

# AUTOMATION SYSTEM FOR CURTAIN WALL INSTALLATION II ( ASCI II )

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As a trial of automation for a curtain wall which is one of heavy materials, the prototype of an ASCI(Automation System for Curtain wall Installation) was proposed and applied in real construction site. Human-robot cooperation is one of the solutions to improve ASCI. The aim of this paper is to develop a control algorithm for ASCI, which is a human-robot cooperative system, and the practical applications of the study on curtain wall installation. The procedure for development of the control algorithm starts from an analysis of environment, robot, and human modeling. The control algorithm for human-robot cooperation based on force control and the experiments of human-robot cooperation through application on the curtain wall installation are also contained. Expected effects from this system are simple construction procedure, a raise of efficiency and accuracy, retrenchment of the construction cost and period, and safety assurance of operators.

Keywords: Automation system, Curtain wall, Installation

## 1. Introduction

Recently, the tendency in construction is high-rise buildings in order to improve space utilization. Therefore, construction materials have been towards larger and heavier. Curtain wall is one of the most useful exterior materials due to some interests.(e.g. shortening the construction period, preventing excessive design, etc.) The size and weight of curtain wall have to be limited in consideration of feasibility on entire process from production to installation. In fact, however, a curtain wall is excessively designed to pursue beautifulness and satisfy the requirements from customers. Because of the lack of suitable construction equipment for curtain wall

installation, the process is complicated and hazardous, relying on a existing equipment and a large amount of manpower. The curtain wall installation system which is a mini excavator combined with an attachment (adsorption device) is described in Fig 1. To solve these problems, an automation system using a mini excavator and 1DOF rotational mechanism was proposed. Although this system improved working conditions at construction sites more or less, it still left difficulties in precision construction, which had not been designed for curtain wall installation. As shown in Figure 2, we developed an ASCI, suitable for the automated construction. This system had a multi-degree-



**Figure 1.** A mini-excavator with 1DOF mechanism



**Figure 2.** ASCI (Automation System for Curtain wall Installation)

of-freedom manipulator which was suggested to increase productivity and improve safety during installation works.[1]

Unlike general manufacturing industry, the approach for construction automation has to be different because of unpredictable environment and a variety of materials.[2] As a result of ASCI applications, some factors were found to be improved.

- ✓ A robot that can follow operator intention in various works at unstructured construction sites
- ✓ A robot that shares work space with an operator
- ✓ Coordination of operator's force and the robot's amplified force
- ✓ Intuitive operational method that can reflect dexterity of an operator

To improve these factors, construction method is required to amplify force of operator with a certain force augmentation ratio so that operator can manage a heavy material with relatively scaled-down force. And, to feel reaction forces helps intuitive operation by reflection of force from environments. One of the solutions for these requirements is human-robot cooperation.[3][4][5] 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.[6] And then, further work was done by GE. GE designed Hardiman which is exoskeleton typed man-amplifier.[7] In 1980's, kazerooni approached the innovative man-amplifier, extender, which is different from a master-slave system.[8][9][10] 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.[11] To implement the human-robot cooperation in constrained condition, the impedance control method, which was proposed by Hogan, has been used as a basic force control method.[12]

Fig. 3 describes the conceptual model of ASCI II which human-robot cooperation is applied on. This system considers the interactions among human, robot and environment. We focus on the human-robot cooperative control in this paper. Using target dynamics, the interactions among human, robot and environment are modeled. We designed an impedance controller for the interactions among human, robot and environment. A position controller was added inside the impedance

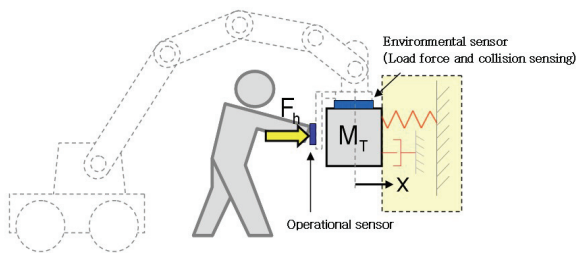


Figure 3. Concept of human-robot cooperative system

controller to improve the trajectory following performance. Finally, we examined the influences, which the parameters of the impedance model gave to performance of the cooperation system, through a 2DOF experimental system.

