Robotica (2010) volume 28, pp. 945–957. © Cambridge University Press 2010
doi:10.1017/S0263574710000573

An improved multipurpose field robot for installing construction materials

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(Received in Final Form: August 20, 2010. First published online: September 22, 2010)

SUMMARY
Recently, there has been a lot of interest concerning remote-controlled robot manipulation in hazardous environments including construction sites, national defense areas, and disaster areas. However, there are problems involving the method of remote control in unstructured work environments such as construction sites. In a previous study, to address these problems, a multipurpose field robot (MFR) system was described. Though the case studies on construction, to which "MFR for installing construction materials" was applied, however, we found some factors to be improved. In this paper, we introduce a prototype of improved multipurpose field robot (IMFR) for construction work. This prototype robot helps a human operator easily install construction materials in remote sites through an upgraded additional module. This module consists of a force feedback joystick and a monitoring device. The human–robot interaction and bilateral communication for strategic control is also described. To evaluate the proposed IMFR, the installation of construction materials was simulated. We simulated the process of installing construction materials, in this case a glass panel. The IMFR was expected to do more accurate work, safely, at construction sites as well as at environmentally hazardous areas that are difficult for humans to approach.

KEYWORDS: Field robot; Construction robot; Building; Glass panel; Force feedback joystick.

1. Introduction

Recent researches have found that lack of skilled manpower in the construction industry is rapidly becoming a serious problem. One of the solutions suggested to solve these problems is robotization or automatic installation.[1,2] Since the late 1980s, construction robots have been helping operators perform hazardous, tedious, and health-endangering tasks in heavy material handling. Isao *et al.*[3] discussed the appropriateness of automation technology for the installation of a curtain wall. Masatoshi *et al.*[4] proposed the automated building interiorfinishing system and described a suitable structural work method. Li *et al.*[5] discussed a novel mobile robot "finned tube inspection robot" for finned tube inspection at power plants. Bock *et al.*[6] suggested robotization of mounting and finishing operations in building. Lee *et al.*[7] developed an automation system (ASCI: Automation System for Curtain-wall Installation), suitable for mechanized construction, which enables simpler and more precise installation than existing construction methods, while improving safety during installation. Figure 1 shows the ASCI on a building construction site.

Robots can be classified into two groups: those that do repeated work according to a standard program, such as part assembly or welding and coating in the automobile or electronics industries, and those that can carry out work and coexist with humans in atypical, unpredictable environments that are unlike production facilities.[8] In this discussion, a field robot is defined as one that executes orders while moving around in a dynamic environment where structures, operators, and equipment are constantly changing.[9,10] To date, field robots have been designed specifically for a particular environment and used in various industries such as agriculture, construction, engineering, space exploration, and deep-sea diving, due to the inherent dangers and costs associated with these fields.[11–14]

Generally, the basic elements of a field robot consist of a mobile platform for executing a particular operation in a dynamic environment, sensors, and intelligence technology to recognize and cope with barriers in the path of movement, and a manipulator for executing a desired operation in place of a human.[15,16] Until now, the development of field robots has focused on the basic elements, plan for a specific work or a single task. This planning leads to not only the inefficient use of time and resources but also to limited utility. To solve this problem, a multipurpose field robot (MFR) is suggested, as shown in Fig. 2.[17] At the end of the 1970s, Shimizu Co. developed multipurpose traveling vehicle (MTV, for concrete slabs), which could transport and guide various robotic working modules. From the viewpoint of operational characteristics, the MTV can be thought of as a construction robot designed to perform automatic grinding and cleaning of concrete surfaces. On the contrary, the MFR can be considered as a field robot designed specifically for a particular environment and used in various industries such

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Fig. 1. ASCI (Automation System for Curtain-wall Installation).

Fig. 2. Framework of a multipurpose field robot.

as agriculture, construction, engineering, space exploration, and deep-sea diving, due to the inherent dangers and costs associated with these fields.[18]

The MFR prototype combined a mobile platform and a manipulator standardized in modular form as its basic system. Also, the hardware and software necessary for each area of application were composed of additional modules and combined with the robot's basic system. The MFR can execute particular operations in various areas such as construction, national defense and rescue by changing these additional modules. Especially, if we properly apply the MFR to heavy-materials handling work at construction sites, operators can move heavy materials with relatively less force, while complying with the operators' direction. Also, it allows operators to respond promptly to work environments, changing in real time, through the intuitive force reflection in the environmental-contacting conditions especially during

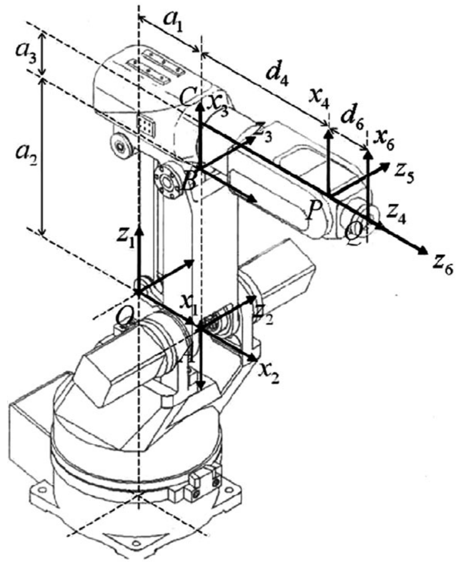

Fig. 3. Multi(6)-DOF manipulator (Samsung Electronics Co. ltd).

works, such as combining heavy material together or press fit.[17]

Through the case studies on constructions, to which MFR was applied, however, we found some factors to be improved. In the case of MFR, the operator should manipulate the human–robot interface device near the MFR in the same space. Therefore, a serious accident may occur when an operator works in poor environmental conditions such as dust or poisonous air, high or low temperature areas, and so on. In this paper, to address this problem, the concept of an improved multipurpose field robot (IMFR) was introduced. An IMFR has additional devices to combine a remote-control system[19,20] into MFR. The hardware of the upgraded additional module was partitioned into a force feedback joystick and a monitoring device. The software of the upgraded additional module was also partitioned into the human–robot interaction and bilateral communication. Development of the suggested IMFR does not end with development of the robot system alone. An operation method appropriate to site environments was proposed to show the robot's full ability and work functionality. The operation method was realized in the form of a construction material installation mock-up test. When construction material is implemented by press fit with material already installed, compliance occurs within the elastic range of the material and it is installed without damaging either object.

2. A Multipurpose Field Robot for Installing Construction Materials

A MFR system for installing construction materials was described by Lee *et al.*[11] The MFR system combines a basic system with an additional module for construction. Considering the workspace and mobility, a six degree-of-freedom (DOF) manipulator and a 3DOF mobile platform were suggested for use in the basic system. Moreover, it was possible to change the elements of the basic system according to load specifications.

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Table I. Specifications of the Multi(6)-DOF manipulator.

Specification		Value
Degree of freedom		6
Weight capacity		58.38 (N)
Arm length (max)		858 (mm)
Velocity of end-effector		30 (°/s)
Weight	Manipulator	588 (N)
	Controller	245 (N)

Table II. Specifications of the mobile platform.

Specification		Value
Maximum load of carriage		9800 (N)
Weight		3920 (N)
Length		1,260 (mm)
Breadth		900 (mm)
Velocity	Maximum	2.5 (km/h)
	Minimum	0.6 (km/h)
Inclination of degree		20(°)
Power consumption		0.8 (kW)
Source of electricity		Charging battery

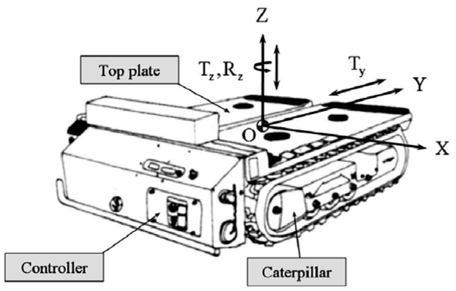

Fig. 4. Mobile platform (Kajima Mechatro Engineering Co.).

