Technology Introduction

Development of Modular Hydraulic Robots Development of a detachable mechanism for convenience in on-site work

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1 Introduction

This report presents the research achievements for fiscal year 2024 of the Humanoid Systems Laboratory* in the Department of Robotics at Ritsumeikan University's College of Science and Engineering and KYB Corporation (which took over initiatives from the former KYB-YS Corporation in FY2023). The report relates to content presented at the 42nd Annual Conference of the Robotics Society of Japan (RSJ) and the 2024 International Conference on Robotics and Automation (ICRA).

Disaster and construction sites involve situations that are difficult for humans to access, leading to a rising demand for work robots that can handle such situations[1]. In recent years, new robotics technologies that offer versatility to meet various needs and enable total cost reduction have gained attention, such as modular robots that can be disassembled into single-joint units, as shown in Fig. 1.

In this research, we are developing modular, hydraulically driven robots that can handle and carry heavy loads in difficult-to-access environments while leveraging the advantages of modular robots[2]. Compared with electric systems, hydraulic drives enable robots to provide high power and excellent impact resistance, as well as optimal performance in the harsh work environments mentioned above.

Previously, we have proposed mechanical connection mechanisms using pins and dowels[3] and wedge fastening methods using ropes[4] to couple modular robots. Furthermore, we have presented a coaxial coupler[4] configuration that allows for freedom in connection orientation.

This report provides an overview of previous initiatives, followed by a description of the structure of a detachable mechanism that can automatically attach/detach and has a high fastening force suitable for heavy-duty applications. It also introduces the results of the prototype evaluation of this mechanism.

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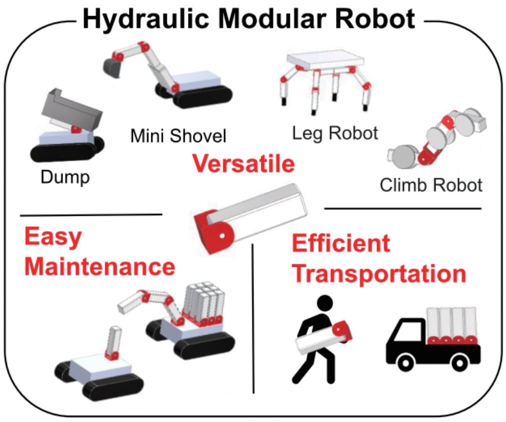


Fig. 1 Overview of modular hydraulic robots

2 Designing a Detachable Mechanism

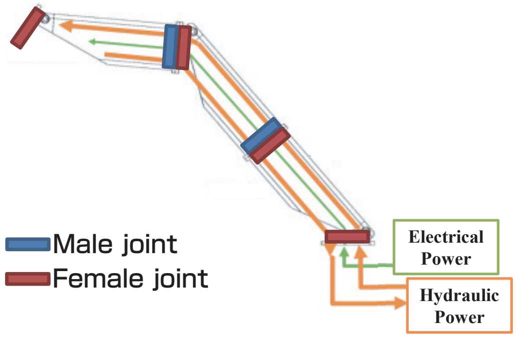
2. 1 Requirements for the Detachable Mechanism

The following lists the requirements for a detachable mechanism applicable to modular hydraulic robots to address the challenges described in the previous chapter:

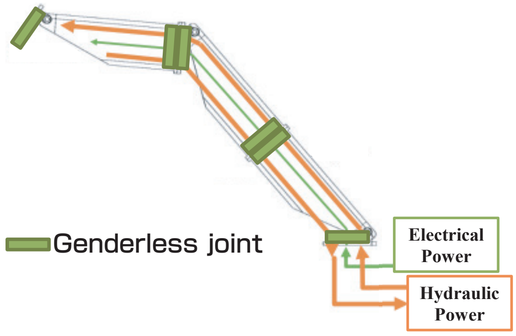
(1) Being able to provide sufficient fastening force under operational conditions;
(2) Being able to lock and unlock via external control and support automation;
(3) Have a genderless structure (no male/female polarity);
(4) Have freedom in the locking orientation;
(5) Being able to connect multiple hydraulic lines while performing attachment/detachment operation;
(6) Being able to establish an electrical connection while performing attachment/detachment operation.

Among those above, the requirement (3) is detailed in Fig. 2. As shown in Fig. 2(a), joints with male/female polarity pose orientation constraints during locking, reducing efficiency and flexibility in assembling work. On the contrary, as shown in Fig. 2(b), a genderless structure with no polarity eliminates the orientation constraints during assembly, improving convenience.

