Development of Fail-Safety system for Building Wall Cleaning Robot

J. Huh[1], S. M. Moon[1], S. W. Hwang[1], S. M. Yoon[1], and *D. Hong[1]
[1]Korea University
Anam-dong 5-ga, Seongbuk-gu
Seoul, Korea
*(*Corresponding author: dhhong@korea.ac.kr)*

ABSTRACT

Recently, there is growing trend to build the high-rise and install curtain walls. Following this trend, we developed robot for building wall cleaning work, which moves along Built-in guide rail of building. Because it moves attached at building wall for cleaning work, it can be seriously affected by potential threats, like earthquake, strong wind, malfunction, and construction error of built-in guide rail. In order to cope with those threats actively, this paper presents the Fail-Safety system.

The building wall cleaning robot consists of two moving system: The Horizontal Moving System which mainly do maintenance work, and The Vertical Climbing System which transport the horizontal moving system floor by floor. We apply the Fail-Safety system to these systems. The Fail-Safety system consists of sensors to detect external situation, and, with information of sensors, give instruction for what to do. This robot system is installed with four kinds of sensors: shock sensor, infrared ray sensor, laser sensor, magnetic sensor. First, shock sensor detects external shock during cleaning work. When shock sensor detects big shock, the robot returns to starting point to inspect how damaged it is. Second, infrared ray sensor detects damage of built-in guide rail. It is to prevent destruction of robot caused by moving along damaged rail. Third, laser sensor gives notice about where obstacle is. It is for robot to avoid crash with obstacle and decrease damage. Fourth, magnetic sensor detects magnetic points, which are installed in rail at regular intervals, and helps robot to find its position, based on location of magnetic points detected. If robot is damaged by external shock and its encoder, which gives information of location to it, is not working, magnetic sensor will give information of robot's location to robot. And then, robot regulates its velocity depending on position of it, and safely returns to starting point.

The Fail-Safety system in this paper is for building wall cleaning robot to sense external threats, and prevent getting worse. Applied to this active protection system, making safe environment of maintenance work is possible for robot system.

KEYWORDS

Building wall cleaning, Fail-Safety

INTRODUCTION

Today, modern construction industry has growing trends toward the high-rise building, and installation of curtain walls. As the number of high-rise buildings equipped with curtain walls increases more and more, demand for cleaning curtain walls is in growth.

Most of these works are maintained by human workers. However, building wall cleaning in the high floor is very dangerous and has risk of accidents like crash and fall. Because of danger, many people avoid this job, and the number of workers rapidly decreases whereas demand for them increases steadily.

In order to solve this problem, we develop the building wall cleaning robot system to substitute workers with prior studies (S.M.Moon et al., 2012; J.Huh et al., 2012; N.Elkmann et al., 2005). This robot system moves along built-in guide rail which is installed in building wall, and cleans curtain walls with its tool mechanism.

During cleaning operation, this robot is manipulated from a height. So, if it is affected by potential threats which include shock, strong wind, malfunction and construction error of built-in guide rail, it cannot be supported with emergency repairs, or inspection. Because of that, the robot, which works in dangerous place, needs the Fail-Safety system. The Fail-Safety system is for robot to keep its operation continually, in spite of malfunction by partial damage, and protect itself from damage by detecting potential risks. So, this paper explains the Fail-Safety system for safe cleaning work, by using sensors.

Building Wall Cleaning Robot System

The building wall maintenance robot system is composed of two moving robots. In figure 1, one is the horizontal moving robot, and the other one is the vertical climbing robot. The horizontal moving robot moves along the horizontal rail, and cleans curtain walls with tool mechanism. The vertical climbing robot has no cleaning functions, but it is very important that it carries the horizontal moving robot to the next floor by its climbing mechanism. With cooperation of two moving robots, the system has ability of full-scale cleaning work

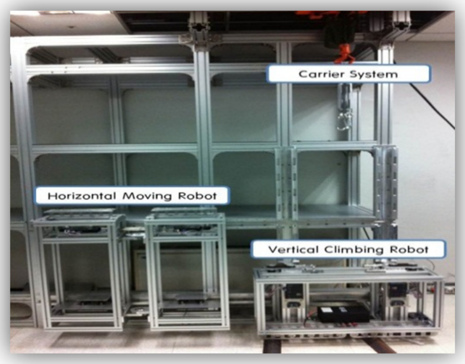

Figure 1 – Building cleaning robot of the built-in guide rail type

The Horizontal Moving Robot

The horizontal moving robot is designed for smooth moving, and its unique wheels suspend it on the rail. When it passes curve line, or rough section, its suspension absorbs impact applied from rail. Wheel mechanism prevents derailment, and sustains weight of the robot.