2. Strategy of human-robot cooperation

2.1 New installation method

The curtain wall installation process for ASCI has been proposed.[2] Based on the existing method, new process using ASCI II is proposed below:

- ① Curtain walls are moved into the target floor by a hoist or tower crane.
- ② The ASCI II is positioned by a hoist.
- ③ The ASCI II picks the curtain wall by adsorption.
- ④ The ASCI II covers the curtain wall near to the frame.
- ⑤ The ASCI II sets outriggers.
- ⑥ In human-robot cooperation, the ASCI II positions the curtain wall precisely.
- ⑦ The curtain wall is squeezed into the frame. (Environment contacting case)
- ⑧ Release the adsorption device and finish

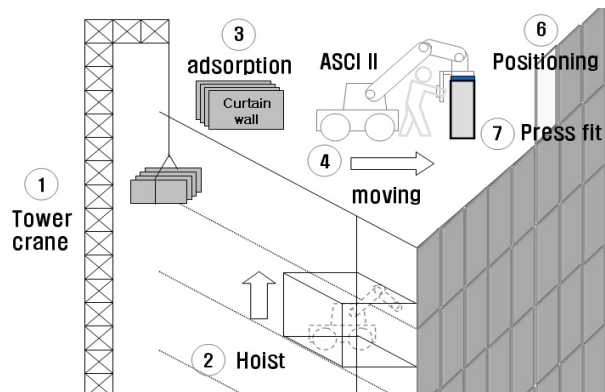
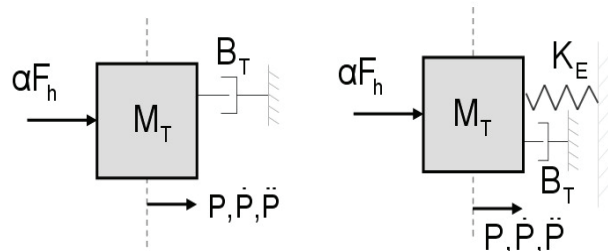


Figure 4. The process of new installation method

As occasion demands, a winch needs to prevent the curtain wall from crashing. Compared to the existing method, one operator decreases because ASCI II, which is a manipulator set on the mobile platform, is controlled by only one operator.

2.2 Modeling of human-robot-environment system



(i) Unconstrained case (ii) Constrained case

Figure 5. Free body diagram of human-robot-environment cooperative system

**Table. 1** Parameters description

Symbol	Meaning
$F_h$	Operational force
$F_E$	Contact force due to environment
$M_T$	Target mass of the object
$B_T$	Target viscous friction coefficient of the object
$P_e$	Real position of the end effector
$P_d$	Desired position of the end effector
$P_c$	Desired position of the end effector with compliance
$M_e$	The mass of object
$B_e$	Viscous friction coefficient of environment
$K_e$	Stiffness coefficient of environment
$a$	Force augmentation ratio $= \left( \frac{\text{Total force imposed to the object}}{\text{The operational force}} \right)$
$K_P$	Proportional gain in the position control loop
$K_D$	Derivative gain in the position control loop

For the robot modeling, curtain wall handling operations can be divided into the environment contacting cases and the non-environment-contacting cases. In the non-environment-contacting cases, the ASCI II is free to move in all directions without any interaction with obstacles.

This case corresponds to the process ③, ④ at 2.1. Here, the impedance equation (1) is described in the environment-contacting cases. The subscript ‘T’ stands for the target dynamic and ‘d’ stands for the desired value. In addition, ‘E’ means environment. Each impedance parameters ( $M_T, B_T$ ) are the positive definite diagonal matrices.

$$M_T \ddot{P}_d + B_T \dot{P}_d = \alpha F_h \quad (1)$$

Table 1 shows the parameters description in impedance

equation. The K parameter, having the property of a spring, was excluded as it disturbed the operation to move an object to a desired position with the operational force.

During the process ⑦, we consider  $F_E$  and  $F_h$  as input values. Dynamic behavior of a robot can be described by an impedance equation (2). An equation (2) is replaced with equation (3) through measuring  $F_E$  by environmental sensor.

$$M_T \ddot{P}_d + B_T \dot{P}_d + K_E P_d = \alpha F_h \quad (2)$$

$$M_T \ddot{P}_d + B_T \dot{P}_d = \alpha F_h - F_E \quad (3)$$

### 3. Human-robot cooperative controller

Fig. 6 shows the overall control algorithm of human robot cooperative system. This algorithm is divided to two parts. One is for dynamic relation of human-robot-environment, the other is impedance control with position control. A human-robot-environment dynamic relation part has a dynamic equation (1) or (3) depending on the influence of environmental force ( $F_E$ ). This part outputs desired target dynamic according to active impedance parameters ( $M_T, B_T$ ). In other words, impedance parameters determine a dynamic behavior of the end effector for interactions with environment. In case contacting force with environment occurs, the end effector should endow with a behavior, considering the compliance. Dynamic behavior in impedance control with position control is determined, as shown in (4).

