Force-regulated impact control of a reinforced concrete box culvert chipping robot

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Abstract

A reinforced concrete box culvert (RCBC) is a box culvert constructed of reinforced concrete. Because the sudden collapse of an RCBC could result in a serious accident, continuous management and maintenance work of the RCBC should be performed. In this paper, the RCBC chipping robot that is developed as an alternative to skilled construction workers for carrying out the concrete-chipping work, one of the RCBC maintenance process, is introduced, and the force-regulated impact control for improving quality of the chipping work is described. In order to implement the proposed algorithm, reaction forces when the robot strikes concrete with chipping tool are collected, and classification to identify the striking object and its hardness is carried out based on the obtained reaction forces. In addition, a variable motion control algorithm is realized by setting the dynamic characteristics of the robot with respect to the reaction force according to striking object and its stat. To verify the effectiveness of the proposed algorithm, chipping work with an RCBC chipping robot is conducted in a simulation environment consisting of reinforced concrete.

Keywords –

Force-regulated impact control; Box culvert maintenance; Concrete chipping; RCBC (Reinforced Concrete Box Culvert); Construction robot;

1 Introduction

A reinforced concrete box culvert (RCBC) is a box culvert constructed of reinforced concrete; it is a structure that allows water to flow under a road, railroad, trail, or similar obstruction from one side to the other. Currently, many RCBCs are located under cities and roads. If a ground subsidence occurs owing to the sudden collapse of an RCBC, it could result in a serious accident [1]. Therefore, continuous management and maintenance work should be performed to prevent RCBC collapse and accidents caused by such failure.

Typical RCBC maintenance work consists of detecting the damaged parts, chipping to remove the deteriorated concrete, cleaning the surface of exposed rebar, etc. In particular, the chipping process, in which workers remove the deteriorated concrete from ceilings or walls of the reinforced concrete structures by using heavy equipment that vibrates significantly, while standing on a temporary structure (i.e., a scaffolding) at a high elevation, poses a high risk of musculoskeletal injury. Moreover, poor working conditions and human error can result in major accidents in this process. This process is regarded as hazardous, and even skilled construction workers avoid undertaking this work. For this reason, the chipping process is one of the construction operations for which there is an urgent need for the application of automatic construction based on construction robot.

Construction robots are spotlighted as a solution for the problems such as such as wage increase, labor shortage and danger to human life caused by construction accidents. Automatic construction based on construction robot has the potential to improve safety, productivity, quality and working environment, and it can reduce the number of non-essential workers, time, costs of construction and the incidence of accidents by performing tasks efficiently and improving working conditions by carrying out work that are dangerous for the safety of human [2-12].

In this paper, the RCBC chipping robot that is developed as an alternative to skilled construction workers for carrying out the concrete-chipping work is introduced, and the force-regulated impact control for improving quality of the chipping work is described. In order to implement the proposed algorithm, reaction forces when the robot strikes concrete with chipping tool are collected, and classification to identify the striking object and its hardness is carried out based on the obtained reaction forces. In addition, a variable motion control algorithm is realized by setting the dynamic characteristics of the robot with respect to the reaction force according to striking object and its stat.

To verify the effectiveness of the proposed algorithm, chipping work with an RCBC chipping robot is conducted in a simulation environment consisting of reinforced concrete. Chipping work with the robot is carried out in both cases, with and without the proposed algorithm, and the performance of the proposed algorithm is verified by comparing and analyzing the quality of each chipping work.

The rest of this paper has five sections. In Section 2 and 3, the chipping robot and proposed algorithm are described. Section 4 describes Performance test and shows the effectiveness of the proposed method. Finally, Section 5 concludes with a summary of the paper.

2 RCBC Chipping Robot

A reinforced concrete box culvert (RCBC) is a box culvert constructed of reinforced concrete. Because the sudden collapse of an RCBC could result in a serious accident, continuous management and maintenance work of the RCBC should be performed.