The feature (6) has already been developed as described in a previous report3). This report presents part of the two developments: a genderless docking mechanism that meets (1), (2), (3), and (4), and a coaxial coupler system that meets (5).



(a) Male and female joints



(b) Genderless joints

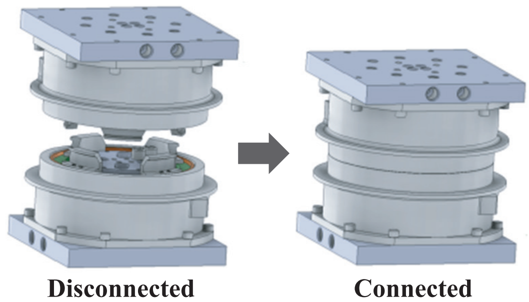
Fig. 2 Genderless joints

2. 2 Genderless Docking Mechanism

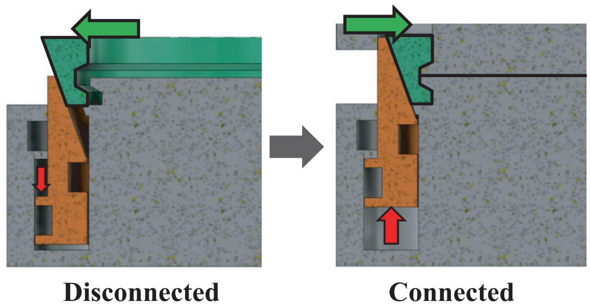
The previous report proposed a mechanism for connecting modular hydraulic robot units that uses a rope to tighten a grooved part corresponding to a wedge-shaped flange, providing a fastening force[4]. This report proposes a new fastening method that uses only hydraulic power instead of ropes. It is a genderless docking mechanism with a hydraulic locking structure, as shown in Fig. 3. The configuration of the mechanism is shown in Fig. 3(b). The internally located ring-shaped part (orange) moves up or down to press the arc-shaped part (green) against the wedge-shaped flange part (gray), generating a fastening force through a wedge effect. The ring-shaped part contains a hydraulic cylinder structure that operates by creating a pressure difference between the upper and lower chambers. A piping port provided in each chamber enables external control of the operation.

2. 3 Coaxial Coupler System

We designed the coaxial coupler system[3] shown in Fig. 4 to connect hydraulic tubes for locking modular hydraulic robot units. These couplers enable simultaneous connection of multiple fluid lines and allow for flexibility in the locking orientation.



(a) Appearance of the structure



(b) Cross section

Fig. 3 Genderless docking mechanism

The internal structure is shown in Fig. 5. Multiple couplers arranged on the same circumference serve as corresponding ports that merge flow paths internally. The flow paths are formed by three circular plates and fastened by bolts.

Specifically, the port joints are concentrically arranged and systematically assigned male/female polarity. This allows multiple oil paths to remain connected even when the joints are rotated 90 degrees apart around the center, as shown in Fig. 6. This structure ensures reliable hydraulic tube connections while allowing freedom in the locking orientation.

