A Design of Robust Control Algorithm for a Decommissioning Hydraulic Manipulator

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Abstract: In the decommissioning process of the nuclear power plant, robotic systems that can work on hazard environment instead of human are essential due to high levels of radiation. Especially, nuclear facilities are large and complex, and also the operation of handling heavy-duty objects is needed during dismantling process. Thus, a hydraulic manipulator was developed to save time and cost for decommissioning nuclear power plant. However, hydraulic systems have many uncertainties and robust controller is necessary for precise control. Most existing robust controllers require acceleration information to cancel uncertainties and improve performance. Acceleration information that is obtained by numerical differentiation is very noise and difficult to obtain directly. Therefore, a method that is robust and does not use acceleration information is required. In this paper, we studied about simple robust control algorithm without acceleration information for decommissioning hydraulic manipulator. In addition, the simulation and experiment are carried out to validate control performance.

Keyword: Robust Control, Hydraulic manipulator, Decommissioning nuclear power plant

1 Introduction

The robot techniques can be an effective solution for dismantling nuclear power plant. The robots can work instead of human in high radiation environments and also reduce lots of time and cost. Especially, the manipulator systems are useful for decommissioning complex structure in nuclear facilities. The core facilities of nuclear power plants such as reactor pressure vessel, steam generator and pressurizer are mostly large and heavy. Thus, a heavy-duty manipulator that can handle heavy-duty objects can be effective to increase productivity and reduce costs in the process of dismantling.

To increase efficiency for decommissioning nuclear power plant, we developed heavy-duty hydraulic manipulator[1]. The manipulator can have a wide workspace of a length of 3.2**m** and also can handle a payload of 250**kg** using hydraulic power.

In the dismantling process, the precise works such as remote cutting operation and pick and pack operation are required. Thus, the manipulator should be controlled precisely. However, the developed hydraulic manipulator has many nonlinearities and uncertainties such as dead zone, hysteresis and friction. Thus, a robust controller is needed precisely to control the developed hydraulic manipulator that is nonlinear system.

To improve the control performance of nonlinear system, many robust controllers have been studied. Most robust controllers require acceleration information to increase performance and compensate uncertainties of system. Actually obtaining the acceleration information of the actual system is difficult because an obtained acceleration information through numerical differentiation has large noise characteristics.

A simple robust controller without acceleration information was presented. Chang and Jung proposed a simple PID controller with robustness by using the fact that Time Delay Control (TDC) [3] and PID controller are expressed as same form in the discrete time domain[4]. This method can have robustness systematically and easily. The simple PID controller was verified that it has robustness by applying it to a 6-dof manipulator.

Therefore, in this paper, we applied the simple PID controller using the relationship of TDC and PID controller to control the developed heavy-duty hydraulic manipulator. In addition, we developed the simulator of hydraulic manipulator and carried out tracking control. Finally, we verified control performance through experiment.

2 Heavy-Duty Hydraulic manipulator

We developed heavy-duty hydraulic manipulator for decommissioning the reactor pressure vessel (RPV) of the Gori-I nuclear power plant. The Gori-I plant will be first decommissioned in Korea. The task of dismantling the RPV is difficult because human workers can't easily access it owing to high level of radiation. Thus, it is inevitable to use a manipulator to dismantle the components of the RPV. The hydraulic manipulator was developed under a scenario of decommissioning the RPV of the Gori-I plant[5].

The hydraulic manipulator has 6 degrees of freedom and a R-P-R-R-R structure, as shown in Fig. 1. The links of the hydraulic manipulator are modularized for improving the assembly property and maintainability. The hydraulic manipulator has a full extension of 3.2**m** and a payload of 250**kg**.

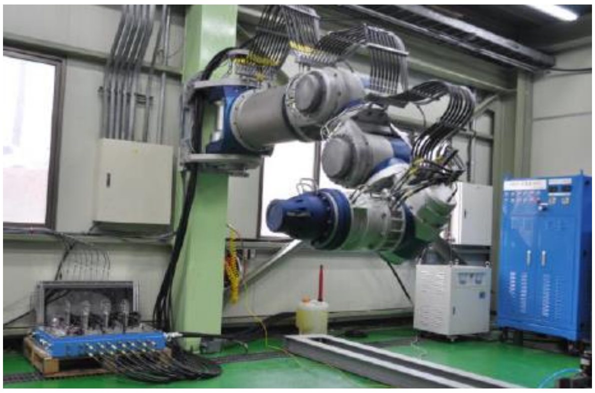

Fig.1 Developed hydraulic manipulator

In addition, a hydraulic supply unit to operate the developed hydraulic manipulator. The hydraulic supply unit offers a pressure of 210**bar** and a flow of 60**l/min**, which is sufficient to operate the hydraulic manipulator. Moreover, a control unit that has a hydraulic servo value, pressure sensor and controller was developed.

