

Development of the Assembling System for Structure Transformable Humanoid with Attach-Lock-Detachable Magnetic Coupling

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Abstract—We propose the method to adapt humanoids the ability to change the body structures that modular robots have by using Attach-Lock-Detachable Magnetic Couplings(ALDMag) to give the ability to detach and attach the robot body with an arm-type robot, and the system to manage the connection state of modularized body elements. Robots and we can use the ALDMag to attach and detach mechanical and electrical connections without actuators. Using xacro for writing the file of the robot model description of each module, we can construct a system that allows the robot to attach and detach modules during task operation. We demonstrated the effectiveness of the proposed method by achieving assembly experiments of a small robot with a life-size arm and experiments with environmental contacts by the small robot.

I. INTRODUCTION

We have proposed various forms of robot systems to satisfy the needs of individual work environments and purposes. Two typical robot configuration methods aim to adapt the robot’s abilities to work in various environments.

- 1) Modular robots which can achieve a variety of configurations depending on the target tasks [1]
- 2) Humanoid robots that have the degree of freedom as humans and aim to achieve similar behaviors[2]

Although each type of robot aims to achieve a variety of work capabilities, conventional modular robots often lose work capacity compared to robots of the same scale because they consume hardware resources in connection mechanisms, and because each module has redundant elements such as batteries, which increase the size of the robot. In many cases, this may result in a loss of work capacity compared to a robot of the same scale. Though humanoids have many degrees of freedom, since the body structure does not change except for the use of tools, they may not be able to adapt if the target environment or work symmetry changes significantly. Although humans and other living organisms are composed of tiny cells, the design concept of humanoid and modular robots is not ideally at odds with each other, as we have not realized the small cell robot due to the restriction of the smallest size of modular. Therefore, by configuring the joint mechanism in a simple and lightweight, we can adapt humanoids to the capability to change their end-effector or leg structure, which touches objects or the environment according to the purpose, just as in modular robots. We propose the Attach-Lock-Detachable Magnetic Coupling(ALDMag) as a connection mechanism to solve those problems, and we can

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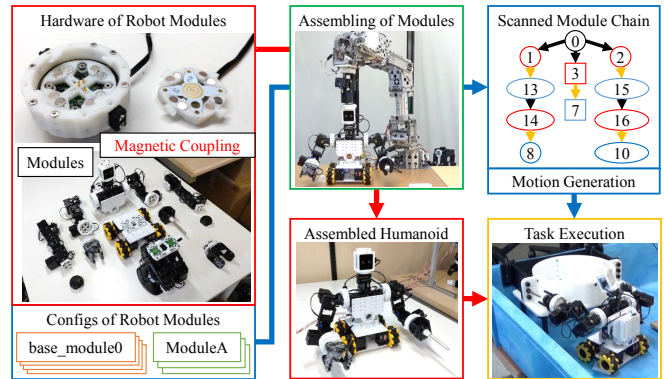


Fig. 1: Overview of Proposed Humanoid System.

use them to attach and detach the mechanical and electrical connections without active actuators such as motors. The proposed mechanism also has electrical joints using pogo pins and pads, allowing dynamically variable connections to modules such as actuators and sensors. Since the robot must tolerate changes in connected devices to use the proposed mechanism during task achievements, we also configure the system to manage modularized robot body information. We develop ALDMag and the body information management system into the bodies of the small humanoid and the life-size arm robot. We will demonstrate the usefulness of the proposed ALDMag and the whole system to manage variable body structure by conducting assembly experiments of small robots with the life-size arm robot and task achievements by the small robot.

II. RELATED WORKS AND OUR CONTRIBUTION

A. Related Works

Researchers have proposed a wide variety of connection mechanisms for the mechanical joining of modular robots together[3]. There are two main types of coupling mechanisms: 1. mechanical coupler[4], [5] and 2. magnetic coupler[6], [7], [8]. The advantage of 1 is that we can use them to support large loads; the disadvantage is that actuators are required to drive them. The advantage of 2 is that we can use them easily joined using magnetic force; the disadvantage is that the weight increases significantly to support a large load. One of the features of this research is that we combined the mechanical coupling and the magnetic coupling. By using the attraction between the permanent magnets to perform the alignment and for driving the mechanical fixation mechanism, we omit the actuator from the connection mechanisms. As methods for

constructing and operating robots that combine modularized bodies, researchers have proposed the following methods: the method for exploring the graph structure of modularized robot body[9], and a method for black-box optimization of structures such as link lengths of real robots[10]. The features of the proposed method include the combination of ready-made products, 3D printed parts, and PCB circuits to construct many connection mechanisms easily, and the function of making robot models interactively by combining many types of modules on the fly. We believe that these features will be useful for the verification of actual robots in optimization studies of body structures composed of modular elements.

