The Study on the Integrated Control System for Curtain Wall Building Cleaning Robot

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Abstract –

The industry's interest in building façade maintenance is rising with the growing number of new high-rise buildings in the metropolises. The conventional method of cleaning the façade of high-rise buildings relies on the use of ropes, gondolas, and the winch system involving human labor. Recently the building maintenance unit (BMU) has been developed and has been applied to building maintenance to prevent safety accidents and to ensure high work efficiency. Diverse robot systems are being applied to building maintenance globally, including in Germany, the United States, and France. In South Korea, the built-in guided robot system was developed. This paper deals with an integrated control system of built-in guided robot system to ensure consistent and stable control. This control system is considered its unique characteristics as a building façade cleaning work. The integrated control system proposed in this paper performs cleaning work in three steps: preparation, cleaning, and return to the initial position, with each module consisting of the robot system performing its task sequentially and independently at each step. In addition, the robot system makes up a network composed mainly of VMR to ensure smooth and stable communication among the different modules. The integrated control system proposed in this paper was applied to the built-in guided robot system for performance verification.

Keywords –

Curtain wall building cleaning robot; Integrated control system; Sensor based control; Built-in guide rail

1 Introduction

As the population density has increased and the function of the city has become more complex, the number of high-rise buildings has been increasing. As the façade of such high-rise buildings can be used for advertising and PR purposes, they are usually designed to embody diverse and unique characteristics in terms of their structure. Moreover, the interest in building façade maintenance as opposed to building remodeling is growing as an effective means to extend the life cycle of buildings. The conventional building facade maintenance methods for the cleaning, painting, and crack inspection of high-rise buildings mainly depend on ropes, gondolas, and the winch system. As these methods are highly dependent on manpower, in contrast to the other construction processes that are being automated, their use also incurs high socioeconomic losses due to accidents. The demand for automated maintenance work for high-rise buildings performed in a dangerous environment is gradually increasing [1, 2, 3].

To address the aforementioned demand, many studies on the automation of the building maintenance unit (BMU) and the related robots have been conducted in Europe, Japan, and the U.S [4].

For example, many research institutes and companies, including Fraunhofer IPA and Manntech in Germany and Nihon Bisoh in Japan, introduced robot platforms in the test operation stage. In particular, Nihon Bisoh has already successfully applied robots to the cleaning work of high-rise building landmarks in Tokyo, Osaka, and Yokohama. SIRIUS-c, a BMU developed by Fraunhofer in Germany, is equipped with two sets of linear translation module in addition to the wire-based vertical mobility function along the building façade. The BMU is designed to perform uninterrupted cleaning while maintaining a constant distance from the building façade with the help of this module. Likewise, Skycleaner 3 in Germany is hooked up with the following unit mounted on top of the building via wires while cleaning the building, with the cleaning supplies transported from the ground level by a supporting vehicle [5].

Skycleaner 3 moves along the building façade using pneumatic cylinders as well as multiple suctions pads installed along the sides of the cylinders. Tito 500 developed by RATIOFOREM in the United States moves up and down the building façade along the vertical wires while cleaning the façade, without bumping onto the glass curtain walls, through the use of a wheel mechanism installed inside the robot, which functions as a damper [6]. RobuGlass, developed by Robosoft in France [7] and Gekko Façade, developed by Serbot in Switzerland [8] were designed to perform cleaning independently by sucking onto the building façade only with suction cups, without using wires.

In this paper, a built-in guided robot system mounted with cleaning supplies and that cleans the building façade by gliding along the rails installed around the building will be introduced, along with the integrated control system required to carry out uninterrupted and stable control by considering the robot's cleaning method and cleaning environment.

2 System Configuration and Work Environment

2.1 Work environment

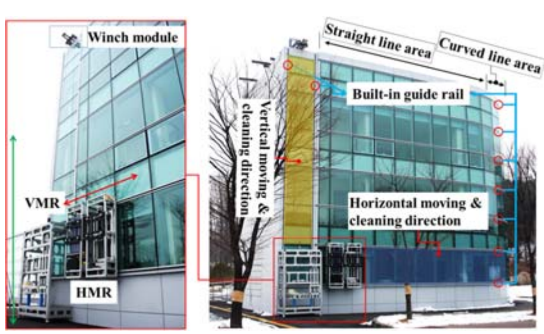

Figure 1. Work environment

The work environment applied to the built-in guided robot system described in this paper is shown in Figure 1. The building on which the robot was tested was a three-story building, with each floor surrounded by curtain walls, each measuring 1,800×1,320 and 900×1,320 mm. The façade of the building to which the built-in guided robot was applied was covered with two sets of rail, one running vertically and the other running horizontally, while the cleaning sections were divided into straight and curved sections depending on the shape of the building.