2.1. A basic system

2.1.1. A multi-DOF manipulator. Figure 3 shows the multi(6)-DOF manipulator of a basic system. This robot is a special case manipulator where the centers of the last three axes meet in the center of the robot wrist. The kinematic analysis in such form of manipulator can be divided into two link chains (the first three link chains and then the other three link chains). Table I shows the specifications of the manipulator.

2.1.2. A mobile platform. A 6DOF manipulator was fitted to the top plate of the mobile platform. Thus, movement of the manipulator was possible according to the platform's DOF. Traveling on uneven surfaces or surfaces with barriers was made possible using caterpillar tread. Table II shows the specifications of the suggested mobile platform. This mobile platform largely consisted of caterpillar tread, a top plate, and a controller as shown in Fig. 4.

2.2. An additional module

An additional module, which is used for construction work along with various devices, was suggested for incorporating the MFR into construction work. This module consisted of hardware (HRI: human–robot interface) and software (HRC control: human–robot cooperative control).

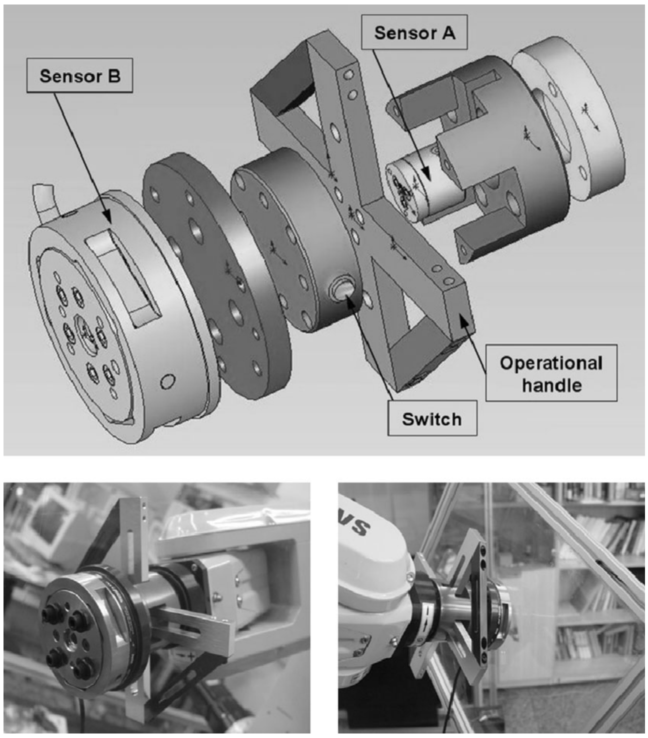

Fig. 5. The first robot controller (HRI device).

2.2.1. A human–robot interface. First, the robot controller needs to be able to implement DOF for a mobile platform and a 6DOF manipulator. The first robot controller (HRI device) is shown in Fig. 5. As seen in this figure, if an operator puts external force containing an operation command on a handler of the robot controller, it is converted into a control signal to operate the robot with sensor A (6DOF Force/Torque sensor; ATI Industrial Automation, Inc.). 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 (6DOF F/T 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. In addition, the switch attached to the HRI device should be able to control the manipulator and mobile platform separately. That is, it plays a role of determining whether external force being inputted is a control signal for the manipulator or that for the mobile platform.

In MFR system, the operator can select between two communication methods: wired or wireless control. The wireless control system is used to carry materials long distances or to move a robot to places that are difficult for an operator to reach. The wired control system is used to install construction materials by cooperation or in an emergency.

For the wireless communication system, it is then possible to choose between the mobile platform control system and the manipulator control system. In other words, it is possible to control a mobile platform and a manipulator with one wireless controller (Fig. 6a). Each control signal is transmitted to the controller of a manipulator and a mobile platform through a main controller via a radio frequency (RF) communication module and a converter.

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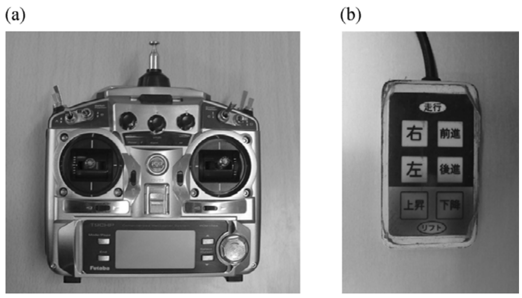

Fig. 6. The second robot controller (remote control system & teach pendant). (a) Remote control system; (b) teach pendant.

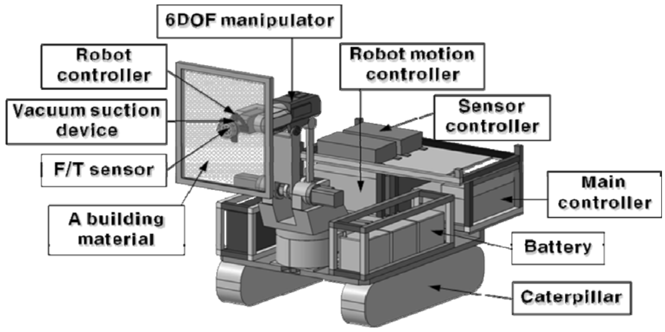

Fig. 8. Configuration of a MFR for handling construction materials.

For the wired communication system, it is again possible to choose between the cooperation-based control system and the emergency control system. Unlike the wireless communication system, the wired communication system uses a separate control unit. The cooperation-based control system operates through main controllers including industrial computers and sensors, and the first robot controller (HRI device) mentioned in Section 2.2.1. The emergency control system can operate through the teach pendant of a manipulator and a mobile platform in emergency situations, as seen in Fig. 6(b).

2.2.2. Human–robot cooperative control. Installation of construction materials by the cooperation-based control system can be largely divided as follows:

(1) Process of carrying materials to an installation position;
(2) Process of inserting them into the correct position or doing press fit, depending on the environment.

In this paper, the former is defined as "free space motion" and the latter as "motion under constrained conditions". Free space motion needs rapid movement with relatively low precision while motion under constrained conditions needs precise motion with relatively low motion velocity. There is a difference in the force supplied from a robot installing construction materials by human–robot cooperation between free space motion and motion under constrained conditions.

Figure 7 shows a block scheme of the suggested human–robot cooperation-based control system to solve problems involving a remote control system. When an operator judges that the position (X) to which a robot carries materials fails to agree with the position (X_d) to which he/she wants to carry them, his/her force is transmitted to sensor A. In particular, external 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 impedance equation. 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 the impedance equation. Relatively rapid and precise motions can be implemented by controlling these parameters.

2.3. Experiments and results

The MFR system was used in experiments for installing construction materials. Figure 8 shows the MFR system that consisted of the basic system and the additional module for construction work. In this figure, the basic system consists of a 6DOF manipulator and a mobile platform with caterpillar tread; the portion that excludes construction material is an additional module (robot controller, end-effector; a vacuum suction device, F/T sensor and controller, etc.) for installing construction materials.

The development of a MFR applied to the construction area is not achieved by actual system production alone. Studies on system operation technology are also necessary for the

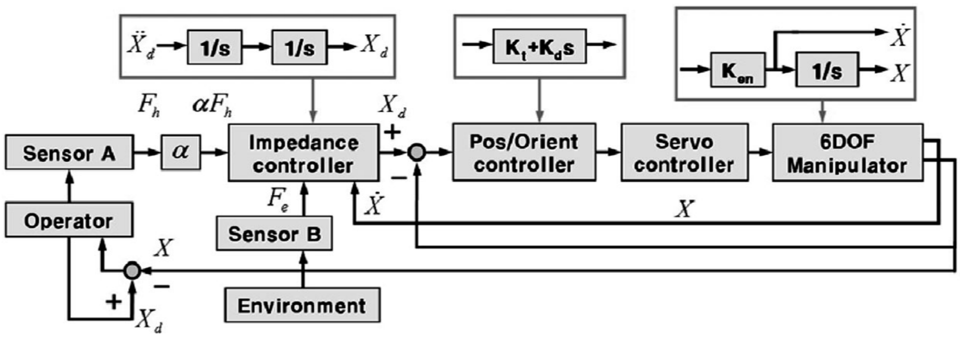

Fig. 7. Block diagram for human-robot manipulation of the MFR.