As mechanisms to change the robot's motion capability, the auto tool changer[11] has been proposed for machine tools to change the tip tool, and connection mechanisms [12] for humans to change the end-effector of robot arms easily without an actuator. Since ALDMag is developed with simple mechanisms that adds ease of attachment and detachment for robots and humans to these mechanisms, another feature of ALDMag is that we can configure the mechanism in various forms depending on the scale and load of each robot.

B. Our Contribution

We present three contributions of this study

- 1) Proposal for ALDMag, which is structurally and electrically attachable and detachable, energy-saving, and easy to mass-produce.
- 2) Development of the method sharing and managing information on body part modules.
- 3) Realization of robot assembly operation by the arm-type robot and task achievements by the small robot

In order to solve the trade-off between size, weight, and performance of conventional connection mechanisms, we propose both the connection mechanism using only permanent magnets and the locking mechanism driven passively, depending on the required joining force, in forms that are easy to mass-produce. A further contribution is the realization of a separation function using the repulsive force between the magnets. Next, we propose the system to manage the body modules and demonstrate its usefulness in applying it to robots with multiple scales and changing robot configurations. Finally, as an example that requires body structure modification, we evaluate the proposed mechanism and management system through the assembly of the body and the realization of the operation in response to the environment.

III. HARDWARE DESIGN AND SYSTEM

A. Hardware System for Magjoint Mechanism

The robot system proposed in this paper is equipped with TTL serial servo motors[13] and multi-sensor boards[2]. The control board (kondoh7) and the motor/sensor devices are daisy-chained and have three lines: VCC, the signal line (UART half duplex), and GND. Since VCC, signal lines, and GND are all connected in the same daisy chain, the control board can communicate with devices without depending on

the wiring topology, and conversely, it is possible to detect when communication is lost. Pogo pins used in modular robot-to-modular robot connection mechanisms are also used in this system to attach and detach electrical connections. The control board and a one-board PC [14] are connected via UART, and we can use PC for calculations such as motion generations and image processing from the camera[15]. We show a detailed system diagram in the video attachment.

B. Overview of Hardware Design of ALDMag

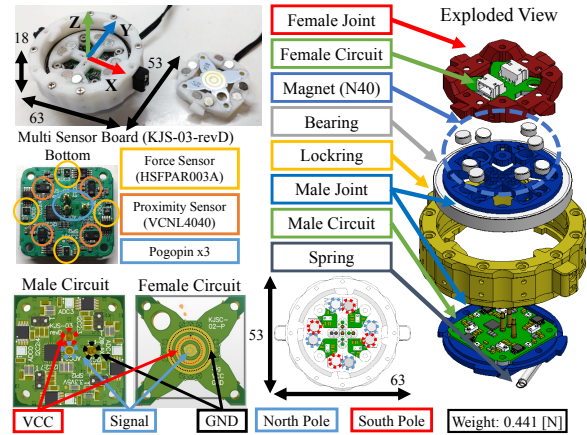


Fig. 2: Overview of Proposed Design of ALDMag.

We show the design of ALDMag in Fig.2. The proposed mechanism of ALDMag consists of the electrical connection mechanism with a pair of interface boards (female and male boards) and a mechanical joint mechanism with permanent magnets and a locking mechanism.

The male board has two types: one with pogo pins added to the surface of the multi-sensor boards[2], and the other with only pogo pins (top) and connectors (bottom) as shown in Fig.4. Multi-sensor boards are equipped with four infrared proximity sensors[16], which can be used for detecting the position and number of holes of the female board to detect the direction and type of the object being joined. Regarding the pogo pins on the male board and the concentric pads on the female board, the three-pole communication system (VCC, signal line, and GND) corresponds to each of them, and it is possible to maintain continuity regardless of the angle at which they are connected.

