Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Vision-Guided Robotic High-Torque Bolt Fastening for Nuclear Power Plant Maintenance

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Keywords: Robot, ROS, Fastening, Hydraulic Manipulator

1. Introduction

High-tensile bolts serve as a crucial fastening mechanism across various industries due to their superior strength, ease of maintenance, and reversible disassembly compared to alternative methods such as welding and riveting. These attributes make high-tensile bolts widely applicable in construction, civil engineering, and industrial plant operations.

Automating the fastening of high-tensile bolts with an impact wrench poses significant challenges for robotic systems. Millimeter-level positioning and precise alignment in posture and orientation are necessary to ensure proper fastening. Additionally, the substantial torque exerted during bolt tightening presents a further complication. The inherent impact forces generated by the wrench may cause mechanical issues for conventional motor-driven robots.

This study introduces a robotic automation method for high-tensile bolt fastening utilizing a hydraulic dual manipulator. The proposed approach minimizes the complexity of sensing systems while addressing alignment challenges. A two-step process is implemented to leverage the compliance of the manipulator, facilitating effective bolt fastening operations.

2. System Configuration

For the automation of bolt fastening using an impact wrench, the ARMstrong heavy-duty hydraulic dual-arm mobile manipulator, developed by the Korea Atomic Energy Research Institute (KAERI) Extreme Robotics Team, was employed. ARMstrong is equipped with two arms, each possessing a payload capacity of 100 kg and six degrees of freedom, plus an additional two for gripping functions.

A commercially available DeWALT DCF892 impact wrench was selected for this study. To control its trigger mechanism, a Dynamixel MX-28 servo motor was integrated. The tool and actuator were integrated using a custom 3D-printed jig designed to securely mount the assembly onto ARMstrong's gripper.

Fig. 1 ARMstrong, the hydraulic dual arm mobile manipulator

The entire system was developed on the Robot Operating System 2 (ROS 2) framework [2], which enabled modular integration of perception, planning, and control components for real-time robotic operation.

3. Fastening Process

Automating bolt fastening requires precise positioning and orientation of the tool head relative to the bolt. An open-loop approach, which does not utilize vision or haptic feedback, was adopted. While this method may introduce misalignment, a two-step fastening process was developed to mitigate this issue.

In the **initial alignment** phase, the tool head is guided toward the bolt's estimated position and posture, without correcting for rotational alignment. To support this phase, a vision-based pose estimation method was implemented using a YOLOv12 [3] model in combination with RGB-D sensor data. The system detects bolts in the 2D image, projects their center pixels into 3D space using depth information, and estimates each bolt's 6-DoF spatial

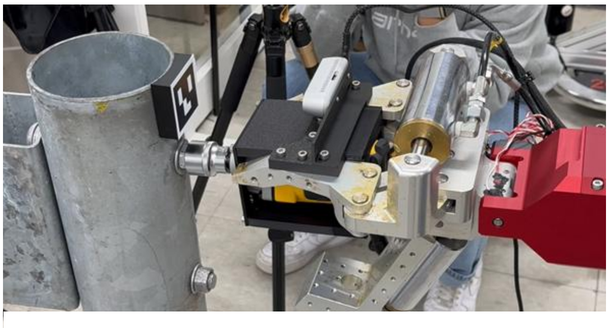

Fig. 2 Experimental setup for the hydraulic dual-arm manipulator system

pose by analyzing local or grouped point clouds. This information serves as a reference for aligning the tool head during the initial phase, improving the likelihood of successful engagement even under open-loop conditions.

In the **adaptive insertion** phase, the impact wrench is gradually rotated while being inserted into the bolt head. The structural compliance of ARMstrong—from its tool head to its mobile base—plays a key role in this step. If precise alignment is not achieved initially, the compliance allows the tool head to dynamically adjust its position and orientation. As the wrench rotates, the tool follows a cycloidal trajectory, effectively "searching" for the correct alignment until the bolt is properly engaged and fastening is completed.

This method provides a reliable approach to bolt fastening without requiring highly precise initial alignment. It highlights the potential for robust robotic operation in industrial automation scenarios, such as construction and maintenance tasks.

4. Conclusions

This study presents an automated fastening strategy using a hydraulic dual-arm manipulator. The inherent compliance of the system facilitates successful bolt connections without necessitating precise initial alignment, thereby improving efficiency and reliability in industrial fastening operations.

The current implementation functions in an open-loop configuration, which limits adaptability to varying environments. Future research efforts will focus on integrating feedback mechanisms such as vision and haptic sensors to enhance system robustness. A vision module utilizing YOLOv12 and depth sensing has already been implemented to estimate the 3D pose of bolts, laying the groundwork for closed-loop visual servoing. Additionally, advanced control algorithms will be developed to refine fastening accuracy. Further evaluations will be conducted under diverse conditions, and potential human-robot collaboration scenarios will be explored. These advancements aim to enable a more versatile and widely applicable robotic fastening solution for construction, maintenance, and manufacturing sectors.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(Ministry of Science and ICT)(No. RS-2022-00144468).

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