The chipping process that is one of RCBC maintenance process is that workers remove the deteriorated concrete from ceilings or walls of the reinforced concrete structures. Because the chipping process is carried out by using heavy equipment that vibrates significantly, while standing on a temporary structure (i.e., a scaffolding) at a high elevation as shown Figure1, there are high risk of musculoskeletal injury. Moreover, poor working conditions and human error can result in major accidents in this process. This process is regarded as hazardous, and even skilled construction workers avoid undertaking this work. For this reason, the chipping process is one of the construction operations for which there is an urgent need for the application of automatic construction based on construction robot.

Figure 1 Chipping process by manpower

A RCBC chipping robot is developed as an alternative to skilled construction workers for carrying out the concrete-chipping work. As shown the Figure 2, the chipping robot consists of a robot mobile platform for movement in uneven terrain, a robot manipulator for chipping work, a chipping tool for removing deteriorated concrete, and a robot motion controller that generates the trajectory for conducting the processes and makes the robot follow the trajectory.

In order to perform the chipping work, the chipping robot moves to the work area through the robot mobile platform. Then, the robot manipulator follows the trajectory concrete-chipping work, and the chipping tool installed at the end of the manipulator strikes the deteriorated concrete. Trajectory generation and control for all these operations are performed through the robot motion controller.

When the work using the RCBC chipping robot is performed at constant speed irrespective of the striking object and its state, hardness, the concrete is removed unevenly according to hardness and this causes an uneven chipping surface, i.e. fall in chipping quality. Therefore, in order to improve the chipping quality, motion control for adjusting the chipping speed according to the striking target and its state is necessary.

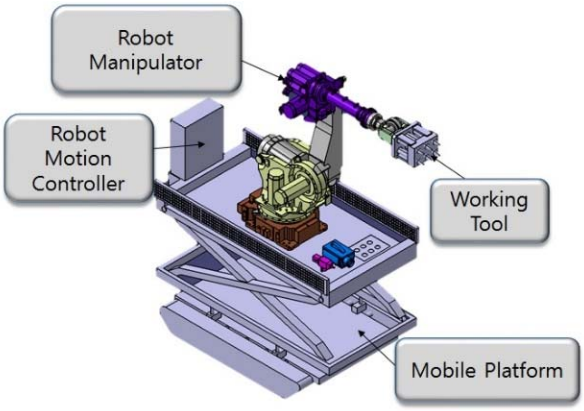


Figure 2. Components of RCBC chipping robot

In this paper, for improving the chipping quality, a force-regulated impact control algorithm that classifies a striking object of the robot and its state from reaction force, and control speed of chipping according to the state is proposed.

3 Force-Regulated Impact Control

The force-regulated impact control is designed to control chipping speed of an RCBC chipping robot according to the object that the robot strikes for improving chipping quality. In order to control the chipping speed according to the object the robot strikes, the desired reaction force between the chipping tool and the chipping target, is decided, and force control is applied based on the reaction force generated when hitting the target. Because the chipping is a task to strike the target, which is the concrete wall of RCBC, with a chipping tool, a lot of impacts are generated according to the striking object and the reaction forces include impulse. The impulse not only deteriorates the performance of force control but also results in contact loss [13-14].

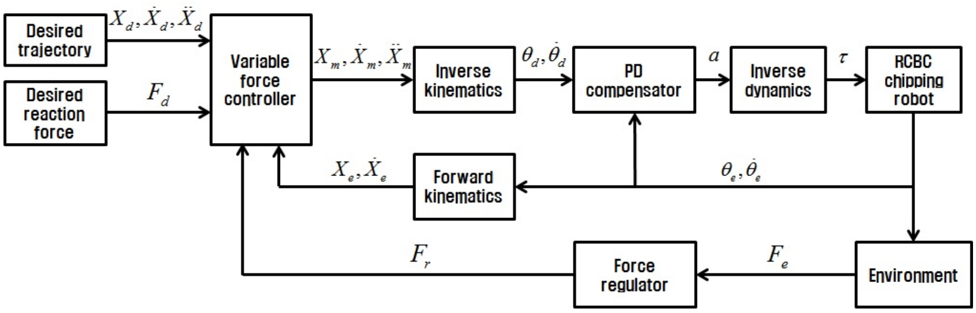


Figure 3 Block diagram to control RCBC chipping robot

Therefore, in order to control the chipping speed based on force control, it is necessary to apply variable force control which changes its dynamic characteristics according to the impulse. In this paper, variable force control for regulating the reaction force between the chipping tool and the working environment while controlling the impulse is proposed.