Next, for the mechanical connection mechanism, all mechanisms have a gender-less shape with up to eight neodymium magnets (N40, $Radius, Height = 2.5$ [mm]) in alternating directions. The surface shape of the mechanism bears shear forces and the attraction between the permanent magnets enables alignment at the time of connection and maintaining of the connected state. Since this mechanism has a simple structure that can be used by simply embedding magnets in parts with a specific surface shape, we can easily configure with a variety of variations such as those in Fig.4.

On the other hand, one problem of this mechanism is that the connection is broken when it receives the force or moment that exceeds the attraction between the permanent

magnets. Therefore, as shown in Fig.2, we propose ALDMag with an additional locking mechanism to bear the force and moment exceeding the attractive force to use them at the root of the limb or other points. This mechanism consists of a pair of female shapes with a pawl structure to be fixed and a male shape with a ring with pawls to fix the female shape. If the allowable load is sufficiently small, the claw mechanism for fixation can be omitted, as in the Connectable Twin Male, Female Joints shown in Fig.4. The mechanism can be easily mass-produced with off-the-shelf mechanical elements, FDM 3D printed components, and PCB boards.

C. Attach and Detach Functions of ALDMag

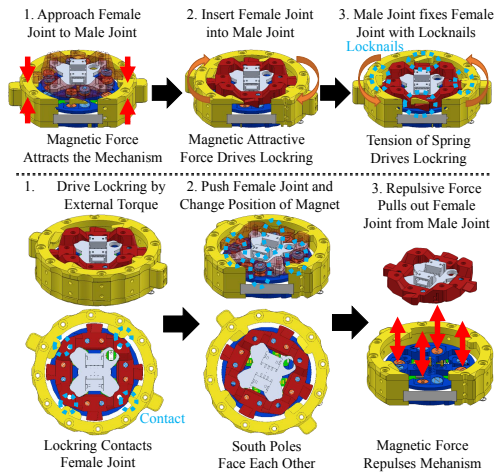


Fig. 3: Sequence of Attach and Detach Motions of ALDMag.

We explain the sequence of attaching and detaching functions in the Fig.3.

- 1) Move the female mechanism (device side) and the male mechanism (robot side) closer. (1 in Fig.3 upper)
- 2) Attractive force between magnets pulls the female mechanism into the male mechanism. (1 in Fig.3 upper)
- 3) The pawls of the female side pushes the pawls of the male side and rotates the ring. (2 in Fig.3 upper)
- 4) When the female mechanism is completely inside the male mechanism, interference between pawls is eliminated. (2 in Fig.3 upper)
- 5) The spring in the male mechanism drives the ring, causing the pawl in the male mechanism to overlap the pawl in the female mechanism, locking the female mechanism in the direction of exit. (3 in Fig.3 upper)
- 6) If the male mechanism have the multi-sensor board, the proximity sensors detects the holes of the female mechanism to estimate the direction of connection.

Concerning 1 and 2, the attraction between male and female mechanisms is used to attract each other so that the elements can be easily connected without the need for precise positioning operations such as pe-in-holes. About 3, 4, and 5, by devising the shape of the pawls of the male and female mechanisms, the attraction is converted into a

force that rotates the ring on the male mechanism for locking after the attaching is complete. We show the details of 6 in Subsection III-D.

We show the sequence of detaching actions below.

- 1) Turn the ring on the male mechanism and press the side of the female mechanism to rotate the female mechanism in the same direction. (1 in Fig.3 lower)
- 2) Permanent magnets in male and female mechanisms are misaligned, and the same poles face each other at a certain position. (2 in Fig.3 lower)
- 3) Repulsive between the same magnetic poles causes the female mechanism to exit from the male mechanism. (3 in Fig.3 lower)

Concerning 1, by pushing and turning the side of the female mechanism with the pawl of the ring, the mechanical lock is released, but the mechanisms are still attached by the attraction between the magnets. Concerning 2 and 3, as the female mechanism is turned further, the position of the magnets shifts between the male and female mechanisms, and the repulsion between the magnets increases between the same poles. Separation is achieved by increasing the repulsive force in the direction that the female mechanism exits the male mechanism while the attraction decreases.

