A STUDY ON ANTI-JERK CONTROL OF BUILDING MAINTENANCE ROBOT SYSTEM

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ABSTRACT

The increase in the number of higher and larger buildings is expected to require the buildings' outer wall maintenance process, which includes cleaning, painting and monitoring, still depends on manpower. In this study, we proposed the robotic building maintenance system and aimed to reduce the jerk effect through the motion control of the system, improve the performance of the maintenance task, and ensure longer life and safety by improving the stability of the building structure and robot system. Through the results of the motion control and field-test with the proposed system, in specific, horizontal sliding module (HSM) showed that the jerk oriented by impact force was significantly reduced, feasibility of the proposed method was verified, and the robotic challenges were explored.

KEYWORDS

Building maintenance robot, Sensor based system, Motion control, Anti-jerk control

INTRODUCTION

With the recent urban trends of high density and high concentration, higher and larger building structures are being constructed. The increase in the number of higher and larger buildings is expected to continue, and will require larger and heavier construction materials and equipment. Construction and maintenance with large and heavy materials and equipment still depend on manpower, but the labor force is increasingly aging and manpower demand and supply are worsening. Chu et al., (2010) insisted that these are causing economic and social problems. It is known that much of the outer wall maintenance process for high-rise buildings, which includes cleaning, painting and monitoring, still depends on manpower. Advanced countries, including Europe and Japan, already use robot and automation systems to gradually reduce their dependence on manpower. Examples of the application of such systems to diverse buildings can be classified according to the system types: robot systems that have guiderails on the buildings for movement; gondola/winch drive systems that have been most widely used since the 1960s; and hybrid systems that have the advantages of the two aforementioned systems. Although diverse guiderail-type robotics and automated systems are being introduced in Japan, there are few or no studies on pertinent issues such as the systematically efficient operation method or the improvement of the stability of the integrated system (Lee et al., 2012).

In this study, problems with the operation of the guiderail-type building maintenance robot (BMR) system are analyzed, the motion control method of ensuring the system stability is introduced, and the feasibility of its application is verified via tests and field applications.

SYSTEM ANALYSIS

System Configuration

The buildings’ outer wall maintenance system in this study has a vertical climbing module (VCM) and a horizontal sliding module (HSM), both of which operate along the built-in guiderails installed on the outer walls. The VCM uses the winch on top of the building and serves as the elevator in the building, and the HSM uses a main wheel and two auxiliary wheels with two electric motors and serves as the railway vehicle. For elevators, regulations and rules on their system acceleration/deceleration have long been established and included in the installation specifications, which represent the regulatory systems for the convenience of users via system stability improvement. For general vehicles, the abrupt vibration of systems has been controlled since the late 1990s to improve the stability of the systems (Kim et al., 2011).

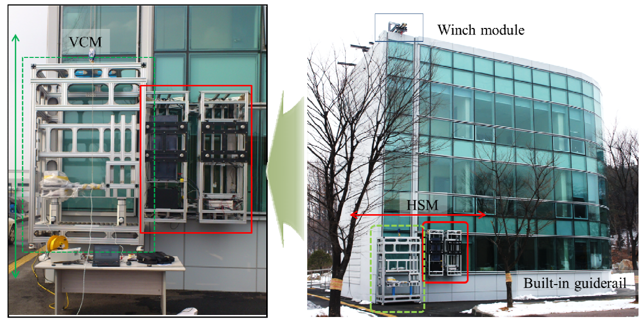


Figure 1 – System configuration

For railway vehicles, which are most similar to the HSM of the built-in guiderail-type BMR system in this study, the system behavior and characteristics were analyzed according to the rail conditions. Relevant studies have defined the discontinuous sections, including the downward joint gaps, upward joint gaps, clearances and bending angles, and especially included the prediction and evaluation of the vertical acceleration according to the upward joint gap height (Mazilu et al., 2010; Vijay et al., 1984). In this study, the faster motion and the higher joint gap resulted in a greater vertical acceleration; and when the response exceeded 0.35 to 0.5 G (gravitational acceleration G = 9.8 m/s^2), which is the standard vertical acceleration for bridges, structural supplementation was required.

Previous studies have shown that the excessive vibration of the mobile system, which is the jerk, must be reduced to ensure safety and convenience (Wen et al., 2005; Wua & Thompson, 2003). The buildings' outer wall maintenance robot has no passenger, but abrupt vibration during its operation may affect the rail and the building because the rail is coupled with the building in one environment, and may lead to irregular cleaning quality.