2.2 System configuration and roles

The built-in guided robot that performs cleaning in the work environment shown in Figure 1 is composed of an HMR (horizontal-moving robot), a VMR (vertical-moving robot), a winch module, and a monitoring module. The VMR performs cleaning while moving along the rail installed horizontally across the façade whereas the HMR plays the role of transporting the VMR to each floor while moving along the rail installed vertically along the façade, as well as of cleaning the façade. The winch module moves the HMR and VMR to their target floors, respectively, while the monitoring module sends the cleaning command, monitors the current position of the cleaning robot, and transmits the robot status information to the control staff and various other systems

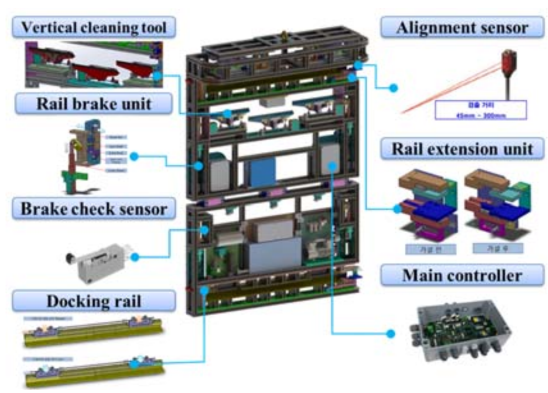

Figure 2. Configuration of VMR

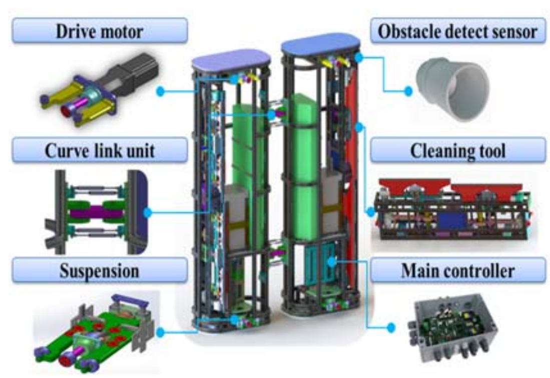

Figure 3. Configuration of HMR

The VMR and HMR, which play the key roles in the

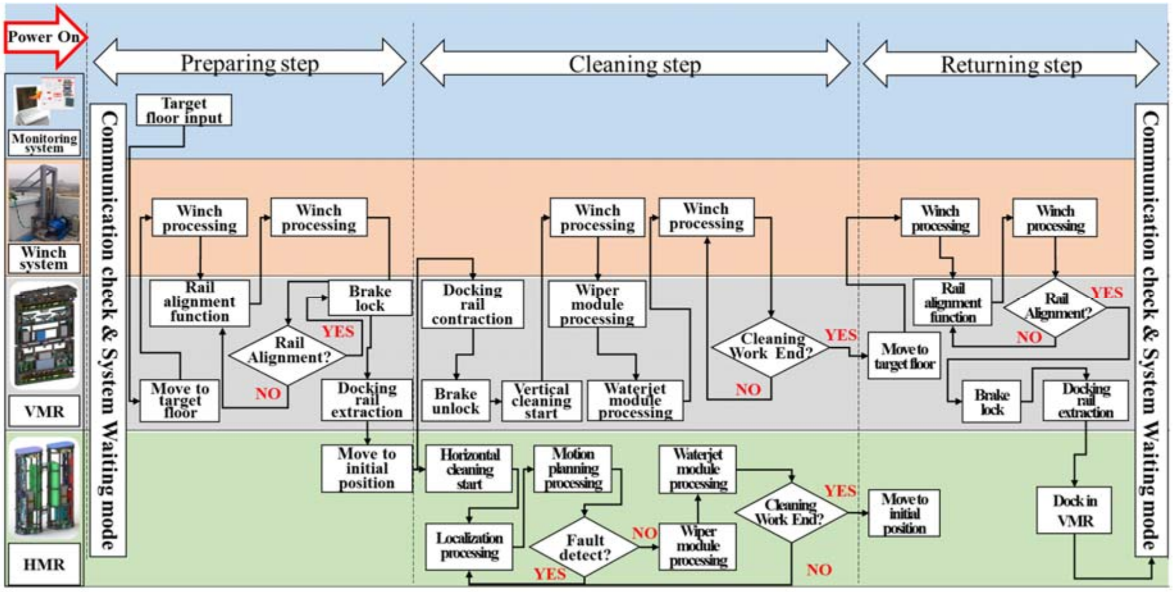

Figure 4. Integrated control system for built-in guided robot

built-in guided robot, are configured as shown in Figure 2 and 3. The VMR contains four brake units and brake check sensors designed to prevent safety accidents due to a shift in its weight, as well as a docking rail, which allows the HMR to dock in the rail running horizontally along the building. The two rail extension units connect the building and the docking rail while the vertical cleaning tool mounted on the VMR is used to clean the curtail walls covered with rails running vertically. The HMR is made up of two units connected with each other via a curb link unit so that it would be able to move along regardless of whether the section to be cleaned is a linear or curved section. Also included in the package is an obstacle-detecting sensor, which detects any obstacle along the path, such as a suspension or a window, to prevent damage due to vibration shock while moving along the horizontal rail along the building. A rail cleaning unit, a small compressor designed to remove the contaminants (fallen leaves, dust, bird nests) inside the horizontal rails, is also included.

3 Integrated control system architecture for the Built-in Guided robot

3.1 Integrated control system architecture

To clean a building, the monitoring system, winch system, VMR, and HMR perform cleaning by either transmitting or receiving the control command sequentially via communication between the modules, or in certain sections, each module performs the given task independently according to the specific control command prescribed for the section. Figure 4 shows the structure of the control system for the built-in guided robot system, including the control flowchart among the modules in accordance with the cleaning work sequence.

All the modules of the built-in guided robot remain in the standby mode after the power is turned on, until the communication check is completed. Upon receiving from the monitoring system (an interface for the initial operator) the command to start the work on the floor, the VMR then decides the target speed and direction of the winch by calculating them with the rail alignment function. Once the VMR and HMR arrive at the target floor, the VMR locks the brake and expands its rails. When the VMR executes the rail expansion command, the HRM moves to the horizontal rail along the building. The HMR’s arrival at the initial position located on the horizontal rail of the building marks the completion of the preparation stage by both the VMR and HMR.