3 Modeling of hydraulic manipulator

We developed a simple model of the developed hydraulic manipulator to simulate the performance of control algorithms.

3.1 Hydraulic servo system

To obtain the hydraulic equations, the dynamics model of servo valve is needed. This can be derived using Bernoulli's equation as shown in Equation (1).

$$Q_L = C_d w x_v \sqrt{(P_s - \operatorname{sgn}(x_v) P_L)/\rho}, \qquad (1)$$

where Q_L is flow rate on load, C_d is discharge coefficient of servo valve, w is valve gradient, P_s is supply pressure, P_L is pressure difference across the load, ρ is density of oil, and x_v is displacement of spool displacement defined as $x_v = K_v u$. K_v is current constant and u is input current.

For the linearization of Equation (1), Taylor series expansion and ignoring the second order term are as follows:

$$Q_L = K_q x_v - K_c P_L, \qquad (2)$$

where $K_q = \partial Q_L / \partial x_v$ is flow gain and $K_c = -\partial Q_L / \partial P_L$ is flow-pressure coefficient.

In addition, the fluid continuity equation of the hydraulic motor is expressed as Equation (3).

$$Q_L = D_m \dot{q} + C_{tm} P_L + (V_t / 4\beta_e)\dot{P}_L, \qquad (3)$$

where D_m is volumetric displacement, C_{tm} is total leakage coefficient, V_t is total volume of pipeline, β_e is bulk modulus of oil, and $\dot{q}$ is angular velocity.

The hydraulic equation that expressed as differential equation is derived through Equation (2) and (3) as follows:

$$\dot{P}_L = (4\beta_e / V_t)(K_q K_v u - D_m \dot{q} - K_c P_L) \qquad (4)$$

The torque of hydraulic motor can be calculated as shown in Equation (5) after obtaining the pressure difference (P_L) through the hydraulic equation in Equation (4).

$$\tau_m = \eta N D_m P_L \,, \qquad (5)$$

where τ_m is torque of hydraulic motor, η is mechanical efficiency, and N is gear ratio.

3.2 Dynamics model of Manipulator

Applying the torque of hydraulic motor to the manipulator can be expressed as Equation (6).

$$\mathbf{M(q)\ddot{q}} + \mathbf{h(q,\dot{q})} = \boldsymbol{\tau}_m(\mathbf{\dot{q},u}) - \mathbf{B}_m\mathbf{\dot{q}}, \qquad (6)$$

where $\mathbf{M} \in R^{6\times6}$ is inertia matrix, $\mathbf{h} \in R^6$ is total force vector such as centrifugal, Coriolis and gravity force. $\boldsymbol{\tau}_m \in R^6$ is torque vector of hydraulic motors, and $\mathbf{B}_m \in R^{6\times6}$ is viscous damping coefficient diagonal matrix.

4 Robust controller

Precise control of the hydraulic manipulator is necessary for efficient dismantling process. Since the hydraulic system has many nonlinearities, a robust controller is essential for precise control. However, most robust controller require acceleration information to compensate uncertainties of system. Acceleration information is not easy to obtain, and it has a very noisy so that low pass filter must be used together.

To avoid this problem, we apply simple robust controller without acceleration information. This method to select PID gain through a robust controller while using a simple PID controller widely used in the industrial field[4].

The control input of Time Delay Control(TDC), widely known as a robust controller, in the discrete time domain is shown in Equation (7).

$$\begin{aligned} u_{tdc}(k) = u_{tdc}(k-1) \\ &+\bar{m}\Big[\{e(k-1) - 2e(k-2) + e(k-3)\}/L^2 \\ &+K_d^{tdc}\{e(k-1) - e(k-2)\}/L \\ &+K_p^{tdc} e(k-1)\Big], \end{aligned} \qquad (7)$$

where $e = q_d - q$ is position error, $K_d^{tdc} = 2\zeta\omega_n$ is differential gain, $K_p^{tdc} = \omega_n^2$ is proportional gain, L is sampling time, $\bar{m}$ is inertia term, ζ is damping ratio and ω_n is natural frequency.

Moreover, the control input of PID controller in the discrete time domain is shown in Equation (8).

$$\begin{aligned} u_{pid}(k) = u_{pid}(k-1) \\ &+ LK_d^{pid}\Big[\{e(k-1) - 2e(k-2) + e(k-3)\}/L^2 \\ &+ (K_p^{pid}/K_d^{pid})\{e(k-1) - e(k-2)\}/L \\ &+ (K_i^{pid}/K_d^{pid})e(k-1)\Big], \end{aligned} \qquad (8)$$

where K_p^{pid} is proportional gain, K_d^{pid} is derivative gain and K_i^{pid} is integral gain.

