to high installation positions and handling fragile building materials. Below, we describe the design of a ceiling glass installation robot. After analyzing a target project, we establish a design concept for a proposed robot. Finally, we describe the detailed design of the robot.

KEYWORDS

Ceiling Glass, Installation Robot, Hardware Design

1. INTRODUCTION

The importance of applying the "Automation System and Robotics in construction" has been raised, as a result of the need for improvement in safety, productivity, quality, and the work environment [1], [2]. Consequently, operations involving automation systems and robots are widely found at construction sites. Since the late 1980s, construction robots have helped operators perform hazardous, tedious, and health-endangering tasks in heavy material handling. Iwamoto et al. stated a similar problem that reduces the need for a labor force and provides improved productivity and safety [3]. Isao et al. discussed the appropriateness of the automation technology for installation of a curtain wall [4]. Masatoshi et al. proposed the automated building interior finishing system, and a suitable structural work method is described [5]. Lee et al. developed an automation system (ASCI; Automation System for Curtain Wall Installation) that is suitable for mechanized construction, which enables simpler and more precise installation than existing construction methods, while improving safety during installation [6].

Robots 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 [7]. 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 remote-controlled system is the natural way to implement construction robot manipulators.

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. Ceiling glass is one type of building material for interior finishing. The demand for larger ceiling glass has been increasing along with the number of high-rise buildings and the increased interest in interior design. The objective of the study is to introduce robotic technology for installing ceiling glass on construction site. Ceiling glass installation robots are receiving special attention because of the difficulties of transporting the glass to high installation positions and handling the fragile building material. In order to address these conditions, the form of a ceiling glass installation robot is different from other construction robots.

A discussion follows that describes the design of a ceiling glass installation robot, which is introduced to address the above problems. After analyzing a target project, a concept design was produced for the proposed robot. Lastly, a detailed design of the robot is described, which is based on the concept design.

2. ANALYSIS OF TARGET PROJECT

The existing ceiling glass installation process, which is complicated and hazardous, relies on scaffolding (or aerial lift) and human labor. This process exposes operators to falling accidents or vehicle rollovers. In addition, inappropriate working posture is a major element that increases the frequency of accidents by causing various musculoskeletal disorders and decreasing concentration [8]. That is to say, it becomes a direct cause of decreasing productivity and safety in construction.

Figure 1 shows the construction site and ceiling glass installation position (soffit of building) related to this study. The building size is 32m × 22m and the installation position of the ceiling glass is 7.9m above the ground. Ceiling glass used for installation is classified into two categories. The first category is ceiling glass that has 1500mm × 1500mm dimensions and is 80kg. The second category is ceiling glass that has 750mm × 1500mm dimensions and is 40kg. This paper introduces the 'Module T&H-bar' installation method, which represents the 'Lay-in' to place the ceiling glass on ceiling frames.

According to analysis of the target project, it is deduced that the functional needs for implementing a ceiling class installation robot are as follows:

- The ceiling glass installation robot must be able to lift heavy ceiling glass, an operator, and the installation equipment. It requires engines, batteries, or motors to lift the weight.

Figure 1 Construction Site and Installation Position

- The ceiling glass installation robot must be able to handle heavy and fragile ceiling glass. It requires sophisticated force and position control including human-robot cooperative control. That is to say, the operator must be able to perceive external information that is received by the robot.
- The ceiling glass installation robot must be devised to help operators, not to replace them. This requires a smart HRI (Human Robot Interface) to interact with operators and robots. The robot must share the work space with an operator.
- The ceiling glass installation robot must be able to reflect the technical operator's skills that are required to obtain homogeneous construction quality. Thus, the robot must follow the operator's intentions in various environments at unstructured construction sites.
- The ceiling glass installation robot must belong in the working process. This is required to prevent operator accidents and help operators increase productivity, by reducing the recovery time from accidents and increasing the operator's duty time.

3. CONCEPT DESIGN

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 existing systems. 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 develop the suggested robot.

According to analysis of the functional requirements, a concept design was generated, which will influence the suggested robot.

- An aerial lift is needed that can support heavy ceiling glass, an operator, and the installation equipment with enough work space to reach about 7.9m above the ground.
- A multi-DOF manipulator is required to install heavy ceiling glass, which replaces a large mount of human labor. The manipulator has to be chosen according to work space and payload.
- This robot is a semi-automated system to cope with a constantly changing work environment. Thus, the robot works and coexists with operators in atypical work conditions. The operator uses the multi-DOF manipulator from the deck of an aerial lift.
- The gripper is based on vacuum and mechanical devices, while the ceiling glass gripping is performed manually.
- After gripping the ceiling glass the manipulator is operated by an operator. An operator supplies external force containing an operational command on the HRI device. Therefore, the manipulator can be controlled by an intuitive installation method that can reflect the dexterity of a technical operator.
- The deck of an aerial lift serves simultaneously as an operator's work space and a manipulator. Therefore, the operator's safety and productivity is influenced by the design of the deck.
- The control strategy of the suggested robot is a combination of the force applied and the robot.