The force-regulated impulse control is designed to control the impulse through two control strategies as follows:

- In order to prevent the deteriorating of the chipping performance caused by impulse, the sensing external force is regulated by force regulator.
- In order to the control chipping speed, the desired trajectory is compensated by the variable force controller

Figure 3 shows the block diagram to control RCBC chipping robot. For the chipping process, desired trajectory, X_d, and desired reaction force, F_d, are generated. When the regulated reaction force, F_r, is not same desired force, $F_r \neq F_d$, the desired trajectory is compensated to modified trajectory, X_m. In order to obtain the modified trajectory, the present position of robot, X_e, which is calculated by forward kinematics, and regulated reaction force are used. From the modified trajectory, the desired joint trajectory, θ_d, is calculated, and input torque, τ, to move the RCBC chipping robot is obtained from the PD compensator and inverse dynamics.

The force regulator is designed to classify the external force based on whether it is an impulse that deteriorates the control performance and to regulate $\mathrm{F_e}$ based on this classification. To realize the force regulator, selective moving average based on classification is used. The selective moving average is described as follows:

$$F_{r(i)} = \frac{1}{m}\sum_{j=0}^{m-1} F_{e(i-j)} \qquad (1)$$

where

$$\mathrm{j} = 1, 2, \ldots, \mathrm{m}-1,$$

$$\Delta F_e = F_{e(i-j)} - F_{e(i-j-1)},$$

$$F_{e(i-j)} = \begin{cases} F_{e(i-j)} & \left(|\Delta F_e| \le \Delta F_{th}\right) \\ F_{e(i-j-1)} & \left(|\Delta F_e| > \Delta F_{th}\right), \end{cases}$$

$F_{r(i)}$ denotes the ith regulated reaction force, $F_{e(i-j)}$ denotes the i-jth sensing reaction force, ΔF_{th} is the criteria of classification, and m is the number of sampling for the moving average. From the force regulator, the regulated reaction force, F_r, is obtained and it is applied to the variable force controller to compensate chipping speed.

For controlling the chipping speed based on force control, a variable force controller is designed. To implement variable force control, a model of the chipping robot and chipping target, is designed to mass-spring-damper system as shown Figure 4.

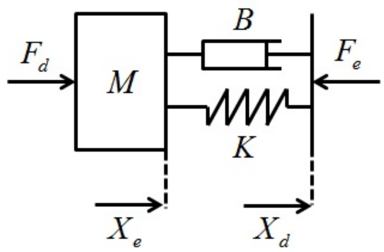


Figure 4 model of the chipping robot and chipping target

The dynamic equation of the model is descried as follows:

$$K\Delta X + B\Delta\dot{X} + M\Delta\ddot{X} = F_d - F_r, \qquad (2)$$

where,

$$\Delta X = X_d - X_e,$$

X_d and X_e denote the position of chipping tool, F_d and F_e denote the desired and real reaction force. M, B, and

K denote the mass, damping, and stiffness of impedance coefficient. From equation (2), the modified desired trajectory, X_m, is obtained as follows:

$$\ddot{X}_m = \ddot{X}_d + \frac{K\Delta X + B\Delta\dot{X} - (F_d - F_r)}{M_v}, \quad (3)$$

where

$$M_v = \begin{cases} M & (\varepsilon < \alpha) \\ \varepsilon M & (\varepsilon \geq \alpha) \end{cases} \quad (\varepsilon = |F_r(t) - F_r(t-L)|).$$

$\Delta\dot{X}$ denotes the derivative of ΔX, $\ddot{X}_d$ denotes acceleration of the desired trajectory, M_v is the variable impedance coefficient, α is threshold of M_v, and ε denotes differential of reaction force. $\ddot{X}_m$ denotes the acceleration of the modified trajectory, and modified trajectory, X_m, is obtained by integrating the value. M_v is changed according to ε. When ε is less than α, M_v is a small value, which is designed for sensitive reaction with respect to the reaction force. On the other hand, when ε is larger than α, M_v has large value, and it makes the response of the robot to the force less sensitive.