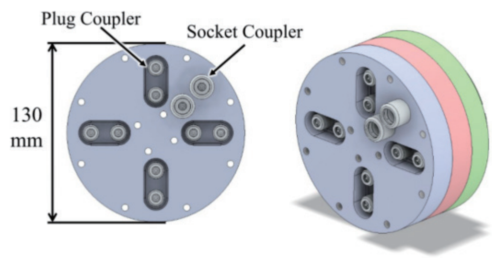


Fig. 4 Structure of the coaxial coupler system

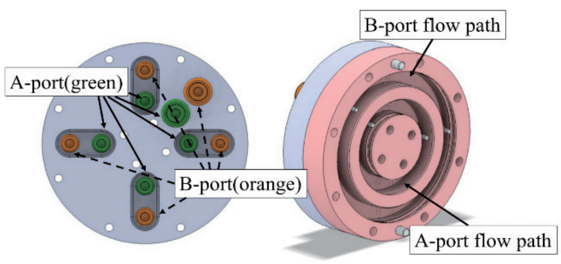


Fig. 5 Port arrangement of the coaxial coupler system

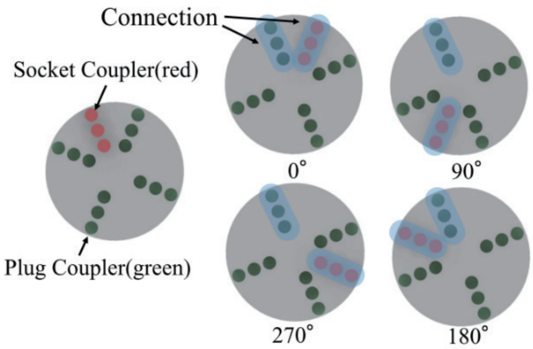


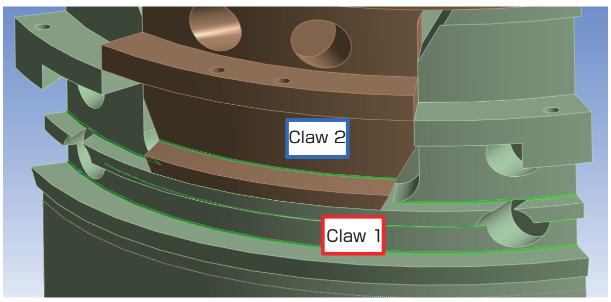
Fig. 6 Connections of the coaxial coupler system

3 Strength Analysis Verification

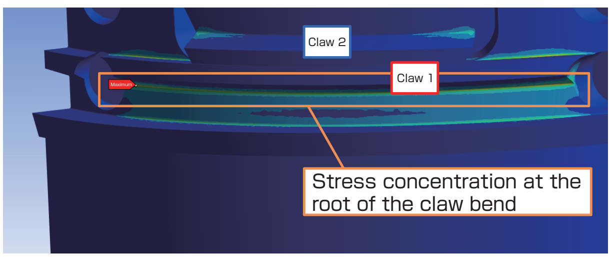
Before conducting prototype experiments to confirm the principle of the proposed mechanism, we used finite element analysis software to evaluate the strength of the constituent materials under experimental conditions. The purpose of this analysis was to establish safe experimental conditions. An example of the analysis results is shown below.

3. 1 Strength Analysis of the Genderless Docking Mechanism

As mentioned in Chapter 2, the genderless docking mechanism creates a fastening force by pressing a retainer against a wedge-shaped flange. This structure raises concerns about local deformation of the wedge section due to the pressing force. We conducted an analysis to validate the stress distribution of the wedge section and the strength of the materials when a pressure load is applied to generate the fastening force. The results of the analysis are shown in Fig. 7. Although the analysis showed stress concentration at the root of the claw bend in the wedge section, actual service conditions revealed that the stress level was below the materials' yield strength. Thus, structural safety was verified.



(a) 3D model of the wedge section



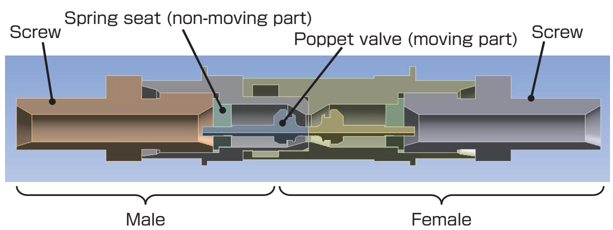
(b) Strength analysis of the wedge section (equivalent stress)

Fig. 7 Example of strength analysis of the docking mechanism

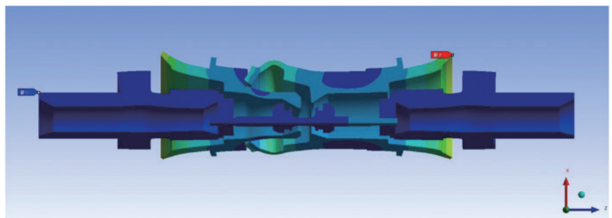
3. 2 Strength Analysis of Hydraulic Couplers

We conducted a finite element analysis to evaluate the structural adequacy of the hydraulic couplers in the coaxial coupler system mentioned in Chapter 2 when subjected to pressure loads in both the connected and disconnected states. In the connected state, we examined whether the coupler components could withstand the internal pressure generated when fluid passes through them. In the disconnected state, our focus was on the poppet valve installed within each coupler. We evaluated the valve structure and the strength of the surrounding parts under the pressure generated when the valve blocks fluid flow.