Figure 2 shows a schematic of the ceiling glass installation robot that was determined by analyzing the concept design.

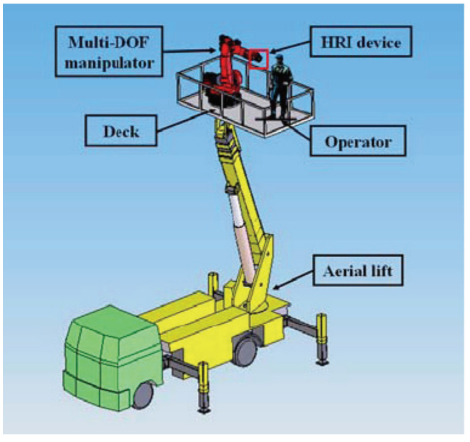


Figure 2 Schematic of Ceiling Glass Installation Robot

4. DESIGN OF ROBOT SYSTEM

The hardware design of the robot system is classified into three parts: an aerial lift, a multi-DOF manipulator, and an HRI device.

4.1 Aerial Lift

Aerial lifts are designed for enabling altitude work. In this study, the aerial lift raises the manipulator, ceiling glass, and an operator up to 7.9m. A discussion follows concerning the selection of the aerial lift and the design of the work deck.

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. Table 1 shows the specifications for the selected aerial lift. The rotation range is related to a base coordinate system {O}, as shown in Fig. 3. In order to implement automated lifting, the kinematic analysis of the aerial lift (RRPRR type manipulator) must be considered, as shown in Fig. 3 and Table 2.

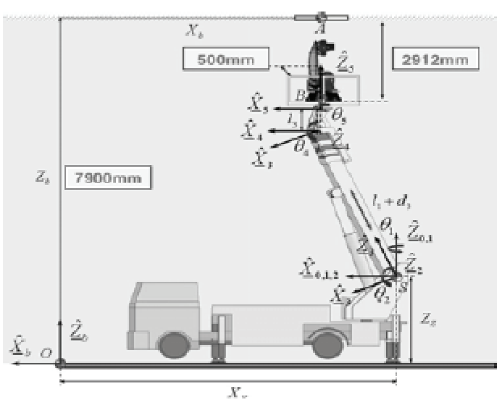


Figure 3 Coordinate Systems of the Aerial Lift

The design of the aerial lift deck is important to serve as the work space of an operator and a manipulator, in order to increase productivity and safety. When ceiling glass pieces, an operator, and the multi-DOF manipulator are lifted by the aerial lift, the position of ceiling pieces and the manipulator on the deck influences the operator's allowable movement.

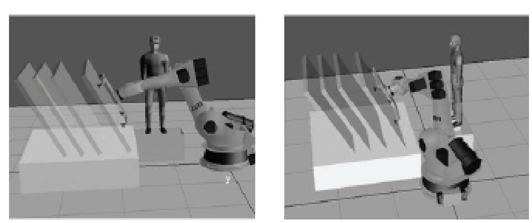
Table 1 Specifications of the Selected Aerial Lift

Items		Details
Max. payload		2000kg
Boom	Rotation (Y range axis)	-17~70°
	Rotation range (Z axis)	360°
	Max. working radius	5~7m
Outrigger		H type
Width (set outrigger)		4.2m

Table 2 D-H Table of the Aerial Lift

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\pi/2$	0	0	θ_2
3	$-\pi/2$	0	l_1+d_3	0
4	$\pi/2$	0	0	θ_4
5	$-\pi/2$	l_2	l_3	θ_5

Moreover, the deck shape must be optimized to increase operation dexterity, in order to avoid obstacles and allow for a smooth approach to the target position. Two cases were proposed concerning the position of the ceiling pieces, as shown in Fig. 4. After simulating the operation's movements and manipulator's operation, it was found that case 2 requires more motion by the manipulator than case 1, and needs a larger work space than case 1. Therefore, case 1 was selected, in which the ceiling glass is positioned in front of the manipulator on the deck, as shown in Fig.5. The operator's body size was considered, in order to prevent WMSD (Work-related Musculo-Skeletal Disorders), as shown in Figure 6.