Accordingly, this study aims to reduce the jerk generated during the HSM operation in the BMR system and to improve the stability and efficiency of the robot system so as to supplement the problems that may affect the building and the robot system, help lengthen the life of the building, and ensure uniform buildings' outer wall maintenance work quality via automation and intellectualization.

Control Architecture

The control structure of the system can be represented as three layers, as shown in Figure 2. The first layer is the global information layer that contains the most basic data, including the shape of the building and the data on the built-in guiderail of the building. The second layer is the stage wherein the overall conditions and status of the system are identified, including the system location, dynamic condition and abnormalities. In this study, odometry sensors, infrared sensors and IMU sensors were used to understand the system status, position and dynamic behavior. More sensors could be applied according to the system operation environment. The third layer, which is the top layer, is the connection stage wherein

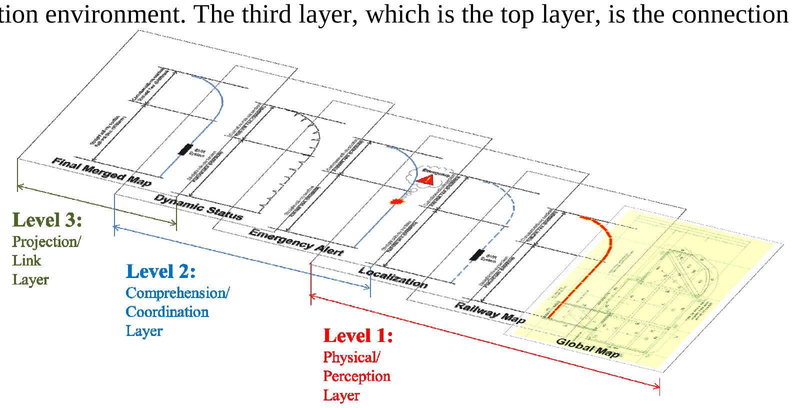


Figure 2 – Layered architecture of HSM control

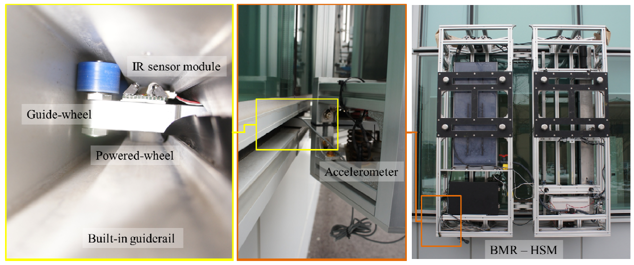


Figure 3 – Configuration of sensor integrated HSM

the data from the two aforementioned layers are integrated and provided to the user or the top control system for monitoring. The top layer information can be provided via wire and radio communication such as ZigBee and Ethernet, which serve as control rooms for high-rise/complex buildings.

System and Operating Environment Modeling

The HSM has two mobile platforms, as shown on the right side of the following Figure 3. This is because the system must be bent when it moves along the bent surfaces of the buildings' outer wall. The module moves with two upper drive wheels and two lower guide wheels. An acceleration sensor was installed in the system to detect the dynamic behavior, and an infrared sensor was installed to identify the discontinuous sections in the rail. The settings for the acceleration sensor included a measurement range of ±2 G (1 G = 9.8 m/s^2), a frequency response of 300 Hz and a sampling frequency of 100 Hz. Although the sensor measurement range was ±2 G, it actually ranged from –3 to +1 G because the basic gravitational acceleration +1 G existed.

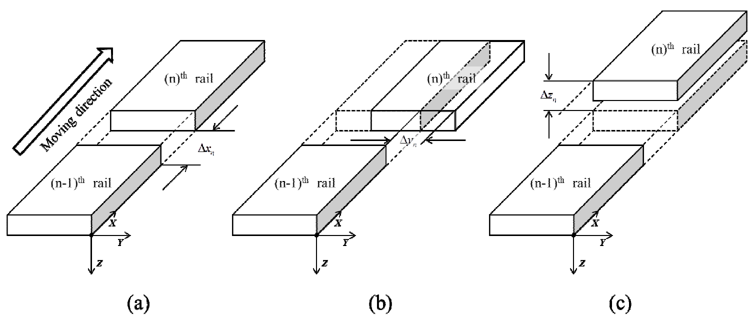


Figure 4 – Definition of error related with rail-joint: (a) X-axis, (b) Y-axis, (c) Z-axis direction