D. Estimation Method of Connected Direction

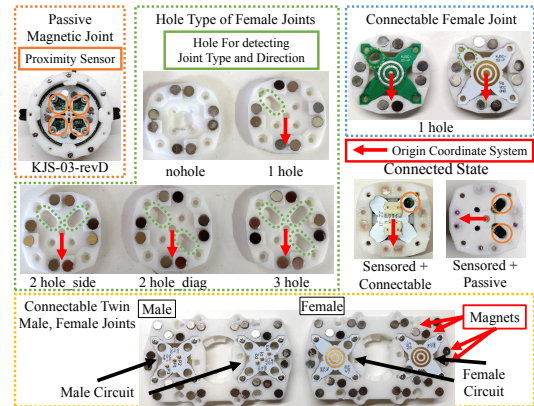


Fig. 4: Coordinate Systems of Modules for Estimation.

Regarding the estimation of the connection direction, we show the coordinate system of each mechanism in Fig.4. The information that can be detected depends on the number and arrangement of holes. The one with no through holes ("nohole") or four holes ("4hole") is only for the presence or absence of device, the one with two holes and diagonally opposite holes ("2hole_diag") is for the presence or absence of detachment and two different connection directions, the other three types ("1hole, 2hole_side, 3hole") can be detected the presence or absence of detachment and four connection directions.

We outline the method for recognizing the connection direction from the values acquired by proximity sensors. The proximity sensors [16] are sensors that measure the distance to an object by measuring the reflection intensity of infrared rays, but in this paper, we use them for detecting the presence

of holes. By comparing the maximum reflection intensity of the four proximity sensors and the threshold value, the presence or absence of detachable elements are determined, and by further comparing the values between the proximity sensors, the number and arrangement of holes are estimated. The result of the experiment of visualization of an actual robot as an evaluation is shown in the video attachment.

IV. BODY CONFIGURATION SHARING SYSTEM

A. Overview of Proposed System

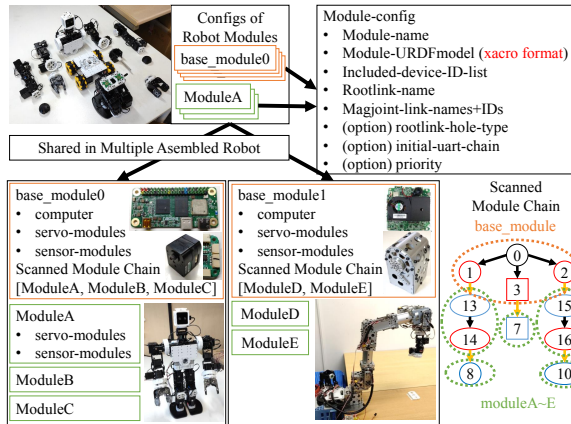


Fig. 5: Overview of Body Configuration Sharing System.

For the software system shown in Fig.5, the following two components are unique in this study.

- 1) Modulitized robot models and implemented to the connection of them and use the same multiple modules
- 2) Implemented the dynamic connection state-switching function of modules based on the state of the actual robot composed of modules.

Regarding modularization, merging, and reuse of robot models, defining robot models in a single file which can be used in multiple locations as modules is important, rather than being defined as different robots in various configurations when the same end-effector geometry is commonly used in the right hand and left hand or in various robots.

In this study, while using URDF[17] as the basic file format of the robot model, namespaces for link names and joint names are given as arguments using xacro[18], the macro that can be used in the URDF description. This function allows robot models to be used as submodels by other robot models and used in multiple locations, and we can describe connection relationships between the connection points of the links. Namespaces are given using the information of connection points defined by Magjoint-link-names in base-moduleX and ModuleY in Fig.5.

B. Method of Making Scanned Module Chain

Using the base-moduleX and ModuleY information shown in Fig.5, we present below the steps to configure the Scanned Module Chain.

- 1) Obtain the IDs of the devices present in the communication system of the body.