Unlike in the preparation stage, where the tasks are performed sequentially via inter-module communication, in the cleaning stage, the HMR and VMR perform their respective tasks independently. In the case of the VMR, the rails contract and the brakes are unlocked once the cleaning work begins. Then the VMR performs cleaning starting from the highest floor and moving all the way down to the lowest floor, by spraying a small amount of water onto the curtain walls and then wiping them dry. In the case of the HMR, it decides its target speed and direction by calculating them with the motion planning function by receiving feedback on the robot’s current location based on the localization algorithm. As the HMR performs cleaning along the horizontal rail surrounding the building, it includes a fault detection function, which protects the robot from the windows or other elements.

Both the VMR and HMR embark on the return maneuver to their original locations once the cleaning is over. As in the preparation stage, the VMR locks up the brakes and expands the rails while the HMR moves back to its initial position and remains in the standby mode. Once the signal indicating that the VMR has completed the expansion of the rails is confirmed, the HMR embarks on the dock-in maneuver. Once the HMR completes the dock-in maneuver, the VRM contracts the rails and unlocks the brakes before returning to the standby mode. The built-in guided robot system allows the operator to check the status of each module by sending the status information to the monitoring system once every second throughout the three stages. In the operator mode, the aforementioned sequential commands can be transmitted by the operator in real time to ensure the smooth return of the robot to the initial location in the event of work failure.

3.2 Communication network

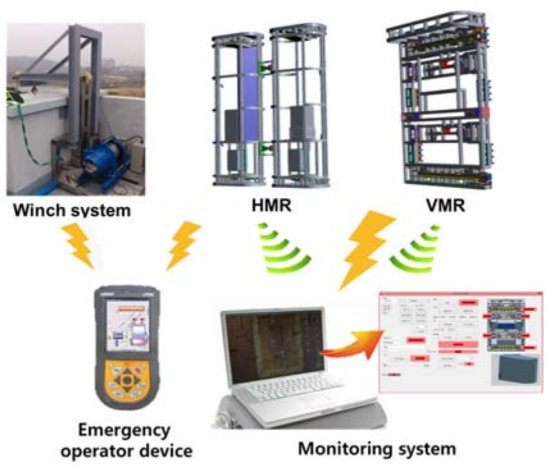

Figure 5. Communication network for robot system

The built-in guided robot system should be able to return to its original location safely in the event of system failure due to an external factor or a system error while performing cleaning work on the building façade. This is where the communication network functioning smoothly between the modules kicks in to improve the cleaning performance and to prevent a safety accident. The built-in guided robot system has a network configured as shown in Figure 5 below. In the built-in guided robot system, which performs the algorithm at regular intervals while sending and receiving various commands, the VMR transmits the control commands that it received from the monitoring system to each module as well as forwards the status information it received from each module and unit back to the monitoring system. Such network configuration can prevent the occurrence of a communication error during the carrying out of the sequential commands. In the event of communication failure between the VMR and the monitoring system during cleaning, the operator shall communicate with each module independently via RF communication, using the handheld operator system.