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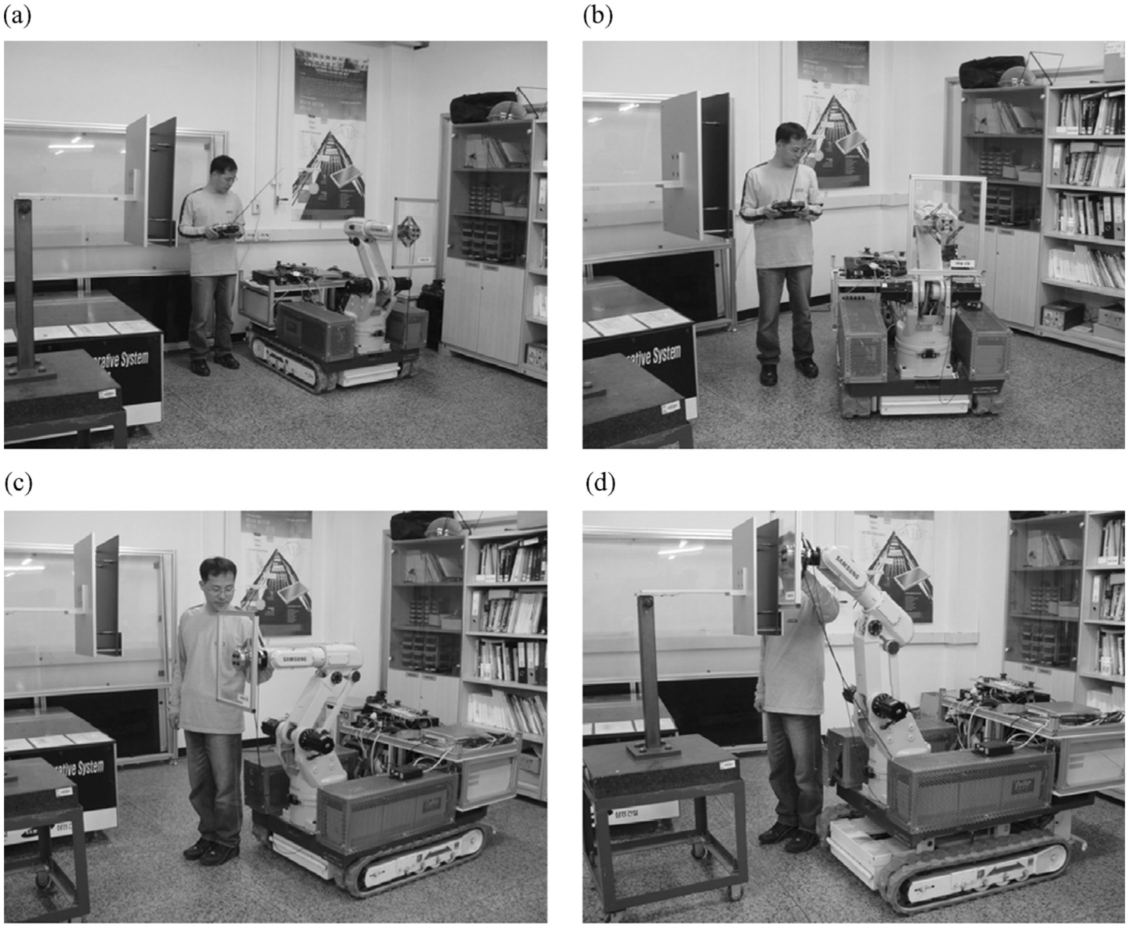

Fig. 9. Simulation for installing construction materials with the MFR. (a) Adsorption of a construction material; (b) transportation through a wireless controller; (c) positioning through human–robot cooperation; (d) installation of a construction material.

developed system to be fully effective in operation. The construction material installation method suitable for a robot which was described in this study is shown in Fig. 9. Each process can be outlined as follows:

(a) First, construction materials piled on the ground are fixed to a robot with a vacuum suction device. The type of loading for materials carried from the ground is determined by the most efficient fixing posture within the operation range of a manipulator.
(b) An operator rapidly moves the robot to an installation site through a wireless controller. Here, a mobile platform whose velocity can be controlled by the input of a control signal is principally used. The posture of construction materials is adjusted by the motion of a manipulator if necessary.
(c) Construction materials carried to the vicinity of an installation position are installed through interaction with materials already installed by an operator. That is, compliance occurs upon contact, so that press fit for materials and systems are completed safely.
(d) After the operation is completed, the robot is returned to the site of construction materials loading through a wireless controller for the next operation.

If we properly apply the MFR prototype, mentioned in the previous study, to heavy-material handling works at construction sites, operators can move heavy materials with relatively less force, while complying with the operators' directions. Also, it allows operators to promptly respond to changing in real time work environments, through the intuitive force reflection in the environmental-contacting conditions, especially during operations such as combining heavy materials together or press fit work.

Through the case studies on constructions, to which MFR was applied, however, we found some factors to be improved. In the case of MFR, the operator should manipulate the human–robot interface device near the MFR in the same space. Therefore, a serious accident may occur when an operator works in poor environmental conditions such as dust or poisonous air, high- or low-temperature areas, and so on. Thus, we deduced the following improvements:

(1) We combine a remote-control system into MFR, for installation of construction materials in cooperation between an operator and a robot.
(2) A robot that can follow operator intention in various work at unstructured construction sites.
(3) Intuitive operational method that can reflect dexterity of an operator

3. Hardware for an Improved Multipurpose Field Robot

The existing MFR system with human–robot cooperation cannot be applied to hazardous environments including

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Table III. Function and type of each force-reflecting joystick's channel.

Channel	Type	Function
Ch 1	Joystick	Translation to X axis
Ch 2	Joystick	Translation to Y axis
Ch 3	Joystick	Translation to Z axis
Ch 4	Joystick	Rotation along X axis
Ch 5	Joystick	Rotation along Y axis
Ch 6	Joystick	Rotation along Z axis
Ch 7	Pushbutton switch	Emergency stop
Ch 8	Pushbutton switch	Robot velocity control

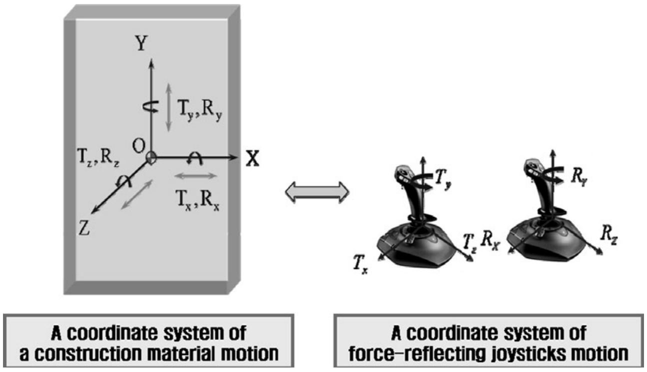

Fig. 10. Mapping between coordinate systems.

construction sites. Generally, the construction robot control made use of a remote-controlled system. This control method, however, has limited applications at real sites because the operator does not get accurate information about work and situations to be able to respond instantly during changing, real time work environments. To address these problems, the concept of an IMFR was introduced. The hardware of the upgraded additional module was partitioned into a force feedback joystick and a monitoring device.

3.1. An improved force feedback joystick

The operator controlled the manipulator using the improved force feedback joystick of the IMFR to perform the installation (Figs. 10, 11). "T" means a translational motion and "R" means a rotational motion. There were eight channels for work performance on the force feedback joystick and a lever rotated to the front, back, left, and right sides. Table III shows the function and type of each channel.

The force reflecting joystick consisted of a lever installed gear box, a motor to execute the force-reflection, a potentiometer to measure the rotating angle of the lever, and a control circuit device.