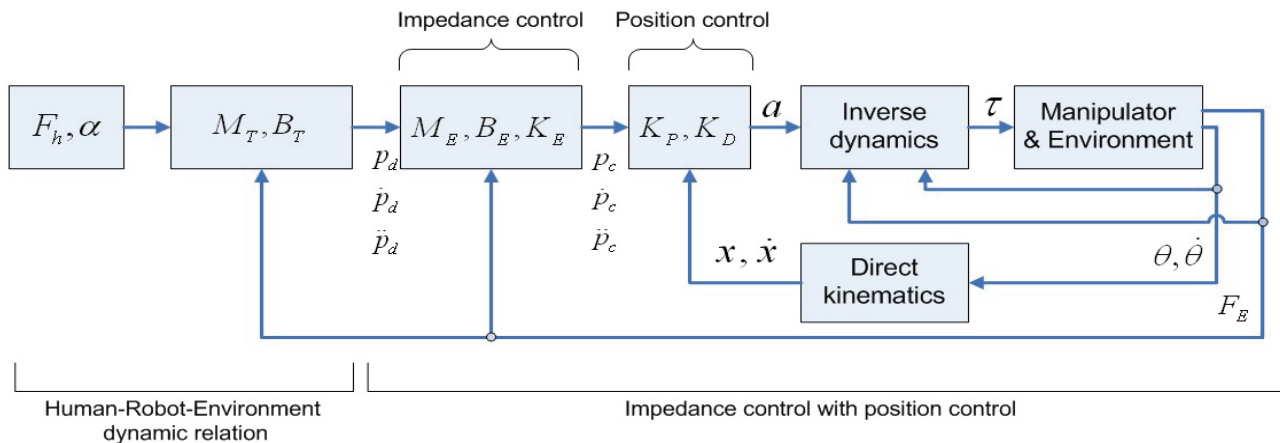
$$M_E \ddot{P}_{dc} + B_E \dot{P}_{dc} + K_E P_{dc} = F_E \quad (4)$$

$$\text{where, } P_{dc} = P_d - P_c$$

$$K_D \dot{P}_{ce} + K_P P_{ce} = 0 \quad (5)$$

$$\text{where, } P_{ce} = P_c - P_e$$

The subscript ‘c’ stands for the compliance. The position error,  $P_{dc}$ , indicates the difference between the desired

**Figure 6.** Overall control algorithm of human-robot cooperative system

dynamic behavior and the compliance dynamic behavior because end effector cannot practically follow a desired dynamic behavior. To reduce error on the position and orientation, the PD compensator is added, as shown in equation (5).

**4. Experiment and results**

**4.1 Experimental system and method**

As shown in Fig. 7, we designed experimental system to verify the proposed human-robot cooperative control. We mounted two sensors in the 2DOF manipulator, moving in the x and y directions. One receives operational force from an operator, and the other, positioned between the end effector and the 150[N] weighing object, can detect the contact force from the environment. With the signals that are received by the two sensors, the control signals, the manipulator should follow, are generated. The experimental method for the human-robot cooperation work can be categorized into four staged.

- ① An indicator, mounted on an object, automatically moves to the home position from the original position.