In figure 2, the horizontal moving robot has tool mechanism which is composed of the brushing unit, the injection unit, and the squeezing unit. These tool units have the ability to avoid obstacles of building wall. By the linear motors connected with them, it is possible for them to move inside, or outside of robot. So, in cleaning work, their linear motors move them outside of robot, on the contrary, when robot is closed to obstacles, move them inside.

In addition, the horizontal moving robot has the water storage to supply water to the injection unit.

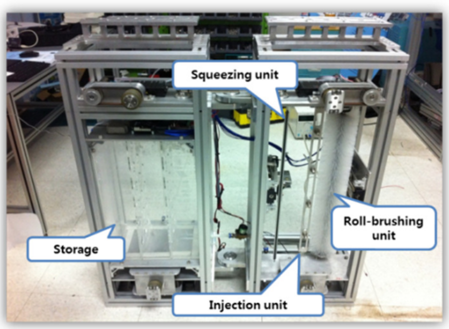

Figure 2 – The horizontal moving robot and its tool mechanism (J.Huh et al., 2012)

The Vertical Climbing Robot

In figure 3, the vertical climbing robot has inch-worm mechanism and hook mechanism, which were developed in a previous study (S.M.Moon et al., 2012). These two mechanisms make precise climbing motion of robot. Additionally, the winch also supports for robot to climb and, when main climbing mechanisms malfunction, it sustains robot.

The main objective of vertical climbing robot is to carry the horizontal moving robot to the next floor. For that, it has to connect with the horizontal moving robot, and that is possible by its docking mechanism. It has pull/push function to drag the horizontal moving robot out of the previous rail, and install it in the next rail.

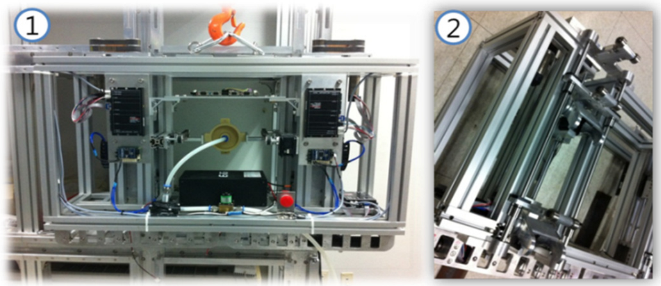

Figure 3 – 1.The vertical climbing robot, 2.The climbing mechanism of vertical climbing robot

Fail-Safety system for horizontal moving robot

When the vertical climbing robot is in malfunction, its winch let it move down to the ground. As the winch has problem, the hook mechanism of vertical climbing robot supports weight of robot, and, during that, workers fix the winch.

However, on the contrary to the vertical climbing robot, malfunction of horizontal moving robot causes many serious problems. When it malfunctions, it can crash with building wall, be jammed in the rail, or fail in docking with vertical climbing robot. In order to prevent that, the fail-safety system must be required for the horizontal moving robot.

Fail-Safety against shock, using shock sensor

Shock is made from various sources, like, strong wind, vibration from building, crash, or moving in rough rail. When its magnitude is excessive, components can be destroyed. Before that situation takes place, the horizontal moving robot has to return to the ground, and be checked to prevent from worsening. Thus, in this paper, shock sensor is installed in robot for this objective.

<u>AU84-TP Dual Zone Shock Sensor</u>

This paper uses the AU-84TP shock sensor. In figure 4, sensor makes two outputs, which are the ALARM TRIGGER(Heavy shock), and the PRE-WARN(Light shock). Depending on magnitude of shock, it determines which output should be sent to the main control system. Sensitivity of sensor is regulated with adjustment screw.

In this system, the PRE-WARN signal is to stop driving of robot, and the ALARM TRIGGER signal is for robot to return to the ground.