By applying this algorithm, it is possible to control the chipping speed based on the force control even during the chipping operation in which the impulse is frequently generated due to impact.

4 Performance Test

To verify the effectiveness of the proposed algorithm, chipping work with an RCBC chipping robot is conducted in a simulation environment. For the performance test, the simulation environment is constructed as shown in Figure 5. The robot for chipping work consists of a 6 DOF manipulator, a robot motion controller, and a chipping tool. As a chipping target, a module of the RCBC is used.

Figure 5 The performance test of proposed algorithm

In order to verify the effectiveness of the proposed algorithm, concrete chipping is carried out for two cases, i.e., with and without the application of the proposed algorithm. The path of the robot for chipping in a simulated environment is planned as shown in Figure 6. First, the chipping tool is advanced to the concrete wall until the tool contact with the wall. After the chipping tool contacts with the wall, the chipping tool starts and chipping is performed.

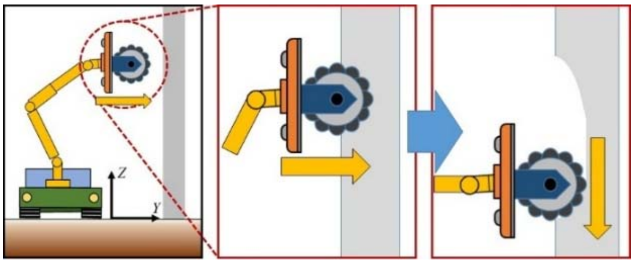


Figure 6 Schematic diagram for performance test

A chipping operation is performed for a predetermined working area, 150 mm x 150 mm, where the depth is 10 mm.

In order to compare the performance of the proposed algorithm, chipping through position control without applying the proposed algorithm is performed.

When chipping is performed through position control, the task is started at 0 sec, and performed at a constant chipping speed, 1mm/s, regardless of the object being hit and its state, i.e., hardness. According to the hardness of the object to be chipped, a large reaction force acts on the chipping tool as shown in Figure 7.

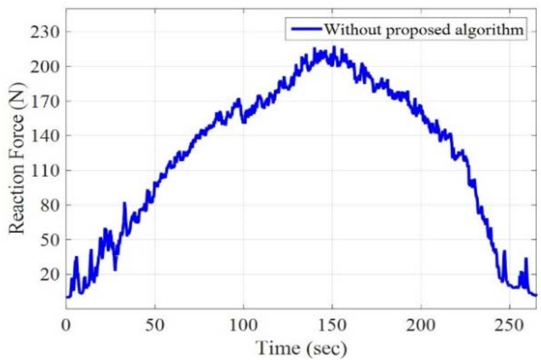
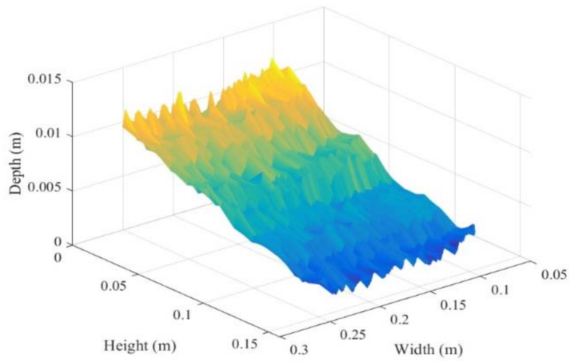
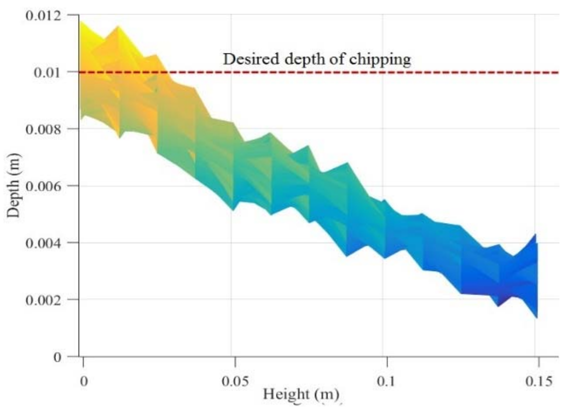