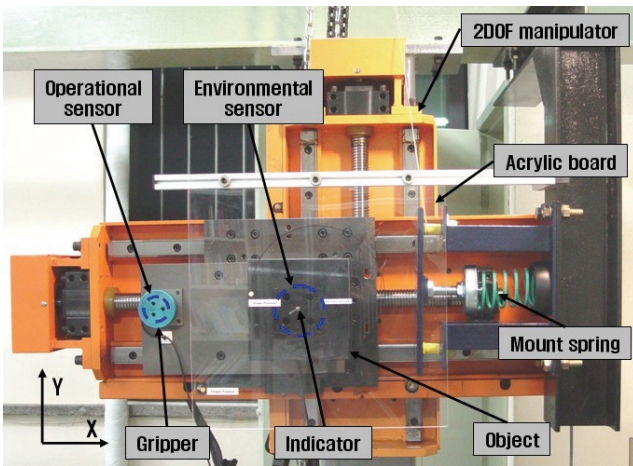


Figure 7. Experimental system

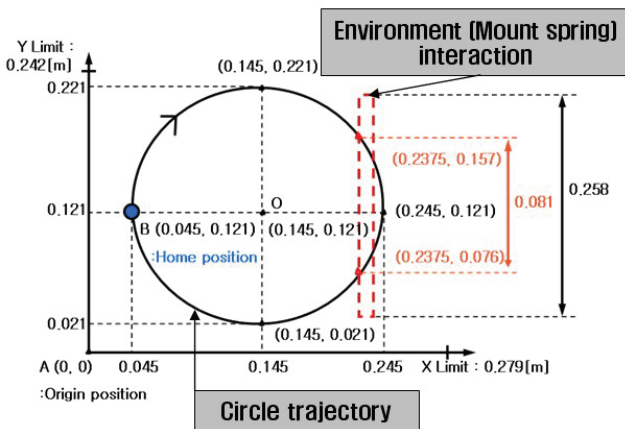


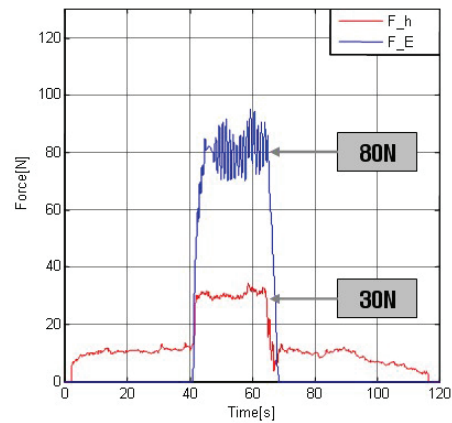
Figure 8. Coordination of experimental system

- ② The operator applies force to the gripper, so that the indicator follows a circle trajectory that is described on an acrylic board.
- ③ Based on the operational force, the robot follows the circle trajectory through the impedance control in the unconstraint condition.
- ④ The robot contacts a mount spring while following the circle trajectory. The contact force, generated at this time, enables the impedance control, and the robot finishes a heavy material handling operation in compliance with environment.

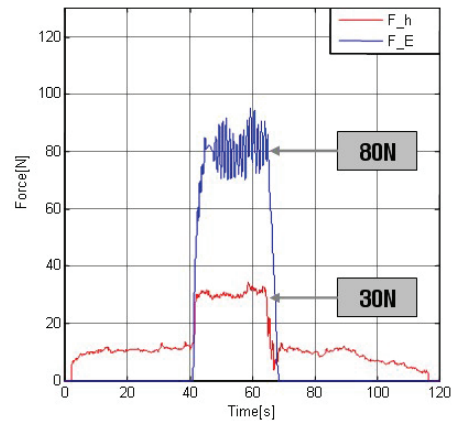
**4.2 Force amplification and force reflection**

The aim of force amplification and force reflection is to observe the dynamic specification ( $F_E$ ) according to the human input force( $F_h$ ) when the object on the end effector contacts with environment. We compare the test results as the force augmentation increases 3 to 6 at  $M_T=15I$ ,  $B_T=7500I$ ,  $M_E=50I$ ,  $B_E=10,000I$  and  $K_E=8,000I$ .

$\alpha$  plays a role of controlling the scale of the force that is required by an operator for a human-robot cooperation work. As shown in Figure 9,  $F_h$  is required to be around 10[N] in case of no contact with the environment, while  $F_h$



(i)  $\alpha = 3$



(ii)  $\alpha = 6$

Figure 9. Comparison of  $F_h$  and  $F_E$  at different force augmentation ratio