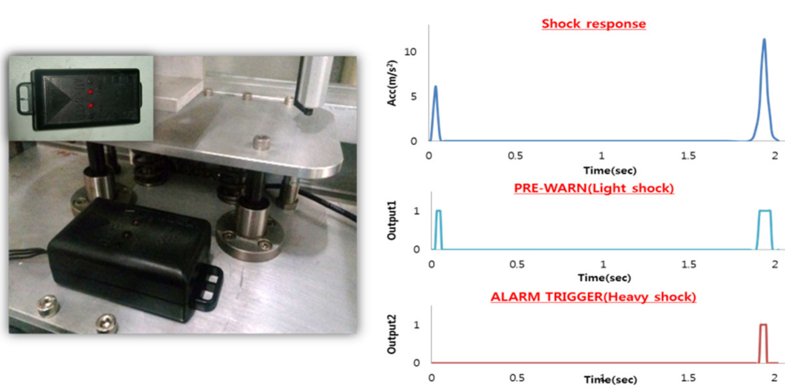

Figure 4 – Shock sensor and its output signals when shock occurs

Equation of force transmissibility for shock sensor

As mentioned earlier, shock sensor of this paper can adjust its sensitivity. For proper regulation of sensitivity, how force is transmitted from external shock/vibration is important.

Figure 5 shows the suspension system of the horizontal moving robot. Wheel of figure 5 is connected with the motor. When wheel is shocked by moving in the rough rail, impact is transmitted to the motor.

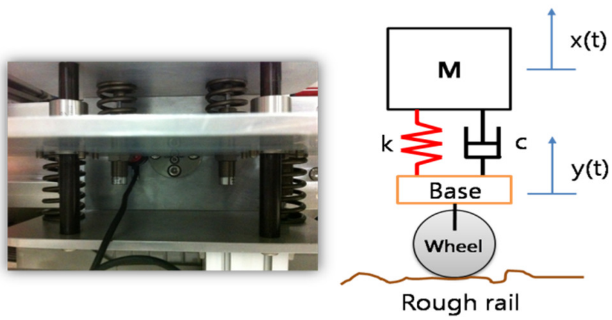

Figure 5 – Suspension system of the horizontal moving robot, and its mathematical modeling

The characteristics of suspension system are described in a prior study (Daniel J. Inman, 2007). In the mathematical modeling of figure 5, the force is transmitted to the mass M, which is the robot frame, through the spring-damper system.

$$F(t)=k(x-y)+c(\dot{x}-\dot{y}) \quad (1a)$$

This force must balance the inertial force of the mass M.

$$F(t)=-M\ddot{x} \quad (1b)$$

For solving the differential equation, it is assumed that the base moves harmonically. Thus,

$$y(t) = Y\sin(\omega_b t) \quad (2)$$

By combining equation 1a, 1b, and 2, the secondary differential equation about x, which is displacement of mass M, can be gained. Solution of the secondary differential equation is given by equation 3a, and 3b.

$$F(t) = m\omega_b^2\omega_n Y\sqrt{\frac{\omega_n^2+(2\delta\omega_b)^2}{(\omega_n^2-\omega_b^2)^2+(2\delta\omega_n\omega_b)^2}}\cos(\omega_b t-\theta_1-\theta_2) = F_T\cos(\omega_b t-\theta_1-\theta_2) \quad (3a)$$

$$F_T = kYr^2\sqrt{\frac{1+(2\delta r)^2}{(1-r^2)^2+(2\delta r)^2}} \quad (3b)$$

In equation 3a, and 3b, r is the frequency ratio(ω_b/ω_n), and δ is the damping ratio(c/2mω_n). F_T can be determined by Y, which is the amplitude of wheel's vertical displacement. Then, calculation of maximum F_T determines the threshold of shock sensor. When the force applied from rail surpasses the calculated threshold, sensor transmits the signal to the main control system, and the main control system gives proper order, which is the emergency stop order, or the return order.

Fail-Safety near damaged rail, using infrared ray sensor

If the rail is broken by damage, its wheels can be jammed in the damaged rail. Against this situation, the robot has to know where the damaged section is. For that, the infrared ray sensor is installed in the robot to detect change of rail shape. In graph of figure 6, when magnitude of its signal decreases below threshold of sensor, it represents that the robot is near the broken rail. And then, the main control system gives order to return to the starting point of rail.

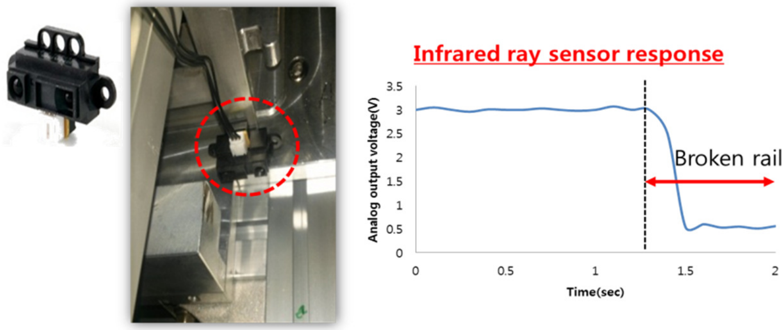

Figure 6 – The infrared ray sensor and its output signal near the broken rail

Fail-Safety near the obstacle, using laser sensor

In driving operation, there are some obstacles like opened windows. To prevent a collision between robot and obstacles, the laser sensor is used to detect obstacles. In graph of figure 7, when the signal of this sensor is near the sensing threshold, which represents safety distance from obstacles, the robot slows down and returns to the starting point of rail.