Figure 7 Reaction force during concrete chipping

The large reaction force hinders the robot from following the trajectory for the chipping operation, which can cause an uneven chipping depth, i.e. a drop in chipping quality as shown in Figure 8 (a) and (b) . At the beginning of the work, the target depth of 10mm is satisfied. As the work progresses, however, the work tool does not follow the desired trajectory due to the reaction force and gradually fails to satisfy the target depth. Finally, the working depth of the chipping robot is 3mm and low chipping quality is confirmed as shown in Figure 8(b).



(a) 3D graph of chipping surface

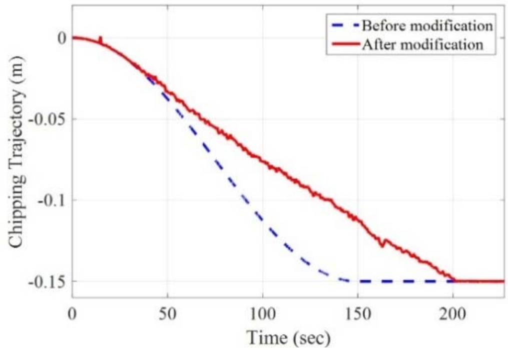


(b) The depth of chipping area

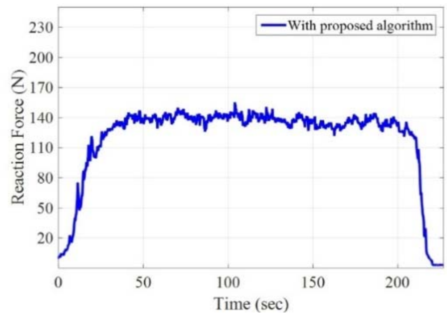
Figure 8 Result of chipping without proposed algorithm.

In this paper, to solve this problem, the force regulated impact control that controls the chipping speed based on the reaction force is proposed. In order to verify effectiveness of the proposed algorithm, the task is performed during 150 sec, and chipping speed is controlled to make the reaction force satisfy 140N.

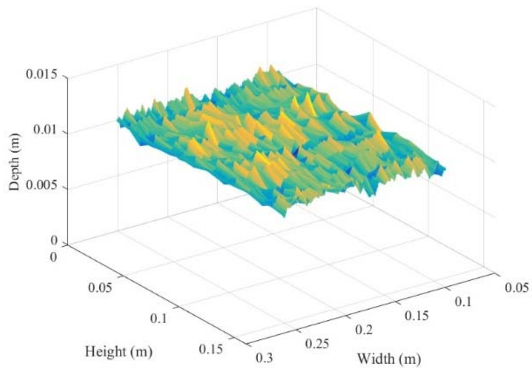
Experimental results for the case when the proposed algorithm is used are shown in Figure 9. Figure 9 (a) shows the trajectory generated for the chipping operation, X_d , and the trajectory modified by the proposed algorithm, X_m. Through the graph, it can be confirmed that the trajectory of chipping robot, that is, the chipping speed, is modified while controlling a reaction force acting on the chipping tool. As a result, it can be confirmed that the reaction force acting on the chipping tool maintains the desired value, i.e., 140N, as shown in Figure 9(b). Also, the depth of the chipping area is satisfied a desired chipping depth, 10mm, compared with that before the algorithm is applied as shown in Figure 9(c) and (d). From the results, it can be confirmed that the proposed algorithm improve chipping quality by controlling the chipping speed.