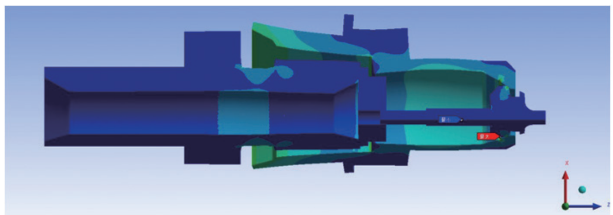
Figs. 8(a) and 8(b) show the strength analysis results in the connected state, and Figs. 8(c) and



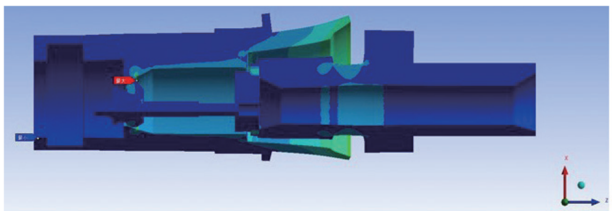
(a) Hydraulic couplers in the connected state



(b) Strength analysis of connected couplers (equivalent stress)



(c) Strength analysis of a single male coupler (equivalent stress)



(d) Strength analysis of a single female coupler (equivalent stress)

Fig. 8 Example of hydraulic coupler analysis

8(d) show the results in the disconnected state. In both states, the stress distribution was below the yield point, which verifies the structural safety of the coupler system under actual service conditions.

3. 3 Strength Analysis of the Coaxial Coupler Unit Fastening Bolts

As described in Chapter 2, a coaxial coupler unit consists of three circular plates assembled by fastening with bolts at the center and outer periphery in order to form fluid paths, as illustrated in Fig. 9. Concerns were raised about the possibility of excessive stress on the fastening bolts due to internal pressure generated by fluid flow, which could result in failure of the assembly. Therefore, we conducted a strength analysis of the fastening bolts under an internal pressure load to evaluate structural safety. The analysis showed that the stress on the fastening bolts under anticipated pressure loads during operation was below the allowable stress of the materials, proving the assembly's structural integrity.

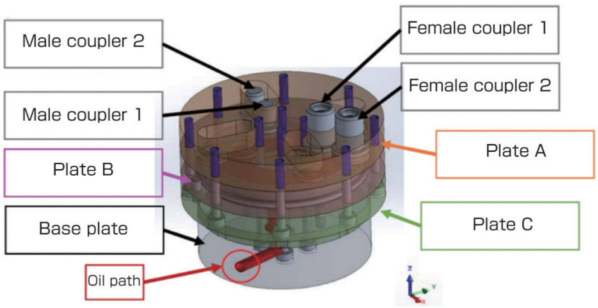


Fig. 9 Coaxial coupler fastening bolts

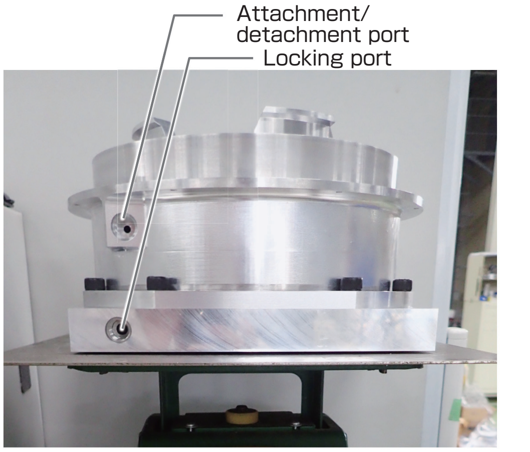
4 Fabrication of a Detachable Mechanism with Both Features

By combining the genderless docking mechanism and the coaxial coupler system described in previous chapters, we prototyped and evaluated a modular robot detachable mechanism with both features.

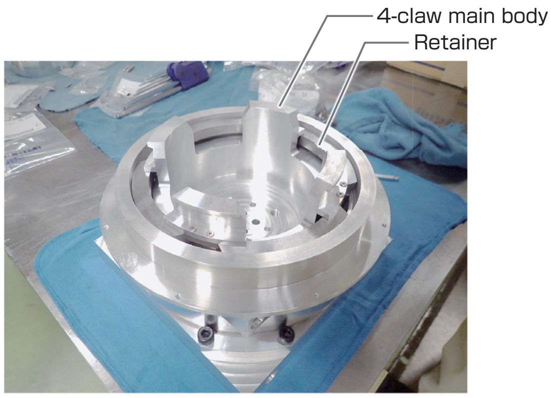
4. 1 Genderless Docking Section

Photo 1 shows the appearance of the genderless docking section that we fabricated. The docking section operates by applying hydraulic pressure through the attachment/detachment and locking ports shown in (a). A lock ring then moves up or down, pressing a retainer outward against the claws of the flange shown in (b). This generates a fastening force.