The laser sensor of this paper can regulate its measurement range by potentiometer which is installed in this sensor.

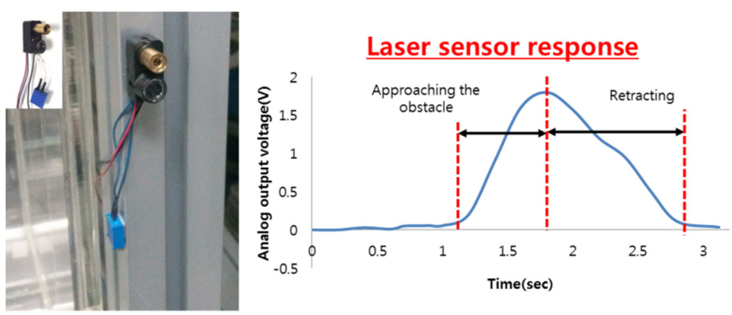

Figure 7 – The laser sensor and its output signal near the obstacle

Fail-Safety against failure of encoder, using magnetic sensor

On the supposition that wheels of robot have little slip with rail, the location of horizontal moving robot can be inferred from rotating angle measured by encoder of motor. However, if unexpected failure of encoder occurs, the control system of the horizontal moving robot will gain wrong location information. Against that, when encoders fail, magnetic sensors are used to replace them.

In the figure 8, each horizontal rail has magnets in the starting and end point. When the magnetic sensors detect magnetic field of these magnets, sensor signal made by magnetic field controls current supplied to motors. And then, current control affects motion of the robot.

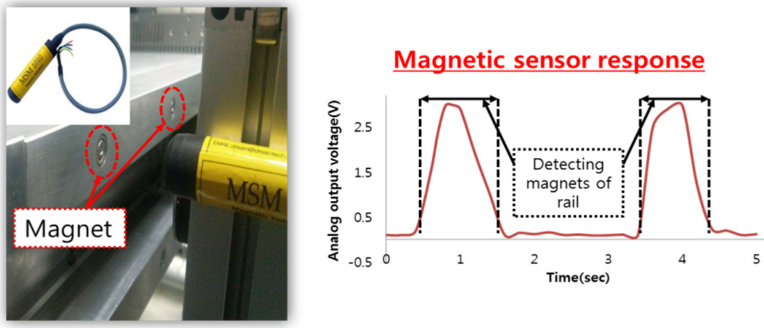

Figure 8 – The magnetic sensor and its output signal near the magnet of rail

The Integrated Fail-Safety system algorithm

Algorithm for encoder failure detection

Before-mentioned, failure of encoder causes mechanic malfunction of robot. During malfunction, the robot cannot reduce its velocity in the end point of rail, and that makes collision with building wall. In the starting point, docking with vertical moving robot has problem. Thus, failure of encoder must be detected before malfunction, and encoder be replaced to the magnetic sensor for continuing operation. For that purpose, 2 algorithms of figure 9 are developed.