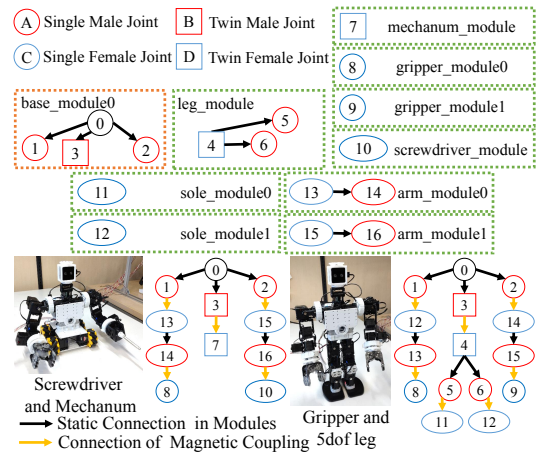


Fig. 6: Overview of Sample of Scanned Module Chain.

- 2) Match the obtained IDs against the expected modules
- 3) Outputs the state of connection between modules as relative position and posture in the coordinate system to combine the whole

To estimate the connected modules, we obtain the IDs of devices that exist in the communication system. The system does not explicitly provide information on devices that may be connected but the main board sends commands from the upper level to the lower level to scan for devices that are present in the communication system.

Next, from the list of device IDs obtained, the connected modules are estimated. We give the set of basemodulesXs and ModuleYs in a specific task in the Fig.5 in advance. When using the ALDMag, we can change the points where the same modules are connected, so it is necessary to describe them so that they do not depend on the communication system of the body, and the ID that each device has is described as Included-device-ID-list defined in the Module-config. Furthermore, we can use the placement of holes in the joint to distinguish each module, and the placement and direction of the holes are estimated using the method shown in Subsection III-D.

Finally, the connection status between modules is output as TF[19]. Here, the relative positional posture among the connection points is output as the TF, using the coordinate system of the connection points defined in Fig.5 and the corresponding Magjoint-link-names and connection direction information. For this purpose, it is necessary to determine the order in which the modules themselves are connected and to describe the Scanned Module Chain. On the other hand, the half-duplex UART communication system used in this study cannot detect the order in which devices are connected, so we define the priorities of modules manually in this study. In this case, priority was arbitrarily determined, but because end effectors, for example, are always the ends of limbs and base-moduleX has the property of coming to the root link side, priority can be determined automatically to some extent.

V. EXPERIMENT

A. Evaluation of Durability of ALDMag

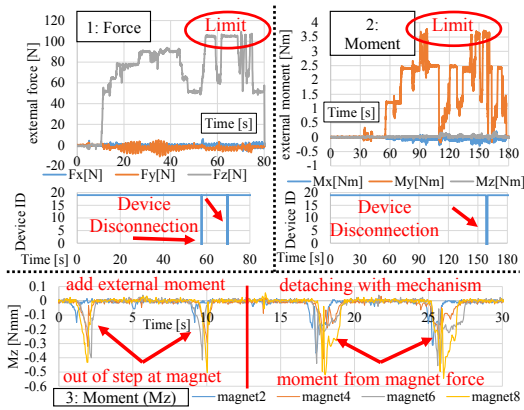


Fig. 7: Result of Evaluation of Durability of ALDMag.

We show the results of the performance evaluation experiments of ALDMag in Fig.7.

We evaluated the ability of ALDMag to maintain the mechanical and electrical connection while subjecting it to vertical forces $F_z(1)$ and shear forces and moments $F_x, M_y(2)$. When a vertical force of F_z was applied (1), a temporary loss of communication with the device connected via ALDMag occurred at a maximum of about 105N, and the mechanical connection was maintained without damage even when a maximum of about 270N was further applied. When moment M_y was given (2), a temporary loss of communication occurred at a maximum of about 3.7Nm and was not broken even at a maximum of about 9.1Nm. These results show that although the maximum load that can be mechanically withstood is large enough for the dead weight of pair of ALDMag (0.441[N]), communication with the device is broken when a certain amount of load is applied.