To verify its operation, we mated two docking sections as shown in Photo 2. We then connected an oil line to the locking port of each of the two docking sections and applied hydraulic pressure from the outside. As the pressure increased, the docking sections moved closer together, as seen in Photo 2, from (a) to (b). We found that they properly docked together. This demonstrated that the wedge effect worked properly.

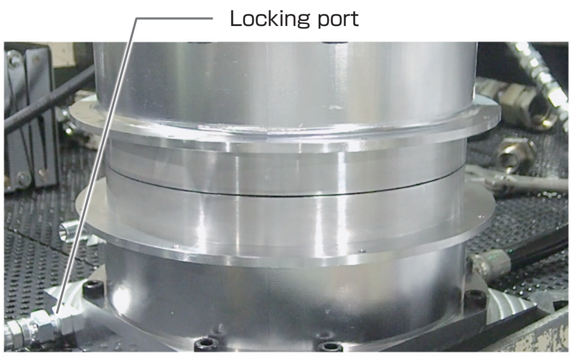


(a) Ports

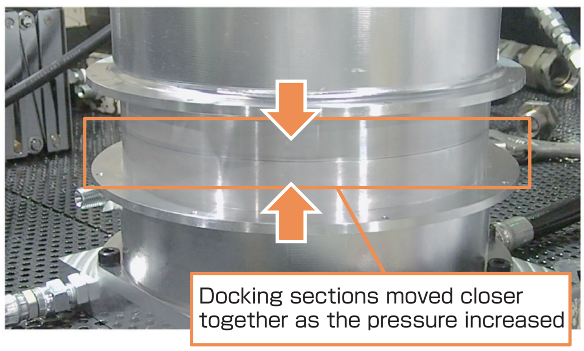


(b) Appearance

Photo 1 Fabricated genderless docking mechanism



(a) Locking port under no pressure



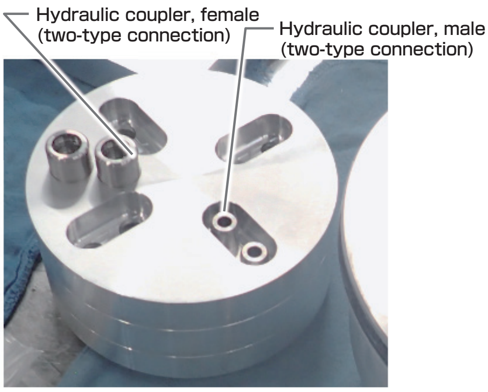
(b) Locking port under pressure

Photo 2 Docking mechanism operation test

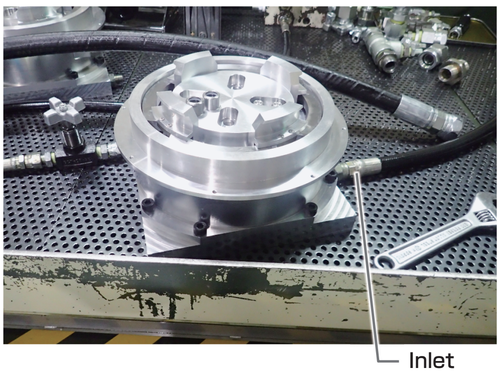
4. 2 Coaxial Coupler Unit

Photo 3 shows the coaxial coupler unit that we fabricated. As described in Chapter 2, the unit is designed to be able to dock with another unit even when rotated at 90-degree intervals, which achieves high flexibility in the locking orientation.

We conducted an operational test to evaluate the performance of the coaxial coupler unit prototype. First, we determined whether the unit leaked oil when disconnected. In the test, we inserted a coaxial coupler unit (a) into the center of the genderless docking mechanism (b), which was presented in the previous chapter. Hydraulic pressure was applied to this single disconnected joint through the inlet. As a result, no oil leakage was found in the coaxial coupler unit, even at a pressure level under actual service conditions. This proves the unit's sealing performance.



(a) Coaxial coupler unit



(b) Combined with the genderless docking mechanism

Photo 3 Coaxial coupler operation test

4. 3 Evaluation of the Mechanism with Both Features

Following the previous section, we conducted an evaluation test to determine the oil flow and leakage of the combined detachable mechanism of the genderless docking mechanism and the coaxial coupler system with their joints connected. During the test, we applied hydraulic pressure to the locking ports and allowed oil to flow into the mechanism through the inlet as shown in Photo 4. We observed the fluid behavior during operation. As a result, the docking mechanism remained properly engaged with normal oil flow, and there was no oil leakage at the connections.