The F/T sensor is utilized for measuring contact force. If the construction material comes into contact with the environment (external objects), information concerning the contact force is transmitted to the reflecting joystick through a wireless module. A motor rotates according to the signal of the transmitted information that was transmitted to the installed control circuit device at the lever in the force feedback joystick. Therefore, the operator will know the contact situation of a construction material through the reaction force by the rotating lever.

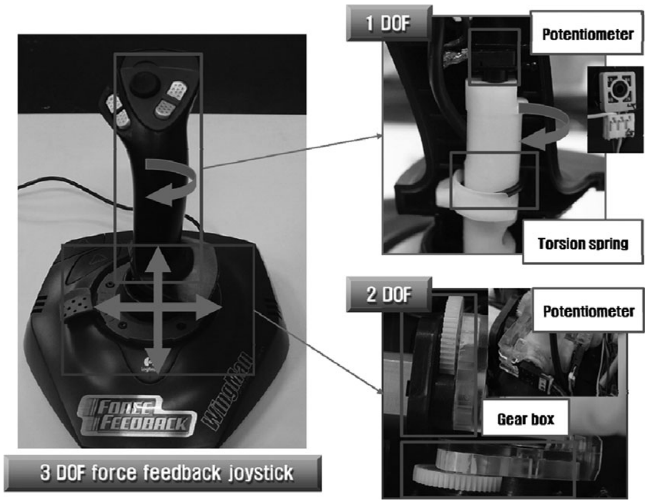

Fig. 11. Improvement of the existing force-reflecting joystick.

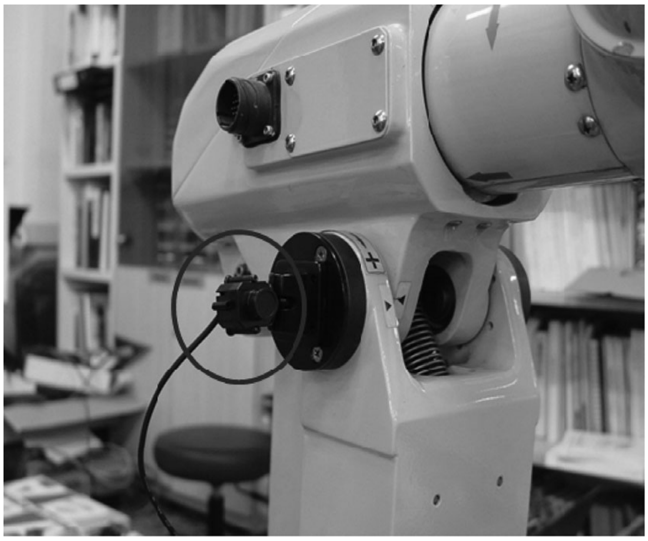

Fig. 12. Monitoring device (wireless CCD camera).

3.2. A monitoring device

Construction materials can be installed safely by understanding the work situation of the robot through a wireless CCD camera on the manipulator as shown in Fig. 12. There can be a long distance between the worker and the robot. The particulars of the CCD camera installation point are as follows:

(1) It obtains the entire motion of robot.
(2) It must recognize an environmental situation easily.
(3) A point is not disrupted in the manipulator movement.
(4) It must always follow the end-effector locations.

4. Control Strategy for an Improved Multipurpose Field Robot

The software of the upgraded additional module referred to a control algorithm, which was necessary for installing construction materials with the IMFR. In this paper, the human–robot interaction and bilateral communication were proposed as methods to control an IMFR.

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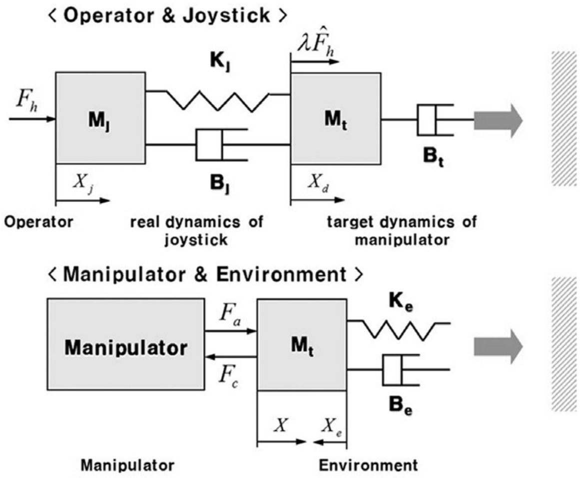

Fig. 13. Free space motion (non-environment-contacting cases).

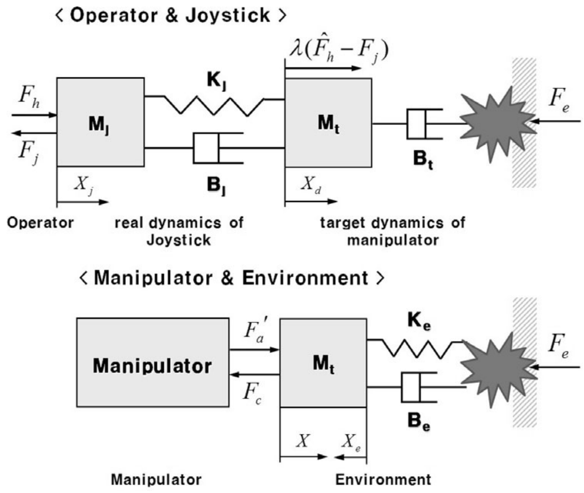

Fig. 14. Motion under constrained conditions (the environment-contacting cases).

4.1. The human–robot interaction

Installation of construction materials by the IMFR can be largely divided as follows:

(1) Process of carrying materials to an installation position with the IMFR system;
(2) Process of inserting them into the correct position or doing press pit, depending on the environment.

In this paper, the former is defined as free space motion (nonenvironment-contacting cases) and the latter as motion under constrained conditions (the environment-contacting cases). Free space motion needs rapid movement with relatively low precision, while motion under constrained conditions needs precise motion with relatively low motion velocity.

Figure 13 shows a free space motion, that is, there has been no contact with environment. External force of an operator ($\hat{F}_h(\hat{T}_h)$) is estimated by real impedance parameters ($M_{pj}(M_{oj})$, $B_{pj}(B_{oj})$ and $K_{pj}(K_{oj})$ ($n \times n$ positive definite diagonal inertia, damping, and stiffness matrices, respectively), dynamic behavior of joysticks ($\ddot{p}_j, \dot{p}_j, p_j$) in an admittance Eq. (1). The subscript "p" stands for the position and "o" stands for the orientation, and "λ" means the power assist ratio of an operator. The dynamics value is used as the reference value for a robot to follow in carrying construction materials. From a viewpoint of human–robot cooperation, the force received from a robot (F_a) is the amount remaining after the force provided by an operator ($\hat{F}_h$) is subtracted from the load of construction materials (F_c), as in Eq. (2):

$$\begin{aligned} M_{pj}\ddot{p}_j + B_{pj}\dot{p}_j + K_{pj}p_j &= \hat{F}_h,\ M_{pt}\ddot{p}_d + B_{pt}\dot{p}_d = \lambda_p \hat{F}_h, \\ \therefore M_{pt}\ddot{p}_d + B_{pt}\dot{p}_d &= \lambda_p(M_{pj}\ddot{p}_j + B_{pj}\dot{p}_j + K_{pj}p_j); \\ M_{oj}\ddot{\varphi}_j + B_{oj}\dot{\varphi}_j + K_{oj}\varphi_j &= T^{\mathrm{T}}(\varphi_j)\hat{T}_h, \\ M_{ot}\ddot{\varphi}_t + B_{ot}\dot{\varphi}_t &= \lambda_o T^{\mathrm{T}}(\varphi_t)\hat{T}_h, \\ \therefore M_{ot}\ddot{\varphi}_t + B_{ot}\dot{\varphi}_t &= \lambda_o(M_{oj}\ddot{\varphi}_j + B_{oj}\dot{\varphi}_j + K_{oj}\varphi_j); \end{aligned} \tag{1}$$