4 Integrated control system architecture for the Built-in Guided robot

4.1 Motion planning algorithm

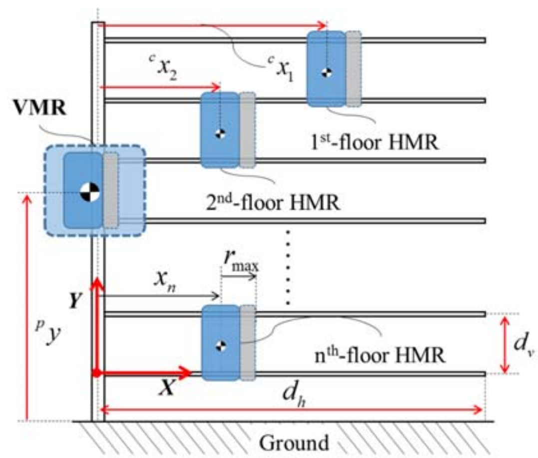

Figure 1. Schematic and coordinate system of the robot system

The coordinate system for indicating the locations of the VMR and HMR is shown in Figure 6. The position of the VMR movement along the vertical rail is Py, and the position from the vertical rail of the HMR along the ith horizontal rail is xi. The length of the horizontal rail is dh, and the vertical spacing between the horizontal rails is dv. The maximum velocity of the VMR is defined as vp_max, and it must always move at this speed during cleaning. In addition, the maximum and minimum velocities of the HMR are defined as vc_max and vc_min, respectively. The maximum value at no contamination is vc_max, and the minimum value at the maximum contamination is vc_min. The velocity of the HMR according to the contamination level between these two speeds has a linear relationship. Here, it is assumed that when the HMR moves at the changing velocity of the contamination level, sufficient cleaning is performed to remove the contaminants at the location. As the contamination level is associated with the distance of each horizontal rail, the value can be expressed as ci(xi). The integral value of the contamination level by the distance from the ith horizontal rail is expressed by si, as shown below.

$$s_i = \int_0^{d_h} c^i(x^i)dx^i \quad (1)$$

As $0 \le c^i \le 1$, $0 \le s^i \le d_h$ is true. Equation (1) considers the range of the time required for the HMR to perform cleaning according to the contamination level. If equation (1) has the minimum value, $s^i=0$, and the HMR always moves at the maximum speed because the contamination level cannot be measured. The time required for the HMR to return to its original location after cleaning is $2d_h/v_{c\_max}$. On the other hand, if equation (1) has the maximum value, $s^i=d_h$, and the contamination level of all the areas of the horizontal rail is the maximum value (1). Therefore, the range of time that it takes the HMR to perform cleaning on the i_{th} horizontal rail and to return to its original location (t_{i_HMR}) can be expressed as follows:

$$\frac{2d_h}{v_{c\_max}} \le t_{i_{HMR}} \le \frac{d_h}{v_{c\_min}} + \frac{d_h}{v_{c\_max}} \quad (2)$$

4.2 Rail alignment algorithm

For the VMR to be able to clean the areas between the floors, it should first move to the inter-floor rails that connect the floors. The rail alignment algorithm controls the precise location and speed of the HMR so that the VMR could dock into the horizontal rail surrounding the building. First, the two laser sensors (Sharp EX-L211) are mounted on the upper/lower half of the HMR's rail extension module, as shown in the following figure, to perform the algorithm and to detect the space and building wall inside the horizontal rail with ON/OFF signals. Assuming the DIO signals from the laser sensor mounted on the upper section as S1 and DIO signals from the sensor mounted on the lower section as S2, the rail alignment algorithm attempts to align the HMR rails with the building's horizontal rails while moving slowly from the lower floors to the upper floors to prevent failure due to the weights of the HMR and VMR. As mentioned earlier, the HMR moves from the lower floors to the upper floors, and if S1 and S2 detect the inner cavities of the horizontal rails of the building one by one while doing so, the HMR defines the rails as aligned. The rail alignment algorithm performs the aforementioned definition in accordance with the following five modes, depending on the locations of the building's horizontal rails and the HMR's rails. Mode 1 signifies an occasion

