

Position-Based Impedance Control of a Hydraulic Manipulator for Nuclear Accident Response without Pressure Sensors

Seongjin Park^a, Jinyi Lee^b, Ki Hong Im^b, Jongwon Park^{a*}

^aMajor of Artificial Intelligence, University of Science and Technology, Daejeon, 34113, Republic of Korea

^bKorea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 04535, Republic of Korea

*Corresponding author: jwpark@kaeri.re.kr

***Keywords:** Hydraulic manipulator, Dual-arm robot, Force control, Impedance Control, Position control

1. Introduction

Driven by global net zero policies, the accelerated construction of nuclear power plants has led to growing concerns regarding potential accident risks. Studies indicate that deploying robots in place of human personnel during a nuclear accident can significantly enhance emergency response and rescue capabilities. Consequently, leading research institutions and governments globally are accelerating the development of robotic platforms capable of executing critical missions in disaster environments [1].

In this context, the Korea Atomic Energy Research Institute (KAERI) is currently developing the ARMstrong robot for nuclear accident response operations. The robot is designed on a compact mobile platform capable of passing through fire doors, allowing unrestricted mobility within human-centric environments. By adopting a high-power-density hydraulic system, it is capable of performing heavy-duty tasks with a payload capacity of 100 kg per arm. Furthermore, to enhance operational efficiency in unstructured environments, an intuitive control system was established by utilizing a miniature master controller modeled after the robot's shape [2].

In an effort to extend the robot's application scope from conventional disaster response to general industrial fields, various industrial applications have been explored. To verify its field applicability, a robotic bolting task was demonstrated at a construction site [3].

For this bolting task, rather than developing a dedicated robotic tool, a commercial tool was directly mounted onto the robot's gripper. This approach not only verified the robot's capability to operate commercial tools but also confirmed that basic operational precision could be achieved relying solely on the simple position control of the hydraulic manipulator [4].

However, a significant limitation was that this approach required drastically reducing the operational speed to approximately 10–15% of the maximum speed. Therefore, to achieve practical performance improvements such as increased operational speed, it is necessary to diversify the control strategies beyond the conventional position control method.

In this paper, we propose a control strategy that integrates an impedance control technique with the existing position controller to enhance the control performance of the hydraulic manipulator, 'ARMstrong'.



Fig. 1. ARMstrong robot applications

2. Force Control Strategies in Hydraulic Manipulators

2.1 Force Control in Hydraulic Manipulators

Electric motor systems generate precise torque through current control, which is integrated with robot kinematics and dynamics to accurately control the force at the end-effector. Similarly, hydraulic systems operate by regulating the valve opening on each axis to control the flow rate, thereby managing the actuator force through the resulting changes in chamber pressure.

However, achieving such precise force control in hydraulic systems is significantly more difficult compared to electric motor systems. This is attributed to the inherent strong nonlinearities, dynamic response delays, and modeling and parameter uncertainties characteristic of hydraulic systems.

To overcome these limitations, various control techniques have been investigated. The first approach ensures control stability through Nonlinear Model-Based Control (NMBC) by integrating precise dynamic models that account for the inherent strong nonlinearities of hydraulic systems. The second approach performs

indirect force control utilizing existing position controllers, without the need for complex force modeling or pressure sensors [1].

2.2 Application to the ARMstrong Robot

The ARMstrong robot utilized in this study incorporates a compact and lightweight design to enable its integration into a mobile platform, resulting in a simplified hydraulic system. Specifically, each joint actuator is only fitted with position sensors, not pressure sensors. Consequently, to implement effective force control while preserving the existing system architecture without the need for additional sensors, the position controller-based force control approach was adopted.

3. Position-based Impedance Control

3.1 Overview

Implementing precise torque control in hydraulic systems is highly challenging and unstable due to complex control factors, such as valve nonlinearities, fluid compressibility, and friction.

As an alternative to overcome these limitations, Position-Based Impedance Control has been proposed. Instead of direct torque control, this method utilizes an internal position controller to ensure that the dynamic interaction between the robot end-effector and the external environment tracks a predefined target impedance [5].

3.2 Control Law

$$\mathbf{F} - \mathbf{F}_d = \mathbf{m}(\ddot{\mathbf{x}}_r - \ddot{\mathbf{x}}_d) + \mathbf{c}(\dot{\mathbf{x}}_r - \dot{\mathbf{x}}_d) + \mathbf{k}(\mathbf{x}_r - \mathbf{x}_d) \quad (1)$$

The equation above represents the target impedance model, which defines the desired dynamic behavior of the robot when interacting with the external environment. Furthermore, this equation indicates that upon the occurrence of a force imbalance ($\mathbf{F} - \mathbf{F}_d$) induced by external forces, the robot's trajectory is dynamically adjusted from the original target trajectory (\mathbf{x}_d) to a new reference trajectory (\mathbf{x}_r) to maintain the predefined target impedance.