where $\varphi = [\alpha \quad \beta \quad \gamma]^{\mathrm{T}}$,

$$T = \begin{bmatrix} 0 & -s\alpha & c\alpha s\beta \\ 0 & c\alpha & s\alpha s\beta \\ 1 & 0 & c\beta \end{bmatrix},$$

$$F_a = F_c - \hat{F}_h. \tag{2}$$

Figure 14 shows a motion under constrained conditions involving contact with the environment. To estimate a joystick's reaction force (F_j), we introduce the scale-down ratio of contact force "ψ" in Eq. (3). This reaction force converts to the joystick's desired dynamic behavior ($\ddot{p}_{dj}, \dot{p}_{dj}, p_{dj}$) depends on the real impedance parameters ($M_{pj}(M_{oj})$, $B_{pj}(B_{oj})$ and $K_{pj}(K_{oj})$ ($n \times n$ positive definite diagonal inertia, damping, and stiffness matrices, respectively) of a joystick. The net force transmitted into a robot controller is the amount remaining after the force (F_j) provided by a joystick is subtracted from the external force ($\hat{F}_h$) of an operator, as in Eq. (3). Dynamic behavior (target dynamics) of materials is determined by impedance parameters (M_t, B_t) and the external force ($\hat{F}_h$) and joystick's reaction force (F_j). The target dynamics value is used as the reference value for a robot to follow in installing construction materials.

$$\begin{aligned} &\psi F_e = F_j = -M_{pj}\ddot{p}_{dj} - B_{pj}\dot{p}_{dj} - K_{pj}p_{dj}, \\ &M_{pj}\ddot{p}_j + B_{pj}\dot{p}_j + K_{pj}\dot{p}_j = \hat{F}_h - F_j, \\ &M_{pj}(\ddot{p}_j - \ddot{p}_{dj}) + B_{pj}(\dot{p}_j - \dot{p}_{dj}) + K_{pj}(p_j - p_{dj}) = \hat{F}_h, \\ &\therefore M_{pt}\ddot{p}_d + B_{pt}\dot{p}_d = \lambda_p(\hat{F}_h - F_j); \\ &T^T(\varphi_{dj})\lambda_o T_e = T^T(\varphi_{dj})T_j = -(M_{oj}\ddot{\varphi}_{dj} + B_{oj}\dot{\varphi}_{dj} \\ &\quad + K_{oj}\varphi_{dj}), \\ &T^T(\varphi_j)\hat{T}_h = M_{oj}(\ddot{\varphi}_j - \ddot{\varphi}_{dj}) + B_{oj}(\dot{\varphi}_j - \dot{\varphi}_{dj}) \\ &\quad + K_{oj}(\varphi_j - \varphi_{dj}), \\ &T^{\mathrm{T}}(\varphi_j)(\hat{T}_h - T_j) = M_{oj}\ddot{\varphi}_j + B_{oj}\dot{\varphi}_j + K_{oj}\varphi, \\ &\therefore M_{ot}\ddot{\varphi}_d + B_{ot}\dot{\varphi}_d = \lambda_o(T^{\mathrm{T}}(\varphi_j)(\hat{T}_h - T_j)); \end{aligned} \tag{3}$$

$$F_a' = F_c - \left(\hat{F}_h - F_j\right) + F_e, \tag{4}$$

where $F_e = F_{th} + F_d$.

In the case of inserting construction materials into the correct position or doing press pit, contact force (F_e) occurs from the environment as shown in the Fig. 14. Although contact force is generated upon contacting an object, for this paper, materials are installed through press pit by generating compliance within the elastic range of

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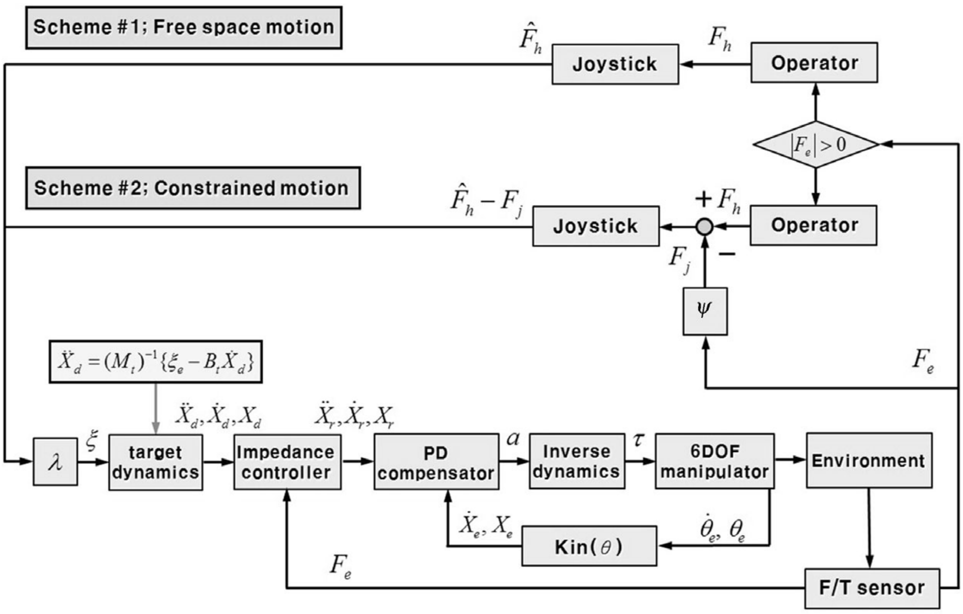

Fig. 15. Block scheme for human-robot manipulation of the IMFR.

environments. Subtracting the external force of an operator ($\hat{F}_h$) from the sum of contact force (F_e), load of construction materials (F_c) and joystick's reaction force (F_j) gives the amount of force (F_a') supplied from the robot to handle construction materials, as shown in Eq. (4). In this expression, F_{th} is the force necessary to make press pit for materials by producing compliance, and is determined by the elastic limit of materials. F_d is the force necessary to move a robot in the opposite direction to prevent materials or a robot system from being damaged.

In case interactions with an environment occur (a constraint condition), the end effector should endow with a behavior, considering the compliance. In this regard, we defined the relationship between the contact force (torque) and the position error of the end effector, through the generalized active impedance, as in Eq. (5). Thus, the end effector can have dependant impedance characteristics to the translation part, for which the contact force F_e was considered, and the rotation part, for which the equivalent contact moment $T^{\mathrm{T}}T_e$ was considered. To implement the above strategy, it is worth introducing a reference frame "p_r" other than the desired frame specified by p_d. In Eq. (5), $M_{pe}(M_{oe})$, $B_{pe}(B_{oe})$, $K_{pe}(K_{oe})$ are the impedance parameters that determine a target dynamic behavior (with compliance behavior) of the end effector for interactions with an environment:

$$\begin{aligned} &M_{pe}\Delta\ddot{p}_{dr} + B_{pe}\Delta\dot{p}_{dr} + K_{pe}\Delta p_{dr} = F_e, \\ &\therefore M_{pe}\ddot{p}_r + B_{pe}\dot{p}_r + K_{pe}p_r = M_{pe}\ddot{p}_d + B_{pe}\dot{p}_d \\ &\quad + K_{pe}p_d - F_e; \\ &M_{oe}\Delta\ddot{\varphi}_{dr} + B_{oe}\Delta\dot{\varphi}_{dr} + K_{oe}\Delta\varphi_{dr} = T^T(\varphi_e)T_e, \\ &\therefore M_{oe}\ddot{\varphi}_r + B_{oe}\dot{\varphi}_r + K_{oe}\varphi_r = M_{oe}\ddot{\varphi}_d + B_{oe}\dot{\varphi}_d + K_{oe}\varphi_d \\ &\quad - T^T(\varphi_d)T_e; \end{aligned} \tag{5}$$

where $\Delta p_{dr} = p_d - p_r$.