There are various definitions of the HSM system operation environment. As mentioned in Chapter 2.1, the rail-type movement system has diverse factors such as joint gaps, clearances and bending angles. The horizontally moving HSM of the BMR system also has such a mechanism. The following Figure 4 shows the mechanism of the operating environment. The aforementioned factors are the causes of the jerks during the movement of the HSM along the rail, which is generated by the rail construction by manpower. The causes of errors in each axis are as follows (Steenbergen, 2006). In this study, only the joint gap that corresponded to the first case, which is that of the discontinuous sections in the moving direction, was defined as the cause of the jerks.

CONTROL ALGORITHM

Rail-joint Detection and Estimation Algorithm

For general control cases, it is assumed that the discontinuous section position information for the rail on which the cleaning robot will move is not given. Therefore, the sensor installed on the robot

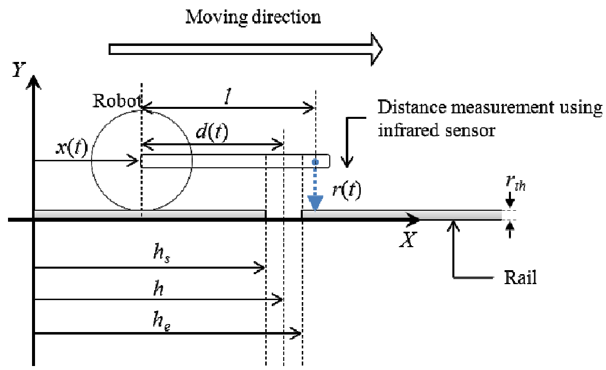


Figure 5 – Definition of error related with rail-joint: (a) X-axis, (b) Y-axis, (c) Z-axis direction

determines the discontinuous points on the rail. As shown in Figure 5, the robot measures, using an infrared sensor, the distance r(t) in the direction vertical to the rail that is in the moving direction as distant as l. When the rail thickness in the y axis direction is rth, the starting point of the discontinuous section of the rail is the point at which r(t) is decreased by rth. That is, the starting point of the discontinuous section on the rail is the point at which r(t) - r(t – Δt) is smaller than or equal to rth when the sample time is Δt. The distance to this point in the x axis is hs. Similarly, the end point of the discontinuous section is the point at which r(t) - r(t - Δt) is smaller than or equal to -rth, and the distance to this point in the x axis direction is he. The center point of the discontinuous section is located at the point h = (hs + he)/2 away in the x axis direction. When the distance along which the robot moves on the x axis from the reference point is x(t), the distance from the robot to the center point of the discontinuous section is d(t) = h - x(t). If the robot reaches the center point of the discontinuous section, d(t) = 0. As the robot moves, d(t) increases until the next discontinuous point is detected.

Motion Planner and Controller for HSM

To reduce the acceleration applied to the robot at the discontinuous point on the rail, the target velocity v_{des} is determined using the distance to the center of the discontinuous section, $d(t)$. A small $d(t)$ indicates that the robot is close to the discontinuous section so the robot velocity must be reduced. A $d(t)$ that is greater than a specific value indicates that the robot is not in the discontinuous section so the current velocity can be maintained.

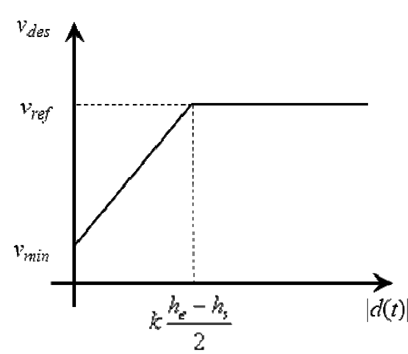


Figure 6 – Definition of error related with rail-joint: (a) X-axis, (b) Y-axis, (c) Z-axis direction

In this study, if the robot decelerates to the lowest velocity, $v_{\min}$, in the discontinuous section, it is assumed that the acceleration at that time can ensure the stability of the cleaning robot and relevant structures. When the reference robot velocity v_{ref} is given, the target velocity v_{des}, which is determined by the change in the magnitude of $d(t)$, is determined by the following motion planner as follows:

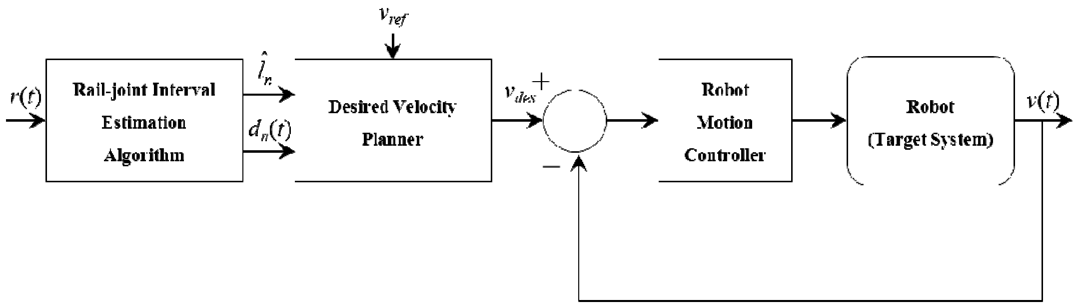


Figure 7 – Block diagram for motion control of HSM

$$v_{des} = \begin{cases} \dfrac{2(v_{ref} - v_{\min})}{k(h_e - h_s)}|d(t)| + v_{\min} & \text{if} \quad |d(t)| \le k\dfrac{h_e - h_s}{2} \\ v_{ref} & \text{otherwise} \end{cases}$$

wherein k is a constant that is selected from within the range of $k > 1$ to reduce the velocity of the robot before it reaches the discontinuous point (Figure 6).

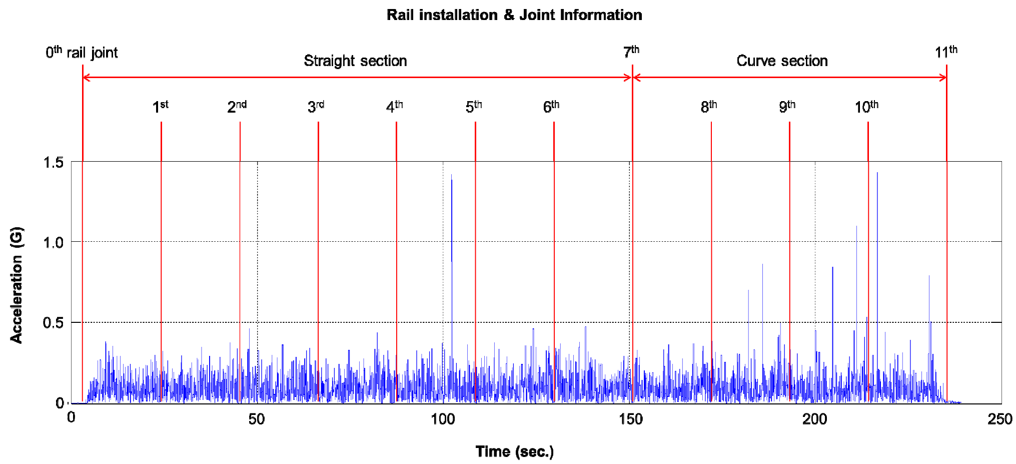
Figure 7 shows block diagram of the motion control for the work of the BMR. The initial input of the overall control algorithm is the distance from the distance sensor $r(t)$. Using this value, the algorithm calculates the distance to the center of the discontinuous section $d(t)$. Then using the given reference velocity v_{ref} and the minimum velocity $v_{\min}$, the target velocity v_{des} is calculated with the equation above. After the motion planning, the internal controller of the BMR controls the torque applied to the wheels to ensure that the robot will operate at the target velocity.

