

# Omni-Directional Connector for Self-Reconfigurable Robots

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**Abstract**— Robots are used for various industries and must adapt to various environments. For this purpose, machine learning has been extensively studied as a method to output motion adapted to the environment. However, if the robot's hardware is not adaptable to the environment, the range of the robot's motion using machine learning is limited. Therefore, this paper focuses on self-reconfigurable robots that change their own shape to adapt to various environments. Most self-reconfigurable robots are assembled with connectors oriented facing in a specific direction; however, their assembly is time-consuming because of the required alignment of the connectors. Therefore, this paper presents an omni-directional connector for self-reconfigurable robots and proposes a fast assembly.

## I. INTRODUCTION

In recent years, robots have been used in various industries, such as manufacturing and services, to improve productivity. To enable their use in various industries, methods for using robots in various environments must be considered. Currently, separate environments are created for robots to operate; however, they cost a lot to create, and tasks using robots are limited by the quality of the environment, which must be solved to promote industrial automation. For this purpose, considerable research has been conducted on achieving robot motion that adapts to the surrounding environment from control based on machine learning [1-3]. However, methods that use machine learning to adapt to the environment require that the robot's hardware have sufficient performance to adapt to the environment. Therefore, if a robot is not mounted with hardware that can adapt to the environment, it will be unable to adapt, even if machine learning is used. This problem can be solved with a single robot mounted with multiple functions that can adapt to various environments; however, this requires a robot that has excessive functions for the task, which also leads to a larger robot size. In addition, adapting a robot to a new environment requires the redevelopment of a robot with functions that are suitable for that environment.

To solve this problem, we focused on swarm robot systems that adapt to various environments based on the cooperative work of multiple robots. A swarm robot system has the advantages of flexibility and scalability, as it can select a combination of functions based on the surrounding environment and the number of robots according to the size of the task. Based on these advantages, the inability to adapt to the environment caused by the hardware can be avoided. In particular, self-reconfigurable robots that can adapt to their environment by changing their shapes have been proposed as swarm robot systems to overcome this hardware limitation. Self-reconfigurable robots [4-18] are connected to each other

using connectors mounted on each robot and can operate as an aggregate of robots that can transform into a variety of shapes. This behavior, in which robots connect to each other to form an aggregate, is known as self-organization. To achieve this self-organization, the connector between robots plays a crucial part as an underlying technology, and the structure type of connectors that would be used for self-organization should be discussed.

## II. RELATED WORK

Murata et al. developed the M-TRAN [7], which is a self-reconfigurable robot with mechanical connectors for movable hooks. Using a similar method, gripper connectors were used with a swarm bot [8] by Mondada et al. Two types of mechanical connectors, active and passive, were used in SYMBRION [9]. SMORES-EP [10] by Lui et al. and ElectroVoxel [11] by Nisser et al. utilized magnetic forces as another connection method. Although these connecting methods can connect robots tightly, the position and direction in which robots can be connected are limited by the orientation of the connectors. Because of this problem, robots take a long time to assemble because of the positioning required to align connectors. The more frequently robots change the shape of the assembly, the longer the time consumed. In this study, we developed omni-directional connectors for self-reconfigurable robots and proposed a fast assembly method.

Self-reconfigurable robots with omni-directional connectors have also been developed [12-14]. A hook connector was used in the Swarmanoid [12] developed by Dorigo et al., and grooves that could be connected to this hook were placed on the sides of the robot in all directions so that each robot could be connected in all directions. However, because the male connector is oriented in a specific direction, a robot using the male connector cannot connect in all directions. Therefore, robot positioning is indispensable for connections.

The Catom [13] by Lakhlef et al. was also connected in all directions using electromagnets. However, a robot that can be mounted using this method must be small owing to the weak magnetic attraction force. Increasing the electric power increases the magnetic attraction force; however, the resulting power consumption is also high because of the numerous electromagnets used.

To solve the above problems, this study developed a connector that can be connected from omni-directions based on a genderless structure without male/female connectors and without consuming a large amount of power, such as

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electromagnets. To develop this connector, this study focuses on the frictional force. The concept of this research was inspired by a structure in which strong frictional forces were generated from alternating layers of paper. This frictional force can connect paper to paper using a strong force without consuming electric power. Therefore, we developed a connector that generates frictional force from a similar structure and mounted it on a robot to enable omni-directional connections.

### III. MOBILE ROBOT

An omni-directional robot with three omniwheels by Viston Robotics, as shown in Figure 1, was used in this study using the proposed method. An omniwheel is a wheel with multiple rollers. The robot could move omni-directionally without changing the direction of its body. This robot makes omni-directional possible connections easier.