Figure 15 shows a block scheme of the suggested human–robot cooperative control system to solve problems involving a remote control system. When an operator judges that the position (X) to which a robot carries materials fails to agree with the position (X_d) to which he/she wants to carry them, his/her force is transmitted to joysticks. In particular, external force ($\hat{F}_h$) estimated by joysticks can be used by operators from various age groups through the force augmentation ratio (λ). 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 F/T sensor, the target dynamics needed for operation are determined by the following Eq. (6) 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 proportional derivative (PD) compensator, 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 Eq. (6). Relatively rapid and precise motions can be implemented by controlling these parameters:

$$\ddot{X}_d = (M_t)^{-1}\left\{\xi - B_t\dot{X}_d\right\}, \quad \xi = \lambda\hat{F}_h \text{ or } \lambda\left(\hat{F}_h - F_j\right), \tag{6}$$

where $\ddot{X}_d$ is acceleration-related target dynamics; $\dot{X}_d$ is velocity-related target dynamics; M_t is inertia-related impedance parameter; B_t is damping-related impedance parameter.

With reference to the scheme Fig. 15, the impedance controller generates the reference position for the PD compensator. Therefore, in order to allow the implementation of the complete control scheme, the acceleration shall be designed to track the position and the velocity of the reference

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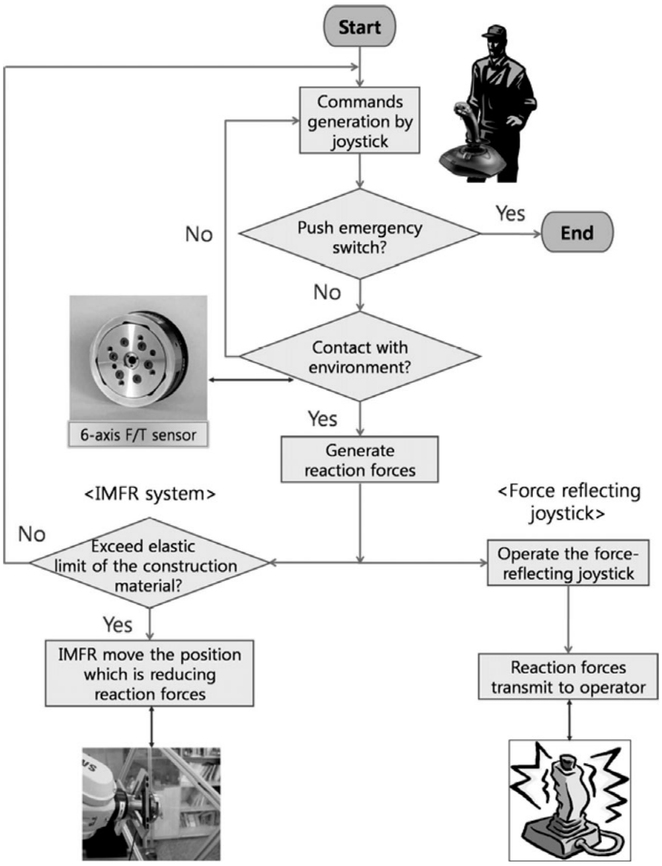

Fig. 16. Signal flowchart for bilateral communication.

frame "p_r", i.e.,

$$a_p = \ddot{p}_r + K_{Dp}\Delta\dot{p}_{re} + K_{Pp}\Delta p_{re},$$
$$a_o = T(\varphi_e)(\ddot{\varphi}_{re} + K_{Do}\Delta\dot{\varphi}_{re} + K_{Po}\Delta\varphi_{re}) + \dot{T}(\varphi_e, \dot{\varphi}_e)\dot{\varphi}_e,$$
$$\text{where } \Delta p_{re} = p_r - p_e. \tag{7}$$

Notice that p_r and its associated derivatives can be computed by forward integration of the impedance Eq. (7) with input $F_e(T_e)$ available from the force/torque sensor.

4.2. Bilateral communication

Bilateral communication can occur for two situations simultaneously. Initially, the operator transmits command signals to the force feedback joystick. Then, the input signals

Table IV. Signal description in Fig. 17.

Signal	Description	Signal	Description
A	Command signals	F	Reaction forces
B	Digital signals	G	Sensor signals
C, H	Wireless signals	I	Reaction forces
D	Control signals	J	Control signals
E	Contact forces	K	Reaction forces

have Cartesian-space coordinate system attributes. These are different attributes than the joint-space coordinate system for the driving actuators of the manipulator. Simultaneously, reaction forces are transmitted to the operator when the end-effector of the manipulator comes into contact with the environment. Figure 16 shows the signal flowchart for bilateral communication. The human–robot interaction algorithm was executed based on the operator's commands (forces), which were input by the force feedback joystick of the IMFR, and information on the reaction forces obtained by the manipulator of the IMFR when it came into contact with the environment. The IMFR system and the construction material can be protected by regulating the system compliance when contact with the environment occurs. If reaction forces exceed the elastic limit of the construction material, then a manipulator moves the position, which reduces reaction forces. At the same time, the operator is able to intuitively control through the reaction forces when the manipulator of the IMFR makes contact with the environment at a long distance. Figure 17 and Table IV show the flowchart of the explained control system.

5. Experiments with an improved multipurpose field robot

5.1. An experimental system

The development of an IMFR applied to the construction area is not achieved by actual system production alone. Studies on system operation technology are also necessary for the developed system to be fully effective in operation. The construction material installation method suitable for a robot which was developed in this paper is shown in Fig. 18. Each process can be outlined as follows:

(a) First, construction materials piled on the ground are fixed to a robot with a vacuum suction device (Fig. 19). The type of loading for materials carried from the ground is

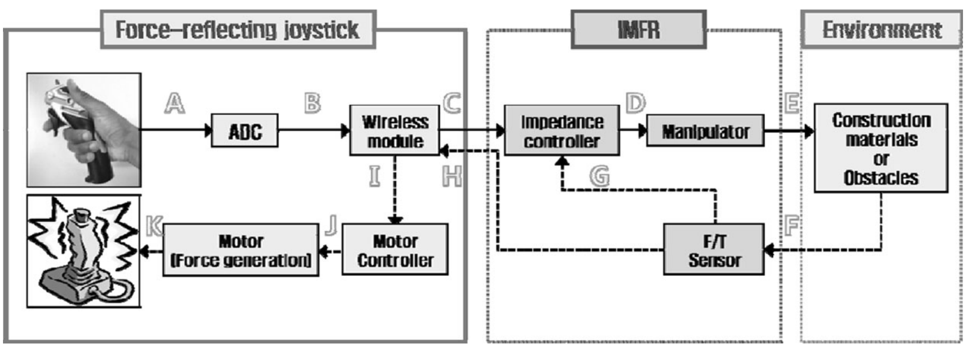

Fig. 17. Signal flowchart of a control system.

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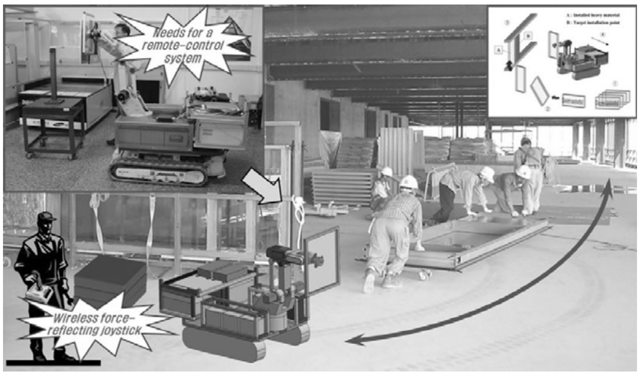

Fig. 18. The suggested construction material installation method.