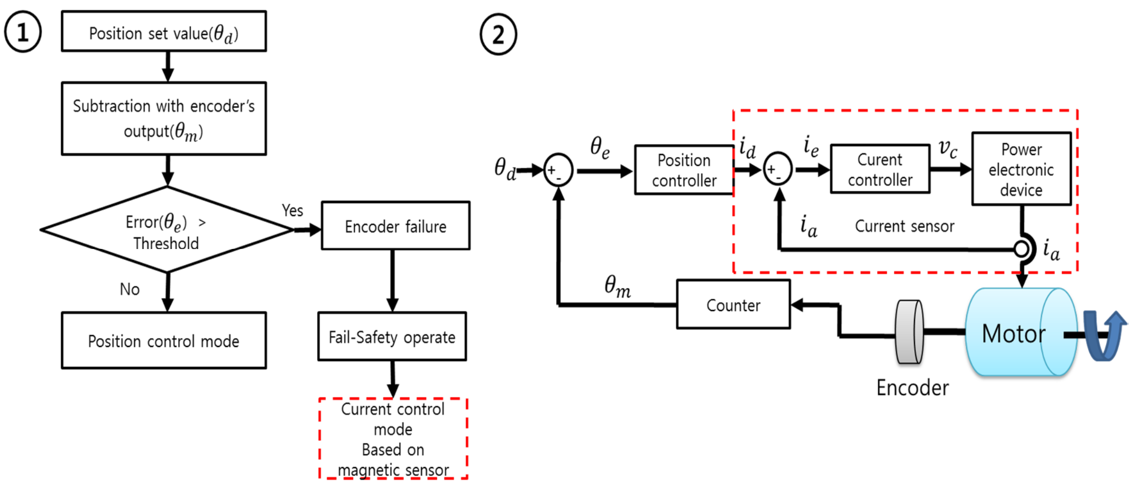

Figure 9 – 1. Algorithm for encoder failure detection, 2. Block diagram of motor control, and current control mode of motor, based on signal of magnetic sensor (red line section)

Algorithm for the Integrated Fail-Safe sensor system

In figure 10, this paper gives proper algorithms to each sensor, and prioritizes their outputs. Among outputs given by sensors, the output of the highest priority is carried out, and makes appropriate safety plan for robot.

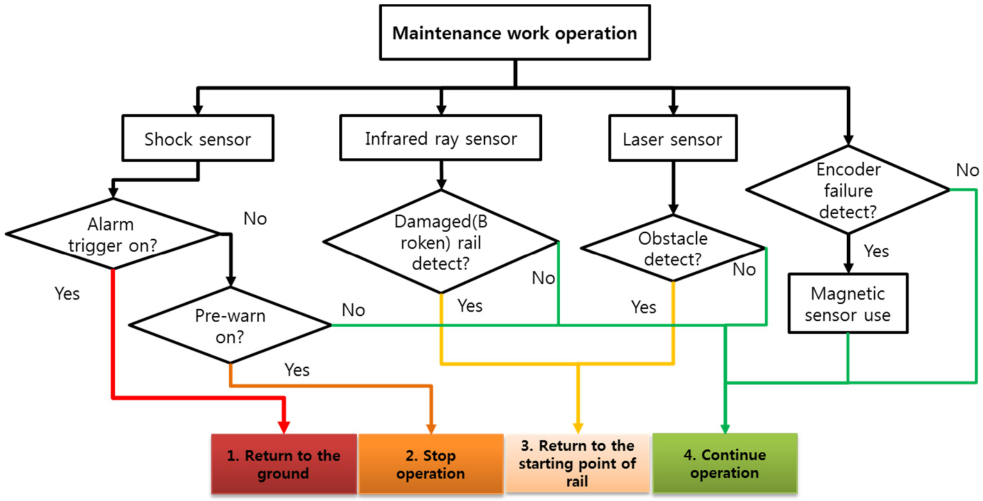

Figure 10 – The integrated fail-safety algorithm

CONCLUSIONS

This paper describes a Fail-Safety system for building wall cleaning robot. For safe working environment, robots have to sense the danger, and cope actively with it. Also, to prevent malfunction caused by failure of components, they have methods to substitute the failed components. Fail-Safety system of this paper is developed for these purposes. So, this system can relieve anxiety about safety of building wall cleaning robot.

ACKNOWLEDGMENT

The work presented in this paper was funded by BMRC(Building-Façade Maintenance Robot Research Center), supported by Korea Institute of Construction and Transportation Technology Evaluation and Planning(KICTEP) under the Ministry of Land, Transport and Maritime Affairs(MLTM).

REFERENCES

S.M.Moon, D.Hong, S.W.Kim, S.Park. (2012). Building Wall Maintenance Robot Based on Built-in Guide Rail. *Proc. of 2012 IEEE International Conference on Industrial Technology*(pp. 509-514)

J.Huh, S.M.Moon, S.W.Kim, D.Hong. (2012). Development of cleaning system installed in horizontal moving system for maintenance of high-rise building. *ISARC Int. Symp. On Automation and Robotics in Construction.*

N.Elkmann, D.Kunst, T.Krueger, M.Lucke, T.Böhme, T.Felsch, T.Stürze. (2005). SIRIUSc — Facade Cleaning Robot for a High-Rise Building in Munich, Germany. *Climbing and Walking Robots*, Part IX, pp. 1033-1040

Daniel J. Inman. (2007). Marcia J. Horton (Ed.), *Engineering vibrations* (3rd ed., pp. 144-152). Prentice Hall.