### IV. OMNI-DIRECTIONAL CONNECTOR

In this study, frictional forces were used to connect the robots. As mentioned above, it is desirable to use a structure that can generate a frictional force similar to that generated by the overlapping layers of paper. However, paper is difficult to use as a material for connectors because of its low durability and excessive softness. Therefore, instead of paper, a sponge sheet was used in the design of the connector to provide the frictional force needed. The connector structure is shown in Figure 2. This layer of sponge sheet is referred to as the "connection unit." Figure 3 illustrates the process of connecting the two robots. As the connecting robots approached each other, the sponge sheets of the connection unit on each side were connected such that they overlapped. Although this sponge sheet is made of a material with a high friction coefficient, it is difficult to connect the robots tightly to the frictional force of the overlapping sponge sheets in the second step shown in Figure 3. Therefore, the frictional force was increased by adding a component that was pressed down from above, as shown in the fourth step of Figure 3. In this paper, this part to be pressed down is called the "lock/unlock unit." By moving the lock/unlock unit up or down, a robot can switch between applying and not applying pressure to the



Figure 1. Omni-directional mobile robot.

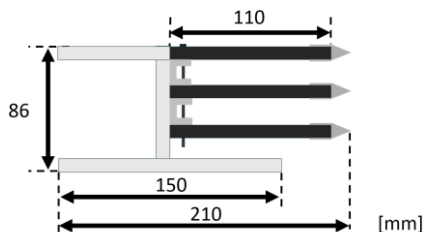


Figure 2. Size of connection unit.

connection unit to lock or unlock the connection between robots. The lock/unlock unit is described in Section IV.C.

#### A. Connection unit

The sponge sheet used in the connection unit was made of rubber with a high frictional force to prevent the sheets from overlapping by simply moving them close together, as shown in Figure 3. Therefore, the sponge sheet was designed so that the other sheet could be easily inserted into the space between them by attaching a sharply shaped component made of a slippery material to the tip of the sheet.

The suitable length of the gap between the sheets was also examined. The larger the space between the sheets, the easier it is for the other sheet to penetrate. However, the redundant space between the sheets reduces the strength of the connection when pressure is applied. Figure 4 shows examples of the examined patterns with spaces of 30 and 20 mm. With the 30 mm width, a large space was observed between the sheets, whereas with the 20 mm width, the space between the sheets was reduced. Therefore, in this study, the width between the sheets was set to 20 mm.

#### B. Sponge Sheet Material

As mentioned previously, sponge sheet sagging is a problem that must be solved. To solve this problem, three sponge sheet patterns, as shown in Figure 5, were used to confirm the effectiveness of the connecting process. In both cases, the spacing between sponge sheets was 20 mm.

The sponge sheet in Figure 5(a) is made of chloroprene rubber. This rubber has a wide range of excellent resistance characteristics. However, this sheet sags owing to the weight of the sharp-edged parts attached to the tips. Under this condition, the sheets frequently do not overlap even when the connection unit is approached.

The sponge sheet in Figure 5(b) is made of polyolefin foam. This material is slightly harder than chloroprene rubber.

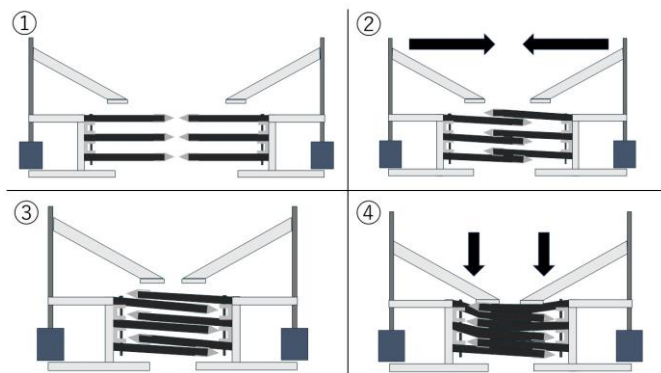


Figure 3. Process of connecting robots.



Figure 4. Spaces between sheets.

Therefore, compared to the sheet presented in Figure 5(a), the sheet in Figure 5(b) did not sag. The sheets were also soft enough to be inserted into the spaces between them, owing to the characteristics of the sponge. However, the sheets began to sag over time. Consequently, connecting with this sheet became difficult because the sheets did not overlap in the procedure shown in Figure 3.

The sponge sheet shown in Figure 5(c) consists of an aluminum plate sandwiched between sheets of chloroprene rubber. The thickness of the chloroprene rubber sheet was 5 mm and that of the sandwiched aluminum plate was 0.5 mm. This sheet did not exhibit sagging compared to the sheet shown in Figure 5(b). However, when testing the connections using these sheets, it was difficult to insert the sheets into the spaces between them. Therefore, a connection unit could not be connected using this sheet.