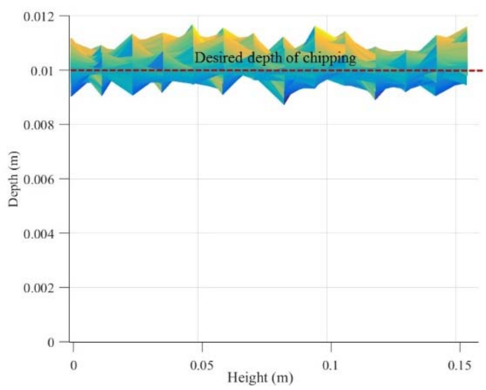
(a)Trajectory of chipping tool



(b) Reaction force during concrete chipping



(c) 3D graph of chipping surface



(d) The depth of chipping area

Figure 9 Result of chipping with proposed algorithm.

5 Conclusion

In this paper, the RCBC chipping robot developed as an alternative for skilled construction workers for carrying out concrete-chipping work, is introduced, and the force-regulated impact control for work quality improvement is proposed. To verify the effectiveness of the proposed algorithm, chipping work with an RCBC chipping robot is conducted for both cases, i.e., with and without the application of the proposed algorithm, in a simulation environment. As a result, it is shown that the proposed algorithm improves the chipping quality by controlling the chipping speed, and the performance of the proposed algorithm is verified. The proposed algorithm is designed to control the motion of an RCBC chipping robot according to the object that the robot strikes. Using this algorithm, deteriorated concrete can be removed while maintaining constant chipping quality. Furthermore, along with concrete chipping, this is also applicable to other fields where variable motion of a robot with respect to the object it is in contact with is required such as in excavation work and manufacturing.

In order to improve the performance of the proposed algorithm, future studies have been planned to apply the RCBC chipping robot to various construction sites, and the proposed algorithm will be supplemented based on the result.

ACKNOWLEDGMENT

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References

[1] Charles J. Nemmers, *Culvert Repair Practices Manual*, U.S. Department of Transportation, 1995

[2] Roozbeh K, *Advanced Robotics in Civil Engineering and Construction*. In Proceedings of IEEE International Conference on Robotics and Automation, pages 375-378, Tokyo, Japan, September, 1985

[3] Warszawski, A, *Economic implications of robotics in building*. Building and Environment, 20(2):73-81, 1985.

[4] Albus, James S., *Trip Report: Japanese Progress in Robotics for Construction*, Robotics Magazine, spring of 1986.

[5] Bernold, L.E. *Automation and robotics in construction: A challenge and change for an industry in transition*. International Journal of Project Management, 5(3):155–160, 1987.

[6] Skibniewski, M.J., *Robotics in civil engineering*, Van Nostrand–Reinhold, ISBN 0442319258, New York, 1988.

[7] Skibniewski, M.J. & Wooldridge, S.C., *Robotic materials handling for automated building construction technology*. Automation in Construction, 1(3):251– 266, 1992.

[8] Wen, X., Romano, V.F. & Rovetta, A., *Remote control and robotics in construction engineering*. In proceedings of the Fifth International Conference on Advanced Robotics, Pisa, Italy, 19-22 Jun 1991.

[9] Cusack, M., *Automation and robotics the interdependence of design and construction systems*. Industrial Robot, 21(4):10–14, 1994.

[10] Poppy, W., *Driving force and status of automation and robotics in construction in Europe*. Automation in Construction, 2(4):281–289, 1994.

[11] Kochan, A., *Robots for automating construction an Abundance of research*. Industrial Robot, 27(2):111–113, 2000.

[12] Seungyeol Lee and Jeon Il Moon, *Introduction of human-robot cooperation technology at construction sites*, Proceedings of the International Symposium on Artificial Life and Robotics (AROB), pp.146-149, 2014.

[13] J.M. Hyde and M.R. Cutkosky, Controlling contact transition, IEEE Control systems, 14(1), 1994.

[14] G. Ferretti, G. Magnani and A. Zavala Rio, *Impact modelling and control for industrial manipulators*, IEEE Control systems, 18(4), 1998.