The control input of the both controllers are expressed in the same form. Thus, the PID gain can be selected by a parameter of the system through Equation (7) and (8) as follows:

$$\begin{aligned} K_d^{pid} &= \bar{m}/L \\ K_p^{pid} &= 2\zeta\omega_n K_d^{pid} \\ K_i^{pid} &= \omega_n^2 K_d^{pid} \end{aligned} \qquad (9)$$

In addition, the control input is shown in Equation (10).

$$u(t) = K_p^{pid} e(t) + K_i^{pid}\int e(t)dt + K_d^{pid}\dot{e}(t) \qquad (10)$$

This method can have same performance as TDC despite using a simple PID controller. Therefore, it is possible to easily improve the robustness without acceleration information.

5 Tracking simulation and experiment

To verify the performance of proposed controller, a trajectory tracking simulation was carried out.

The simulation is a circular path-following control with a radius of 300**mm** and payload of 250**kg**. The simulation conditions are a supply pressure of 210**bar** and a tracking speed of 5**deg/sec**. The simulation result is shown in Fig. 2.

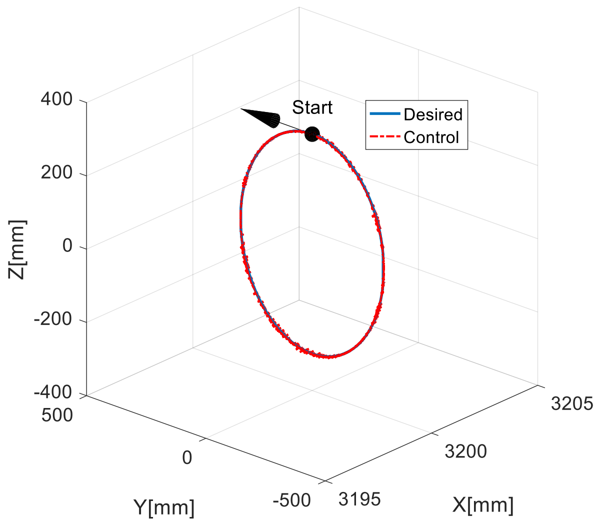

Fig.2 Simulation result

The simulation result shows that the end effector of the hydraulic manipulator follows the target trajectory well. To verify the control performance more, the error information of each axis is shown in the Table 1.

Table 1 Error of the tracking simulation

	X axis [mm]	Y Axis [mm]	Z Axis [mm]
RMS. error	0.0423	0.0322	0.4835
Max. error	0.1760	0.3220	1.9310

The maximum error was 1.9**mm** only in the Z axis, and the maximum error in other axes was less than 1**mm**. In case of RMS error, error of less than 1**mm** occurred on all axes. Therefore, the proposed control method is simple and can be effective for precise control of the hydraulic manipulator.

Next, the performance of the proposed control method is validated through experiment. The experiment was carried out under the same conditions as the simulation, and the result is shown in Fig. 3.

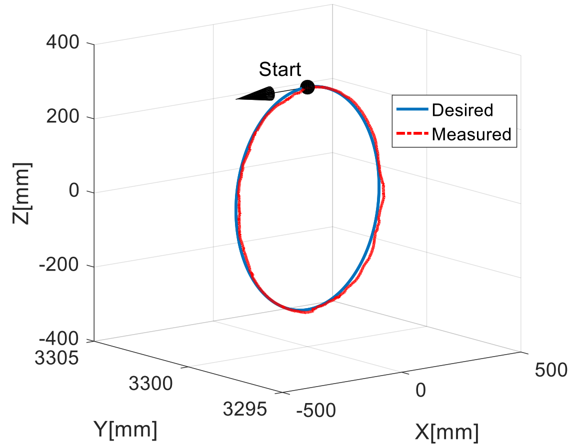

Fig.3 Experiment result

The experiment result shows that the error is slightly increased than the simulation result, but the overall path follows well. Detailed error information is listed in the Table 2.

Table 2 Error of the tracking experiment

	X axis [mm]	Y Axis [mm]	Z Axis [mm]
RMS. error	0.7752	0.1460	0.7639
Max. error	5.2652	0.3439	2.0391

In the case of the experiment, the maximum error was instantaneously increased to 5.2**mm** unlike the simulation due to uncertainties that cannot be modeled. However, since the RMS error is less than 1**mm** in all axes, the proposed control method has robustness. Therefore, it is possible to precisely control the hydraulic manipulator which contains a lot of nonlinearity though the proposed method.

6 Conclusion

In this paper, a robust control method was studied for precise control of the heavy-duty hydraulic manipulator. For simple and precise control, PID controller with robustness is applied though relationship of TDC and PID control. To verify the performance of the proposed method, simulation and experiment were carried out. In the result of simulation and experiment, the hydraulic manipulator followed the circular trajectory with an RMS error of less than 1**mm**. Therefore, the proposed method can precisely control the hydraulic manipulator without acceleration information.

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