Sheets of fan-cut chloroprene rubber with a 1.2 mm wire at the edge of the sheets are shown in Figure 5(d). Chloroprene rubber sheets were used because sheets made of polyolefin foam are hard, and their high frictional force makes it difficult to thread wires through them. As shown in Figure 5(d), the sheet did not sag and maintained a shape suitable for the connection. This shape was maintained over time. Thus, the omni-directional connectors used in this study were created using this sheet.

The connection unit should achieve an omni-directional connection by mounting a layer of sponge sheets surrounding the robot. However, because the robot developed in this study is a prototype and several changes were needed in the mounted parts, the sheets were mounted in four sections for easy mounting and removal.

### C. Lock/unlock unit

The pressure on the connection unit increased the frictional force. Figure 6 shows the structure of the lock/unlock unit. Pressure was applied by moving the pressing unit up and down. The lock/unlock unit was fabricated using a 3D printer. ABS and epoxy resin were used as materials. The pressing part in the lock/unlock unit was circular to enable pressure to be applied to the entire connection unit. A lead screw was used for the up/down mechanism of the lock/unlock unit. The conical pressure

component was fixed to prevent it from rotating, and the lead screw rotates by driving the motor in the center, enabling the up-and-down mechanism of the pressure component. The motor and lead screw were connected and rotated using a coupling.

The size of the lock/unlock unit is shown in Figure 7. A conical shape with a wide space in the center was adopted to allow easy maintenance of these parts, as drive systems such as motors and lead screws were mounted in the center. Because some methods are impossible depending on the overall configuration, especially in the drive area, we decided to use the simplest possible drive method that does not affect the configuration of the surroundings because the system is still in the prototype stage and the configuration may undergo extensive changes in the future. The motor consumes only about 5W to run the motor and actuator only during the merging operation, so unlike conventional electromagnet-based mechanisms, there is no constant power consumption. The lock/unlock unit exerts a pressure of 56.85 N/m<sup>2</sup> on the connecting unit.

## V. EXPERIMENT

Omni-directional connectors developed from these designs were examined for their ability to achieve stable connections. The experimental setup is shown in Figure 8. In this experiment, the connections were examined at various robot positions; the three patterns are shown in Figure 8. Two robots mounted with omni-directional connectors were used in the experiment. To check the overlapping condition of the sheets, only half of the connection unit was mounted on one of the robots. The connection is achieved by moving the robot closer to a stationary robot. The robot was only commanded to move in a specified direction before connecting, with no positional adjustments. Therefore, in this experiment, the time

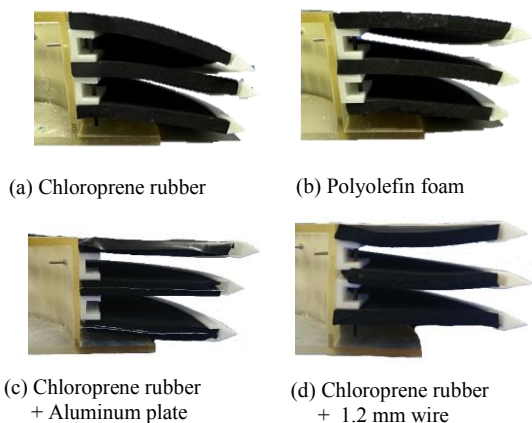


Figure 5. Patterns of sponge sheets.



Figure 6. Lock/unlock unit of the omni-directional robot.

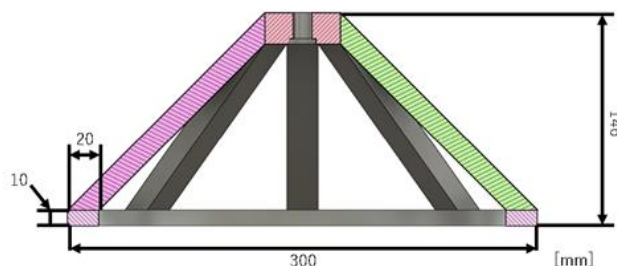


Figure 7. Size of lock/unlock unit.