Finally, when the moment M_z was given (3), the allowable load was different in the direction of the moment because the mechanism was asymmetric concerning the direction of rotation. When the mechanism was turned in the direction where the protrusion on the surface of the mechanism was trapped (left rotation), the mechanism was able to withstand a large load without separating from each other (we show the graph in the video attachment). On the other hand, when the magnets are rotated in the direction in which the protrusion is separated (right rotation), the magnet pairs are pulled apart, and we show the result in the bottom part of Fig.7. The measurement was made by varying the number of magnets on the Female Joint side from 2 to 8, and it was found that the tolerance was about $-0.15[Nm]$ with 2 magnets and about $-0.42[Nm]$ with 8 magnets. When the female mechanism was separated by rotating the Lockring to the right as shown in Subsection III-C, the same measurement results showed that the separation could be performed by applying loads equivalent to the allowable torque described above.

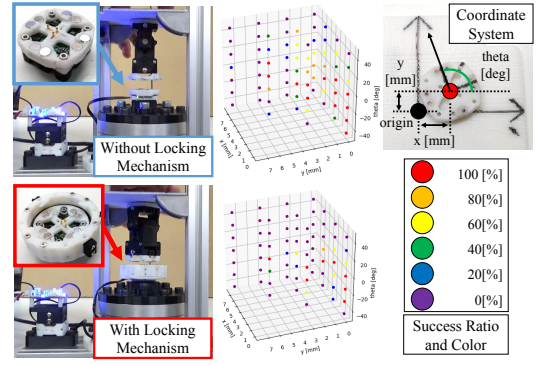


Fig. 8: Success Ratio of Junctioning.

B. Evaluation of Junctioning Mechanism of ALDMag

We show the results of the evaluation of the merging performance of ALDMag in Fig.8. Since ALDMag can be merged using only permanent magnets without including the locking mechanism, we compared those without the locking mechanism and those with the mechanism. We opened 10.5[mm] between the Male and Female Joints, dropped the parts including the Female Joint (8 magnets), and performed each trial 5 times to see if the parts could be joined while in the reference position. We changed the distance $x, y[mm]$ between the drop position and the origin and the rotation angle $theta[deg]$ in each setting. As shown in the results, those without the locking mechanism were able to merge with a higher probability than those with the locking mechanism. In addition, the overall trend was that the success rate was higher for those with negative angular error theta, i.e., those in which the female joint rotated to the right, compared to those with the same degree of leftward.

C. Evaluation of Attach and Detaching Motion by Humanoid

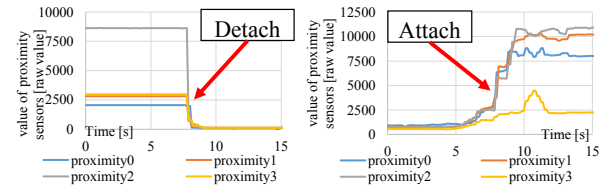


Fig. 9: Result of Evaluation of Attaching and Detaching.

We show the results of an experiment of detaching and attaching motions by a humanoid in Fig.9. In this experiment, the platform on which the end-effector parts can be placed was also configured and placed in a posture that facilitates natural merging after separation, to verify the principle of continuous paw exchange. In addition to the magnetic force, the joint torque of the humanoid is also used for the merging of the mechanism. For the separation, it is necessary to apply the moment greater than that required for the end-effector separation in the Fig.7. The maximum number of magnets that can separate the end-effectors is four, and the robot can detect detachment using 4 proximity sensors.

In the attaching experiment, the Male Joint is pressed against the Female Joint of the end effector, and contrary to

the detaching experiment, the fewer the number of magnets, the greater the pressing force required. As a result of the experiment, even a female joint with a minimum of two magnets can be merged, and the attachment was detected by the sensors. We show the result of the visualization in the video attachment.

D. Experiment of Task with Whole Robot Assembling

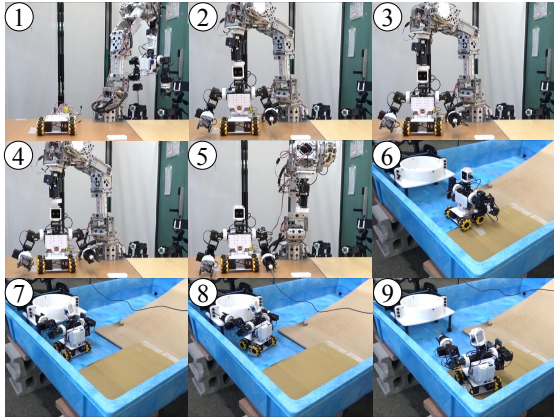


Fig. 10: Picture of Experiment including Robot Assembling.