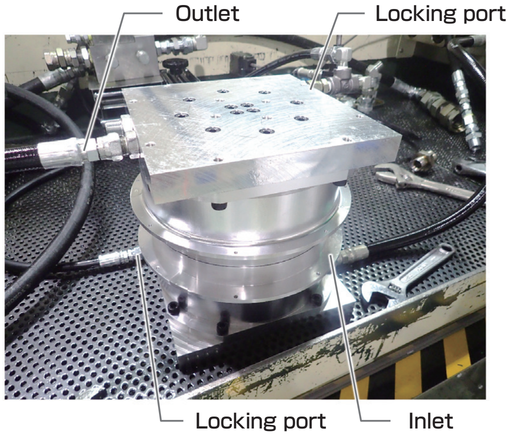


Photo 4 Connected mechanism

These evaluation results demonstrate that the docking mechanism prototype successfully implements both the genderless docking and coaxial coupling features, proving its effectiveness as a practical detachable mechanism for modular robots.

5 External Dissemination of the Outcome

The development outcome of the modular hydraulic robot including the detachable mechanism addressed in this research were displayed on panels at the KYB and Ritsumeikan University Hyon Laboratory booths at the International Fluid Power Exhibition (IFPEX) 2024, hosted by the Japan Fluid Power Association (JFPA).

Furthermore, the detachable mechanism prototype introduced in this report was publicly exhibited at the Ritsumeikan University booth, as shown in Photo 5. Actual robots were also used to demonstrate the mechanism to visitors.

The KYB booth conducted a visitor survey. Of the more than 20 products on display, this modular robot was rated as one of the products that attracted particular interest from many visitors. This suggests the practicality and high social demand for this technology.

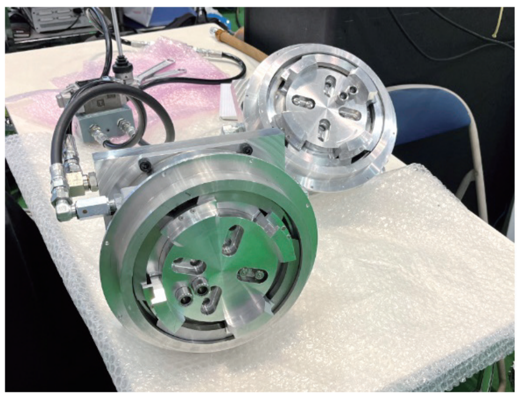


Photo 5 The prototype displayed at IFPEX2024

6 Conclusions and Future Prospects

This report proposes two types of detachable mechanisms for modular robots: the genderless docking mechanism and the coaxial coupler system, both of which enable modular connections. These mechanisms were prototyped and evaluated.

The genderless docking mechanism was verified to properly deliver fastening force due to the wedge effect when hydraulic pressure is applied to the lock ring section. This reliably locks the joints. The coaxial coupler system was verified to provide sufficient sealing performance and prevent oil leakage, even when a disconnected coupler unit is subjected to a pressure test. Furthermore, the coaxial coupler system was also verified to support normal hydraulic flow with no oil leakage in the connected state. These tests showed that both the mechanism and system are functional and reliable under actual service conditions.

Going forward, we plan to improve the joint structure design, including reducing its size and weight, to meet various modular robot requirements. Through these improvements, we aim to build a modular robot system with even greater versatility and practicality.

7 In Closing

Natural disasters, including the 2024 Noto Peninsula Earthquake, require people to work to recover and reconstruct numerous sites where human access is difficult. This applies to modern socioeconomic sectors such as agriculture, forestry, fisheries, civil engineering, construction, logistics, and infrastructure maintenance. In these environments, the modular hydraulic robot presented in this report is flexible and precise technology that can adapt to each site's needs.

We are committed to continuing our initiatives to resolve societal issues from diverse perspectives by leveraging our technological assets, including this technology.

Finally, we would like to express our sincere gratitude to Professor Hyon Sang-Ho of Ritsumeikan University and the members of the Hyon Laboratory for their tremendous support and cooperation in advancing this research activity. We would also like to thank all the people within the company who were involved: the CAE Dept. of the Engineering Div., the Machine Tools Center of the Production Div., and the Developmental Experiment Sect. of the HC Operations, who collaborated on the analysis, fabrication, and evaluation.

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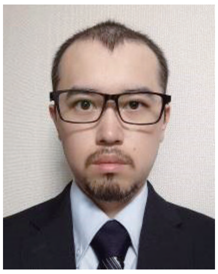

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