Here, \mathbf{F} represents the actual external force measured by the force sensor mounted on the robot's end-effector, while \mathbf{F}_d denotes the desired force. The parameters \mathbf{m} , \mathbf{c} , and \mathbf{k} in the equation represent the target mass, damping, and stiffness, respectively. By tuning these parameters, the physical characteristics (compliance) exhibited by the robotic system during interaction with the external environment can be customized according to the task objectives. The calculation process is detailed below:

1. Definition of the Displacement Offset

$$\Delta \mathbf{x} = \mathbf{x}_r - \mathbf{x}_d \quad (2)$$

2. Reformulation of the Impedance Equation

$$\mathbf{F} - \mathbf{F}_d = \mathbf{m}\ddot{\Delta \mathbf{x}} + \mathbf{c}\dot{\Delta \mathbf{x}} + \mathbf{k}\Delta \mathbf{x} \quad (3)$$

3. Computation of the Acceleration for $\Delta \mathbf{x}$

$$\ddot{\Delta \mathbf{x}} = \frac{\mathbf{F} - \mathbf{F}_d - \mathbf{c}\dot{\Delta \mathbf{x}} - \mathbf{k}\Delta \mathbf{x}}{\mathbf{m}} \quad (4)$$

4. Velocity Update via Numerical Integration

$$\Delta \dot{\mathbf{x}}_{new} = \Delta \dot{\mathbf{x}}_{old} + \ddot{\Delta \mathbf{x}} \cdot \Delta t \quad (5)$$

5. Position Update via Numerical Integration

$$\Delta \mathbf{x}_{new} = \Delta \mathbf{x}_{old} + \Delta \dot{\mathbf{x}}_{new} \cdot \Delta t \quad (6)$$

$$\mathbf{x}_r = \mathbf{x}_d + \Delta \mathbf{x}_{new} \quad (7)$$

4. Experiment

4.1 Experimental Setup

The design of the existing robot wrist was modified to integrate a Force/Torque (F/T) sensor, and a corresponding physical mockup was fabricated. Furthermore, prior to its integration into the actual robot, preliminary experiments were conducted by placing the mockup externally and applying external forces to validate the feasibility of the position-based impedance control.

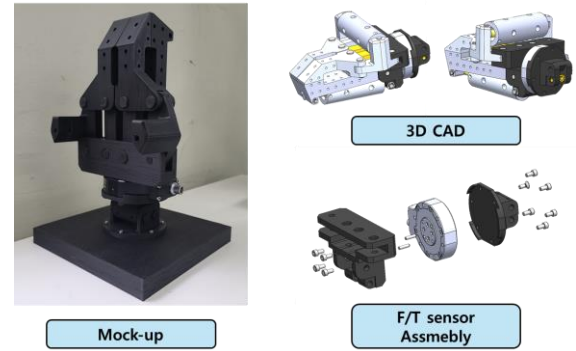
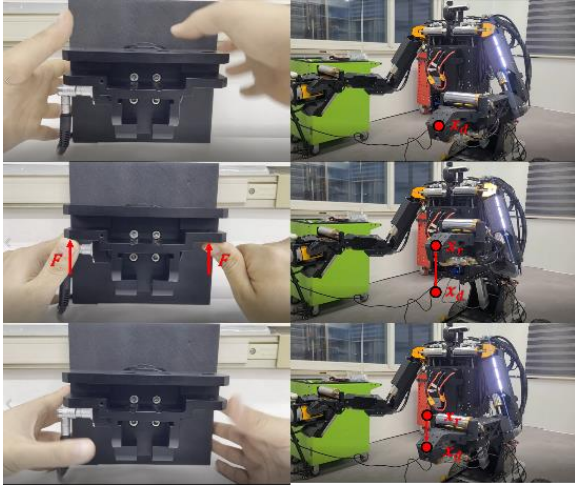


Fig. 2. ARMstrong robot wrist design modification

4.2 Experimental Results

In the experimental setup of the ARMstrong robot illustrated in Fig. 3, the dynamic behavior of the robot was observed by applying external forces to the F/T sensor-equipped mockup while maintaining the reference position, \mathbf{x}_d , fixed. The experimental results confirmed that the robot displaced in the direction of the applied force and, upon the removal of the external force, returned to its initial reference position. This verifies that the predefined virtual impedance model has been successfully implemented within the system.



Conference on Robotics and Automation, Minneapolis, MN, USA, Apr. 1996, pp. 284-290.

Fig. 3. Position-based impedance control test

5. Conclusions

In this study, Position-Based Impedance Control (PBIC) was implemented for the ARMstrong hydraulic manipulator to achieve effective force control while minimizing hardware modifications. The feasibility of the proposed control strategy was successfully verified through experimental validation. Future work will focus on evaluating the controller's performance by applying it to practical tasks that necessitate physical interaction with the external environment, such as bolting and sawing.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Trade, Industry and Energy (MOTIE), Republic of Korea, and funded by the Korea Evaluation Institute of Industrial Technology (KEIT).
(Project No. 20023294)

REFERENCES

- [1] D. Dong, Z. Wang, J. Guan, Y. Xiao, and Y. Wang, "Research on key technology and application progress of rescue robot in nuclear accident emergency situation," *Nuclear Engineering and Technology*, vol. 57, Art. no. 103457, 2025, doi: 10.1016/j.net.2025.103457.
- [2] J. Park, D. Lim, J. Park, and S. Jung, "Experimental studies on design of a dual arm manipulator with hydraulic system for disaster accidents," *Journal of Institute of Control, Robotics and Systems*, vol. 28, no. 11, pp. 1080–1087, 2022.
- [3] Hyundai E&C. (July 1, 2024). "Hyundai E&C takes a step closer to unmanned sites with customized robotics technology" (in Korean). Hyundai E&C Newsroom. [Online]. Available: https://www.hdec.kr/KR/newsroom/news_view.aspx?
- [4] H. Kwon, G. Shin, S. Park, J. Lee, K. H. Im, and J. Park, "Vision-Based Robotic Bolt Fastening in Unstructured Industrial Environments," in *Proc. Int. Conf. Control, Autom. Syst. (ICCAS)*, 2025.
- [5] B. Heinrichs, N. Sepehri, and A. B. Thornton-Trump, "Position-based impedance control of an industrial hydraulic manipulator," in *Proceedings of the 1996 IEEE International*