(a) Case 1 (b) Case 2

Figure 4 Simulations for Deck Design

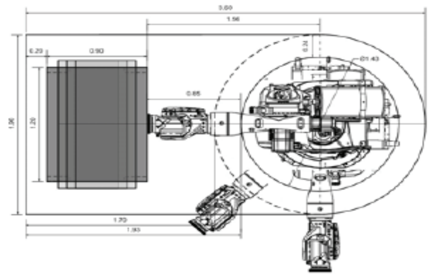


Figure 5 Simulations for Deck Design

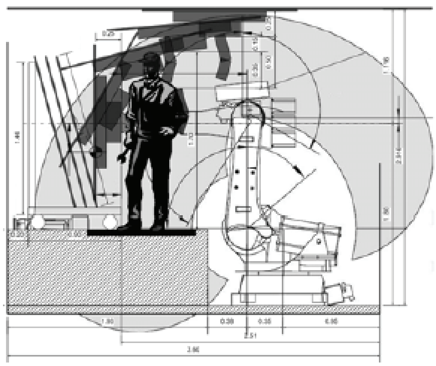


Figure 6 Simulations for Deck Design

4.2 Multi-DOF Manipulator

A multi-DOF manipulator is needed to install heavy ceiling glass, thereby replacing a large amount of human labor, by correlating the operator and manipulator. The manipulator is chosen to help the operators, not to replace them. The manipulator has to be chosen according to the work space and payload. The payload and the weight of any additional devices (vacuum suction device, HRI device) required for installation must be considered. Figure 7 and Table 3 show the coordinate systems and D-H table for the selected model (KUKA Industrial Robots), respectively. 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 should be considered carefully.

The design of a vacuum suction device includes the position of the vacuum suction pads, available payload, and the weight of itself. A section of the vacuum suction pads should be designed in accordance with the width of the smallest ceiling glass. Four vacuum suction pads were used, in which each suction cup can support up to 60kg. The vacuum suction pads are positioned in aquadrilateral formation so that an operator can easily put the device on the center of a ceiling glass piece. Figure 8 shows the vacuum suction device design.

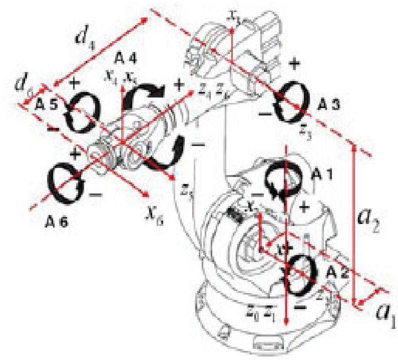


Figure 7 Simulations for Deck Design

Table 3 D-H table of the aerial lift

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\pi/2$	a_1	0	θ_2
3	0	a_2	0	θ_3
4	$\pi/2$	0	$-d_4$	θ_4
5	$-\pi/2$	0	0	θ_5
6	$\pi/2$	0	$-d_6$	θ_5

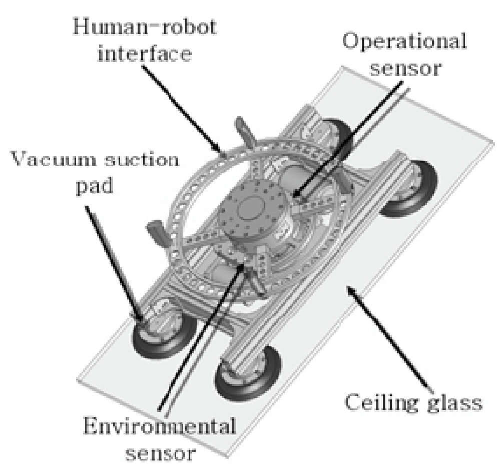


Figure 8 Vacuum Suction Device and the HRI Device

4.3 HRI Device

The HRI device is involved with installing ceiling glass 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 Fig. 8, while it is composed of two 6-axis force/torque sensors. When an operator supplies an external force containing an operational command on a handler of the HRI device, it is converted into a control signal to operate the manipulator with an operational sensor (6-axis force/torque sensor). If the manipulator comes into contact with a ceiling frame, the information about the contact force/torque is transmitted to the robot controller through an environmental sensor (6-axis force/torque sensor). It is important to note that an external force/torque transmitted through an environmental sensor or the operational sensor should occur separately from each other.

5. CONCLUSION AND FUTURE WORK

The ceiling glass installation robot presented in this study combines an aerial lift and a multi-DOF manipulator. One of the advantages of the proposed robot is the ceiling glass handling by human-robot cooperation. Included in this cooperation is the HRI device and the vacuum suction device combined with the multi-DOF manipulator. Development of the suggested robot does not end with the development of the robot system alone. A robotized working process including the suggested robot should be designed.

In this paper, a robot development method was introduced that complements existing systems. According to analysis of a target project, the functional needs were deduced for implementing the ceiling glass installation robot. A concept design was generated based on the functional requirements. The hardware design of the robot system is classified into three parts including an aerial lift, multi-DOF manipulator, and a HRI device.

After fabricating each part of the robot system, integration will be executed. Also, the control strategy and algorithm relating the human-robot cooperation, to which the hardware of the integrated system is to be applied, will be developed.

6. ACKNOWLEDGMENT

This work was supported by the SAMSUNG CORPORATION.

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