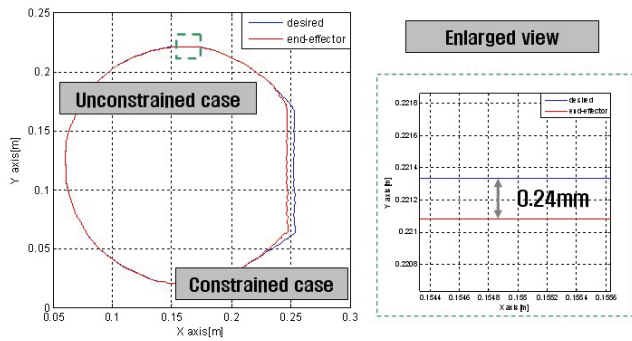


Figure 10. Without position controller

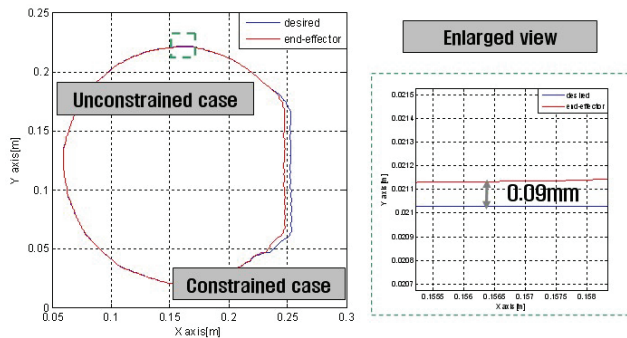


Figure 11. With position controller

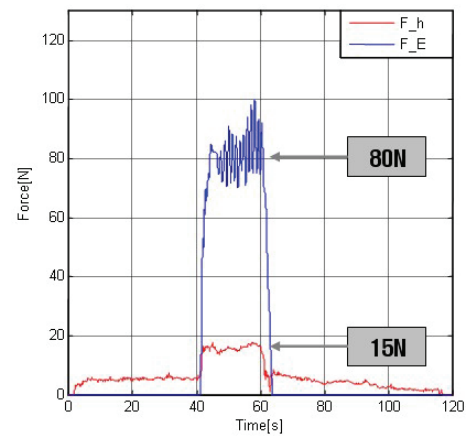
is required to be around 30[N] in case of contact with the environment. As  $\alpha$  increased to from 3 to 6,  $F_h$  is reduced by a half, and  $F_h$  for the environment-contacting case was also reduced to 15[N] by around a half. We can see that the force, required by an operator, gets smaller as  $\alpha$  increases, but there is no significant change in the force ( $F_E$ ) that reflects in the contacting condition.

#### 4.3 Position control

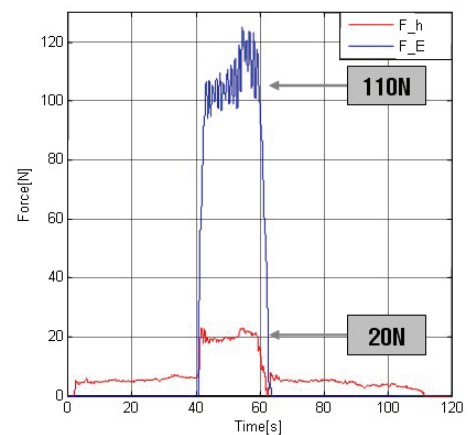
Position control loop gains are  $K_P=15I$ ,  $K_D=1.5I$  in experiment. As shown in the Figure 10, the robot operation without position control loop shows inferior desired-position-following performance in an unconstraint case. By using the position control loop, the high following performance can be obtained as shown in the Figure 11.

#### 4.4 Change of environmental stiffness

The environmental stiffness depends on the characteristics of materials, composing an environment. The purpose of this experiment, changing the environmental stiffness, lies on comparison of the reaction force that is felt by an operator according to operational conditions such as a case contact with an obstacle occurs or a case the press fit is required. The impedance parameters for the experiment were set as  $M_T=15I$ ,  $B_T=7500I$ ,  $M_E=50I$  and  $B_E=10,000I$ . Only environmental stiffness is changed from  $K_E=8,000I$  to  $K_E=11,000I$ . In Figure 12,  $F_h$  is required to be around 5[N] in case of no contact with the environment, while  $F_h$  is required to be around 15[N] in case of contact with the environment and the generated force  $F_E$  is 80[N]. In comparison with Figure 13, there is no change in  $F_h$ , for



(i)  $K_E=8,000\text{N/m}$



(ii)  $K_E=11,000\text{N/m}$

Figure 12. Comparison of  $F_h$  and  $F_E$  at different environmental stiffness

handling the object, in case of no contact with the environment, while  $F_E$  and  $F_h$ , for moving the object, increased from 15[N] to 20[N] and from 80[N] to 110[N] respectively in case of contact with the environment.

## 5. Conclusion

In this paper, we suggested a model of the human-robot cooperation system according to the environmental influence, using the adjustable impedance factors. Also, the process for ASCI 2 using human robot cooperation was proposed. We designed human-robot cooperation controller by the impedance control with an inner motion control loop. We investigate the influence of force augmentation ratio to the system. As a result, we can adjust the force which is required by an operator for human-robot cooperation by controlling the force augmentation ratio. In addition, as environmental stiffness increases, the force, required to an operator, increased, and the force ( $F_E$ ), reflecting in the contact condition, also increased. Through the experiments, we could observe the characteristics of the force augmentation and the force reflection, the merits of the human-robot cooperation system. If we properly apply the human-robot cooperative control system, mentioned in this paper, to heavy-materials handling works at construction

sites, operators can move heavy materials with relatively less force, while complying with the operators' intention. Also, it allows operators to promptly respond to work environments, changing in real time, through the intuitive force reflection in the environmental-contacting conditions especially during operations such as combining heavy material together or press fit work.

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