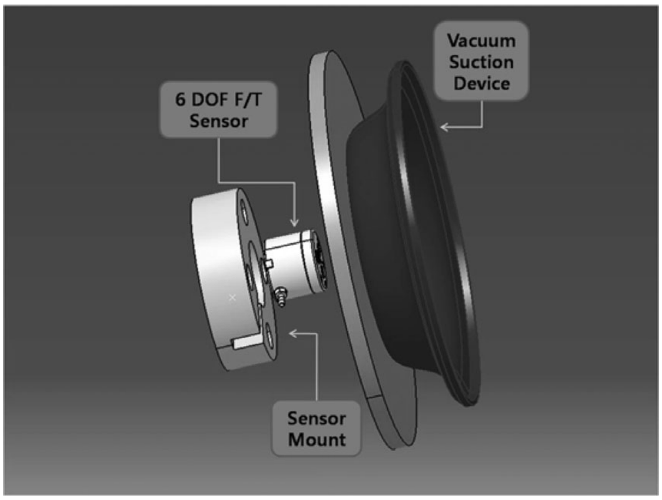

Fig. 19. Vacuum suction device and sensor module.

determined by the most efficient fixing posture within the operation range of a manipulator.

(b) An operator rapidly moves the robot to an installation site through a wireless force feedback joystick. Here, a mobile platform whose velocity can be controlled by the input of a control signal is principally used. The posture of construction materials is adjusted by the motion of a manipulator if necessary.

(c) Construction materials carried to the vicinity of an installation position are installed through interaction with materials already installed by an operator. That is, compliance occurs upon contact, so that the press fit for materials and systems are completed safely.

(d) After the operation is completed, the robot is returned to the site of construction materials loading through a wireless force feedback joystick for the next operation.

An experiment for installing construction material was implemented to evaluate the performance of the proposed IMFR. Its implementation follows the installation method suggested in Fig. 18. The test is implemented indoors with an operation environment similar to that of an actual construction site. A test-bed to implement press fit after inserting construction materials into the correct position was designed as in Fig. 20. Inserting construction materials

Table V. Specifications of a construction material model.

Specification	Value
Length	450 (mm)
Breadth	350 (mm)
Thickness	20 (mm)
Weight	60 (N)
Material	Glass and Aluminum

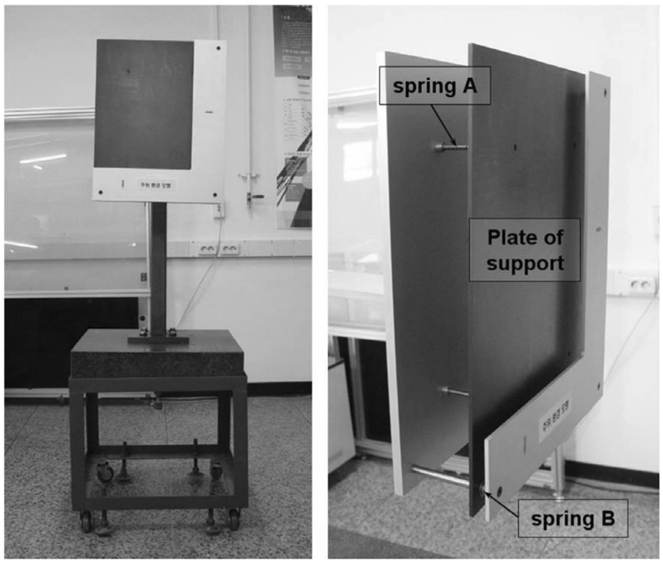

Fig. 20. Test-bed to implement press pit.

between the supporting board and the L-board is substituted for actual installation operation. As the gap is narrower than the thickness of construction materials, they are moved horizontally and vertically with the supporting board connected to spring “A” being pressed in order to complete the installation operation.

If the supporting board is pressed, it means that compliance occurred; if the length of compression exceeds a certain range, the result is contact force which causes the robot to move in the opposite direction. In this experiment, construction materials were limited to 60 N and below (as shown in Table V), considering the specifications of the manipulator, and manufactured into models of curtain-wall or panel. Figure 21 shows the experimental system to evaluate the performance of the proposed IMFR.

5.2. *Experimental results*

Figure 22 shows a simulation for installing construction materials through an experimental system. Initially, a construction material on the ground was gripped to the IMFR with a vacuum suction device, and the IMFR was moved to an installation position by a command signal of the force-reflection joystick. The operator handled the construction materials through a wireless CCD camera that was attached to the body of the manipulator. The construction material was carried to the vicinity of the installation position and installed through interaction with the test-bed. That is, compliance occurred upon contact, so that the press pit for the construction material and the IMFR system was

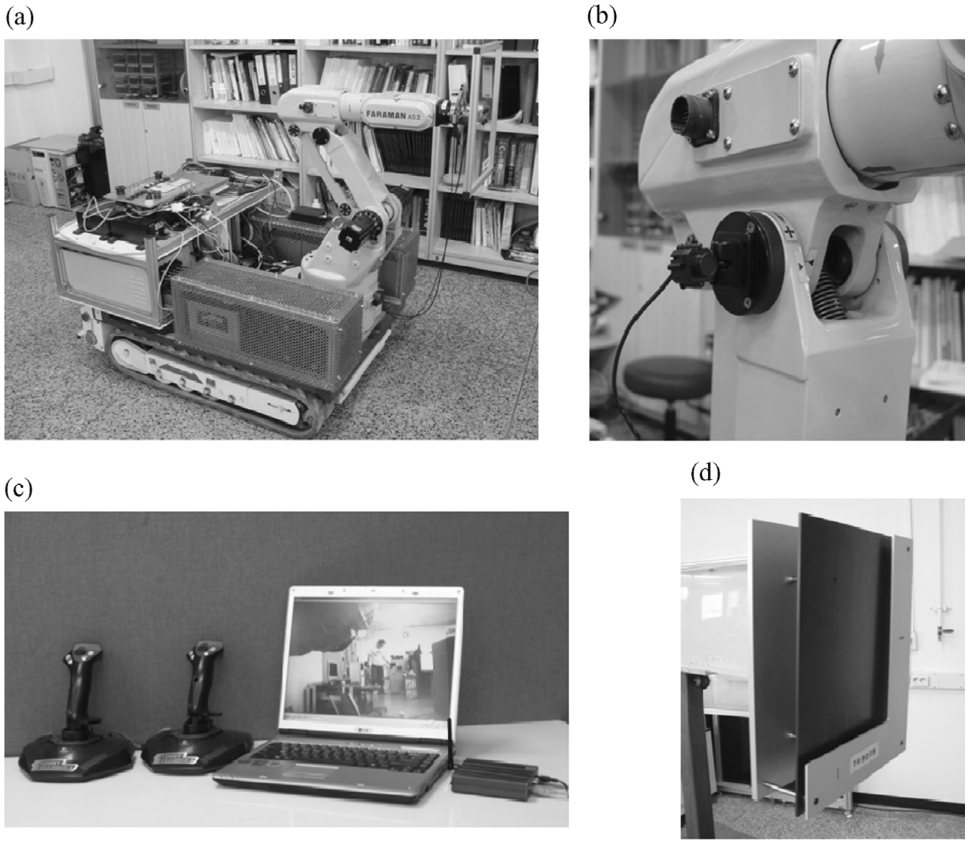

Fig. 21. Experimental system for installing construction materials. (a) Basic system of IMFR; (b) Wireless CCD camera; (c) Force-reflecting joystick and monitoring device; (d) test-bed.