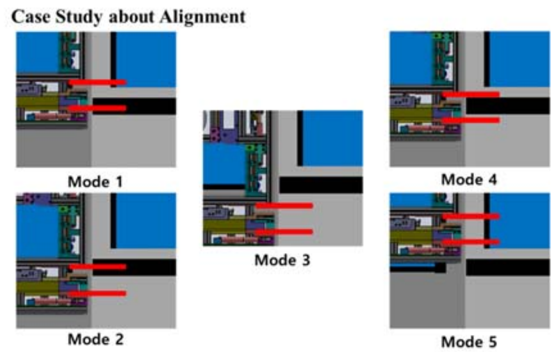

Figure 7. Rail-alignment algorithm

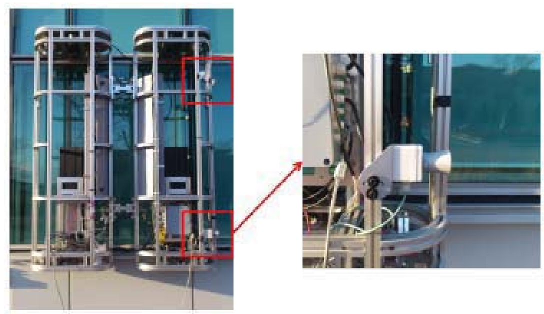

Figure 8 Ultrasonic sensor module for obstacle detecting

where S2 is ON and S1 is OFF, and the HMR glides down slowly until S2 is turned OFF. If S1 is turned ON, the HMR starts to glide up again slowly while the algorithm function stops when S2 is turned OFF. Mode 2 signifies an occasion where S1 is ON and S2 is OFF, and as in Mode 1, the HMR performs its algorithm while slowly gliding up the building. In Mode 3, 4, and 5, both S1 and S2 are OFF, and the process of detecting the rails is included in the algorithm. The survey process in the rail alignment algorithm signifies the process where S2 or S2 detects the inner cavities of the rails while the HMR is gliding up to the upper floors. Mode 3 signifies an algorithm where S1 detects the inner cavities of the building rails, which is followed by the performance of the task in Mode 2. In Mode 4, S2 detects the inner cavities of the building rails, which is followed by the performance of the task in Mode 1. In Mode 5, the robot glides up the building for 15 seconds considering its inter-floor distance and HMR's speed before it glides down again when the S1 and S2 sensors are OFF, and then performs the task in Mode 1.

4.3 Fault detection algorithm

An ultrasonic sensor was used to perceive an obstacle like the opening of the external wall ventilation window. To prevent the building external wall from being perceived as an obstacle, a vibration- and waterproof ultrasonic wave sensor was used at a place with a narrow ultrasonic-wave directional angle and for industrial use (Figure 8). The control system transmits a trigger signal and sends an ultrasonic wave from the sensor behind 20 ms to transmit an analog signal by ultrasonic-wave strength. The control system was designed to judge a signal larger than a specific size as an obstacle, and to determine the location of an obstacle by the reflection time of the ultrasonic wave.

5 Conclusion

This paper dealt with an integrated controller for the built-in guided robot system, which is used to clean the exterior of curtain walls. The built-in guided robot system is designed to fit into the structure of modern high-rise buildings and consists of four modules: a monitoring system, a winch system, a vertical-moving robot (VMR), and a horizontal-moving robot (HMR). Each module of the built-in guided robot performs cleaning while communicating wirelessly with the other modules on the façade of the building. Therefore, each module of the robot system is designed to return to the ground floor safely in the event of a work or communication error. Therefore, the built-in guided robot system proposed in this paper is designed to perform the cleaning task uninterrupted and stably by enabling each module to be controlled sequentially and independently.

The integrated controller of the built-in guided robot system performs the cleaning task sequentially in three stages: preparation, cleaning, and return to the initial location. In the preparation stage, the integrated controller performs the task sequentially while sending and receiving control commands to/from the different modules. In the cleaning stage, the integrated controller lets the VMR and HMR, the actual devices that clean the building, work independently. In the final stage (return stage), the integrated controller waits for the additional input of the operator while performing sequentially. To communicate as many control commands smoothly, the built-in guided robot's network is configured to forward the control commands inputted by the initial operator to each module via the VMR.

In this paper, the performance of the integrated controller was verified by mounting a controller on a built-in guided robot and then deploying it for an actual building cleaning task. Additional onsite tests of the integrated controller with the built-in guided robot working on the façade of a building would be required for further modification and enhancement of the said controller.

Although the building on which the robot was tested was a three-story building, this robot system and algorithms are designed for high-rise building. But the additional test to safely operate in high-rise building will be progressed in future work.

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