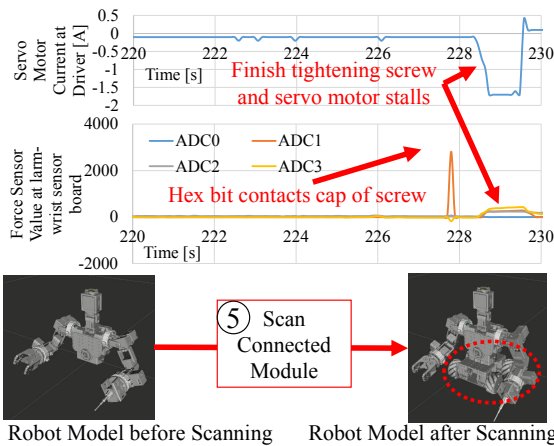


Fig. 11: Result of Experiment including Robot Assembling.

For the assembly and operation experiments of the robot with electric driver end-effector and mechatronics wheels, we show the appearance of the experiment in Fig.10 and the results of the experiment in Fig.11. In ① – ③, a life-size arm-type robot[20] lifts the upper body of the small robot equipped with end-effectors on both arms and moves it to the top of the cart with mechatronics wheels, then merges the torso and cart using Twin Male, Female Joints, ④ and in ④, the Lockring of JMP at the end of the arm was driven by the servo motor to detach the small robot. In ⑤, the small robot scans the IDs of devices on its whole body and detects the newly connected cart with mechatronics wheels as shown in the bottom part of Fig.11. In ⑥ – ⑨, the small robot was remotely piloted to stably descend the hill in the environment using the cart with mechatronics wheels and to realize the task

of tightening screws in the environment with the electric screwdriver end-effector on its left arm. In this experiment, it was assumed that the mechatronics cart was chosen to move stably in the environment of a hill. In the screw tightening task, we can detect the end of screw tightening from the force sensor of the ALDMag and the change in the current value of the motor of the electric driver module.

VI. DISCUSSION

We discuss the results of the experiments. Regarding the evaluation of ALDMag shown in Subsection V-A, the mechanism bore the vertical force F_z which is enough for the small scale robots, but when we applied the moments M_y and M_z , the device was prone to disengage and the magnets were prone to separate. By modifying the fabrication method of the mechanism, the gap inside the mechanism can be made smaller while maintaining the proposed function, which will reduce the deformation inside the mechanism and enable it to withstand larger loads.

As shown in Subsection V-B, the mechanism was able to tolerate a certain error of position and degree in attaching movements. On the other hand, in the experiments shown in Subsection V-C, a certain amount of arbitrary positioning was necessary when performing the detachment/attachment operation, so it is highly important to introduce sensor feedback using proximity, force, vision sensors to realize actual sequential operation.

For the experiment shown in Subsection V-D, a series of movements, such as moving downhill and tightening screws, realized by the robot which is assembled by the mechatronics cart module and the robot body with wide Connectable Twin Male and Female Joints without the locking mechanism. The ALDMag is also used at the base of the shoulder, and the robot was able to maintain a posture in which the arm was extended horizontally when tightening the screws. On the other hand, since this study assumes that all the information on the modules that can be connected is already in the system, it is necessary to configure the newly connected module to be able to transmit its configuration to a higher level to use modules configured by a third party.

VII. CONCLUSION

In this paper, we propose Attach-Lock-Detachable Magnetic Coupling(ALDMag) mechanism and the system to share and reuse the modularized body information as the method to give humanoids the ability to change the body functions and structures of modular robots with the arm-type robot. Using ALDMag and the body information management system, we demonstrated the effectiveness of the proposed method through experiments of partial assembly of the small robot by the life-size arm and experiments including movement in the environment and environmental contact behavior. In the future, we would like to construct a method that automatically selects the body elements to be used from task settings and apply the method to robots of various scales, not limited to humanoids.

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