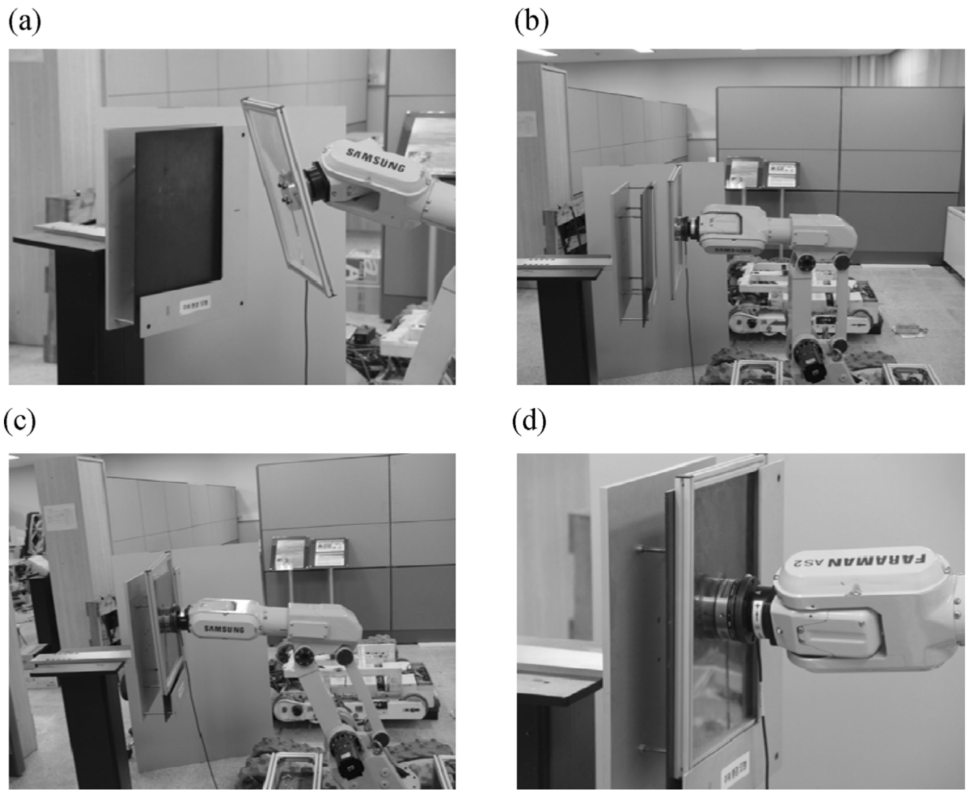

Fig. 22. Experimental process for installing construction materials. (a) Arrangement of coordinate systems; (b) Approach to installation position; (c) Contact between a construction material and a test-bed; (d) Press fit of a construction material.

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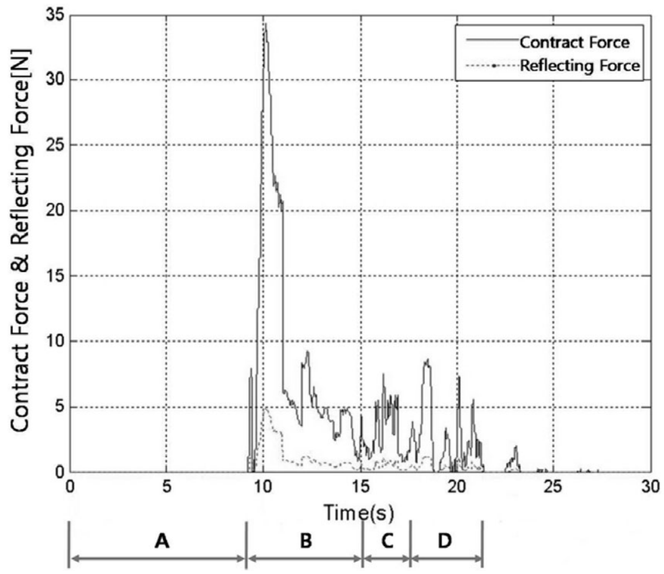

Fig. 23. Experimental result (contact force & reflecting force).

completed safely. Furthermore, at this time, the reaction force was transmitted to the operator and it provided an effective operator command. Precise positioning is performed by human–robot cooperative control. In installing construction materials, an operator is encouraged to collect information on the operation in real time in order to cope with changing environments. Here, the speed or efficiency of operation is proportional to an operator's proficiency.

Figure 23 shows the contact force from the simulation for installing construction materials using an experimental system. Each section can be described as follows:

(1) Section A (from 1 to 8 s) : This range is related to free-space motion, in which the construction material is carried to the installation position.
(2) Section B (from 9 to 15 s) : Contact with the environment (test-bed) begins to occur, generating a maximum of 35 N of contact force (F_e). According to generating a contact force, the force feedback joysticks transfer information on reaction forces (F_j, approx. 5 N) to the operator. To be pressed the supporting board, an operator can manipulate the joystick with excessive motion range (it means that excessive $\hat{F}_h$ and F_e are occurred). By generating compliance within the elastic range of environments as in Eq. (5), a robot system is moved in the direction to prevent materials or a robot system from being damaged. Thus, the contact force is not over 10 N when compliance is occurred.
(3) Section C (from 16 to 18 s) : A construction material is carried horizontally to be inserted between the supporting board and the L-board.
(4) Section D (after 19 s) : Inserted horizontally, a construction material is then inserted vertically.

A comparison was made between the contact force (F_e) with environments and a joystick's reflecting force (F_j), measured and estimated by a sensor during the installation (press fit) of construction materials (d) (Fig. 22). F_e and F_j refer to the mean value of forces measured in the x, y, and z directions by a sensor during operation time T_e and T_j, respectively, as shown in the following Eqs. (8):

$$\left.\begin{aligned} F_e &= \int_0^{T_e} \frac{\sqrt{F_{ex}^2 + F_{ey}^2 + F_{ez}^2}}{T_e} \mathrm{d}t, \\ F_j &= \int_0^{T_j} \frac{\sqrt{F_{jx}^2 + F_{jy}^2 + F_{jz}^2}}{T_j} \mathrm{d}t. \end{aligned}\right\} \tag{8}$$

6. Conclusion

The MFR prototype presented in the previous study combines a mobile platform and a manipulator standardized in modular form to compose its basic system. Also, the hardware and software necessary for each area of application were composed of additional modules and combined with the robot's basic system. The suggested MFR can execute particular operations in various areas, such as construction, national defense, and rescue by changing these additional modules. Especially, if we properly apply the MFR to heavy-materials handling works at construction sites, operators can move heavy materials with relatively less force, while complying with the operators' intention. Through the case studies on constructions, to which MFR was applied, however, we found some problems to be improved. That is, the operator should manipulate the HRI device near the MFR. Therefore, a serious accident may occur when an operator works in poor environmental conditions such as dust or poisonous air, high or low temperature areas and so on.

To address these problems, the concept of an IMFR was introduced. An IMFR is various devices which a suggested MFR apply to remote control. The hardware of the upgraded additional module was partitioned into a force feedback joystick and a monitoring device. The software of the upgraded additional module was also partitioned into the human–robot interaction and bilateral communication.

As mentioned in Table VI, one of the advantages of the proposed IMFR can be handled construction materials through human–robot cooperation in remote sites. For this cooperation, the robot controller (force-reflection joystick) and monitoring device (wireless CCD camera) are combined in the previous MFR system. Also, human–robot cooperative control is done through target dynamics modeling of human, robot, environment, and control of impedance and external force inputted from the F/T sensor attached to the additional module. In addition, a bilateral communication technology and emergency control function were added through other extra equipment.

Development of the suggested IMFR does not end with development of the robot system alone. An operation method appropriate to site environments was proposed to show the robot's full ability and work functionality. The operation method was realized in the form of a construction material installation mock-up test. When construction material is implemented by press fit with a material already installed, compliance occurs within the elastic range of the material and it is installed without damaging either a robot system or materials.

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Table VI. Comparison and analysis of the MFR and IMFR on construction site.

	MFR	IMFR
Control mode	Wire/wireless/HRC	Wire/wireless (with force reflection)/HRC
Number of workers	1	1
Working condition	Install materials intuitively in coexisted spaces	Install materials intuitively in remote sites
Compatibility	Be compatible in various work through a change of a basic system and additional modules	Be compatible in various work through a change of a basic system and additional modules
Safety	Protection construction materials and system through force reflection	Protection not only construction materials and system through force reflection but also an operator through teleoperation

Acknowledgments

This work was supported by the Korea Research Foundation Grant and was funded by the Korean Government (KRF-2008-357-D00010) and the MKE (The Ministry of Knowledge Economy), Korea, under the Advanced Robot Manipulation Research Center support program supervised by the NIPA(National IT Industry Promotion Agency) (NIPA-2010-(C7000-1001-0002)) and SAMSUNG CORPORATION.

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