EXPERIMENTAL RESULT

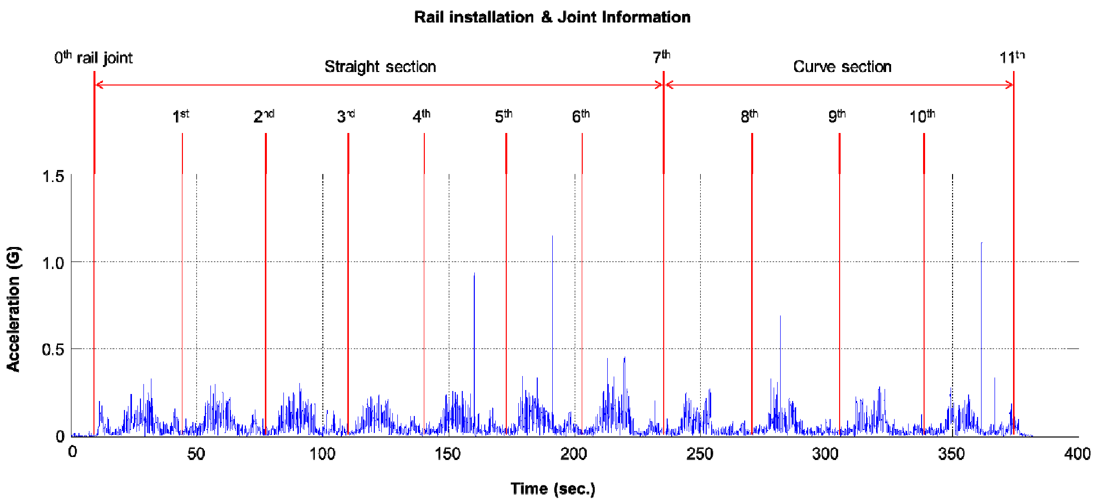
In this study, a method of controlling the motion of the system according to the joint gaps of the rail with discontinuous sections was proposed. In the case of the built-in guiderail for the BMR system, the unit module length was 1,200 mm, the increase/decrease of the displacement was approximately ±2 mm considering the thermal expansion coefficient, and the joint gap information was obtained approximately 50 mm ahead of the HSM system in the moving direction using the infrared sensor, as in the following test. In the test, to determine whether the jerk effect during the motion control was mitigated, the values before and after the motion control application were compared, based on the assumption that the distance information for the joint gap information was known. The rail-joint gap measurements using the infrared sensor ranged from 49 mm to 126 mm, which were diverse, and can be seen as the errors due to the installation by manpower. As defined in Section 2.3, the following joint gap distances are for the x axis direction, which is the moving direction. This means that the change in the system acceleration due to jerks may not be proportional to the joint gap. To verify the feasibility of the motion control, the velocity control according to the joint step was applied to the motion control with known information (Table 1), and the velocity was adjusted from the maximum to the minimum according to the presence or absence of the rail joint gap, regardless of the joint gap size. The maximum velocity was set at 70 mm/s, considering the cleaning and maintenance performance of the HSM and the system performance. The minimum velocity was set as the optimal motion from the experiment design, 25 mm/s, which is the minimum velocity that enables proper movement over joint gaps.

Table 1 – Result of rail-joint distance measure using IR sensor modules

Rail-joint No.	1	2	3	4	5	6	7	8	9	10	11
Interval (unit: mm)	49	49	63	98	70	56	77	91	126	98	91



(a)



(b)

Figure 8 – Experimental Result for acceleration of the HSM: (a) without motion control algorithm, (b) with motion control algorithm

The following are the system acceleration measurements before the motion control. As shown in Table 2, relatively high accelerations were measured in Sections 4 to 5 and 8 to 10. Because the total weight of the HSM was approximately 500 to 600 kg and an acceleration of 1.5 G was applied in the section with the highest acceleration, a force of 9,000N was applied to the rails and rail supports, though only for a very short time (Figure 8, (a)). In the second test, the system velocity was minimized in the sections with joint gaps, and the acceleration was measured (Figure 8, (b)). The motion control significantly reduced the jerk effct and decreased its magnitude. However, in the relatively large joint gaps (Sections 4 to 5 and 8 to 10), the jerk effect was not completely removed, but its magnitude and frequency decreased.

As for the reciprocal execution time for the 11 rail section walls, it took 8 minutes before the motion control, whereas it took 13 minutes after the motion control, which resulted in a difference of approximately 5 minutes for one single floor execution. Therefore, it was expected that the advantages of the motion control, including the longer life of the building and rails due to the reduced impact and the uniform cleaning quality due to the reduced jerk effect, along with the economical view on the time for the cleaning process, could improve the overall system efficiency.

CONCLUSION AND FUTURE WORK

This study aimed to reduce the jerk effect via the motion control of the system, improve the cleaning and outer wall maintenance process performance via abrupt motion control, and ensure longer life and safety by improving the stability of the building structure and robot system. The results of the motion control test with the BMR system, in specific, HSM showed that the impact was significantly reduced and the proposed method was feasible. The results of this study on the detection of the dynamic behavior of a system indicated that the building condition and the BMR system can be periodically monitored. A further study will evaluate the performance of the aforementioned motion control algorithm and, based on it, the feasibility of the integrated monitoring system.

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