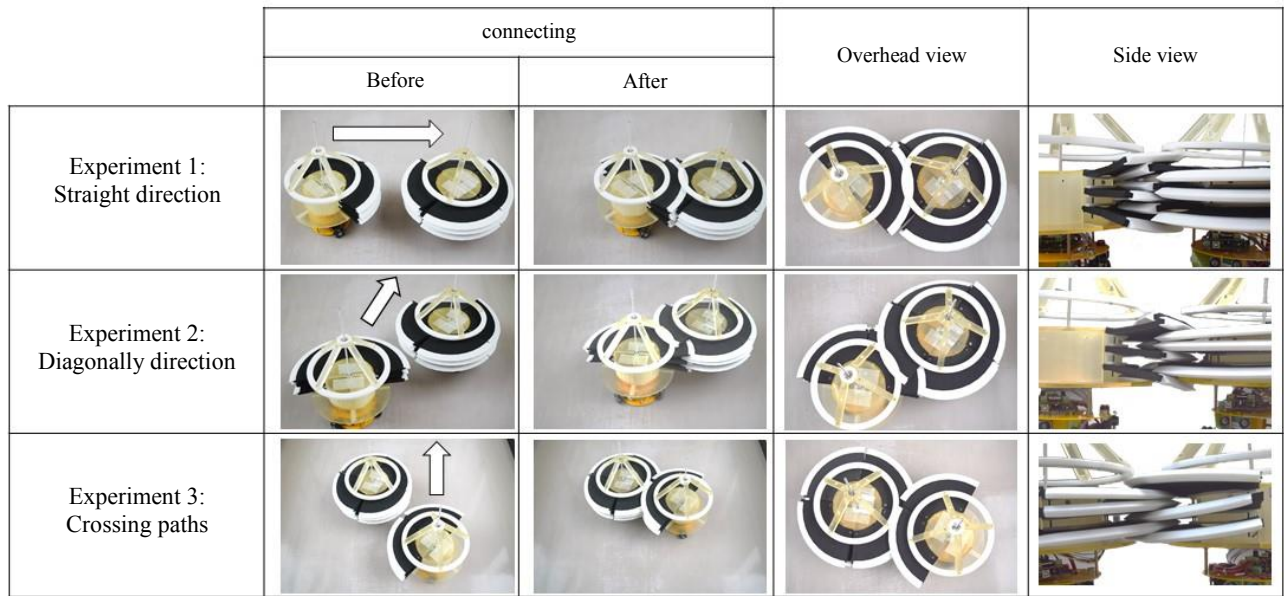


Figure 8. Experiments in connecting robots.

elapsed from the starting position to the connecting position of the robot is approximately 1 s. If these experiments proved that robots could be stably connected using the proposed connector, a high-speed assembly with self-reconfigurable robots, which was not possible using previous methods, can be realized.

In Experiment 1, the robot was connected by making it move straight to another stationary robot. In Experiment 2, the robot was connected in an oblique direction by making it move toward the misposition of another stationary robot. In Experiment 3, the robot was connected with another stationary robot by crossing their paths. The robots were moved and connected at approximately 20cm/s. The experiment was conducted under the assumption that the connection was made on level ground. In all experiments, the sponge sheets successfully overlapped. The positions of the overlapped sheets were also below the pressurized area, allowing the lock/unlock unit to lock/unlock.

In Experiment 2, the robot was connected by making it move in a non-linear direction toward the other robot. In this experiment, the sheets sometimes overlapped. In this connection, there is a dividing boundary between the sheets at positions where they overlap. Consequently, the sheets on either side of the boundary overlapped differently. Owing to this problem, the sheets failed to be completely inserted into the spaces between the sheets. The problem in Experiment 2 was solved by mounting the sheets of the connection unit in a non-divided structure. As mentioned above, the sheets were divided into four sections for ease of maintenance, which was not essential. This problem can be solved by mounting the sheet in a single circular sheet.

Experiment 3 examined the connection between a robot and a stationary robot crossing paths. In this case, the connection was achieved by overlapping the sheets. However, compared to Experiments 1 and 2, the sheet was not inserted deeply in Experiment 3. When the robot tried to move forward further from this connected position, it could not move

forward because the connected part was caught. The proposed connector was designed such that robots could move freely when the lock/unlock unit was raised, and the robots were connected to each other only when the lock/unlock unit was lowered. Therefore, the connector in this study must be improved to allow the robot to pass through even if it is in contact with the connecting unit if the lock/unlock unit is not lowered in Experiment 3. The reason for this problem was thought to be the excessively strong frictional force from the sheet. To solve this problem, the sheet can either be shortened or fabricated from a material with less friction. As it is difficult to select a new material suitable for the sheet, a method for shortening the sheet should be chosen.

## VI. CONCLUSION

This paper focuses on self-assembling robots that can adapt to their surrounding environment and the problem of excessively slow assembly due to the connectors used for connecting robots. To solve this problem, this paper proposes an omni-directional connector and demonstrates an assembly method that does not require positioning to align the connectors. The experiments in this study showed that a robot mounted with a prototype of this connector can achieve the connection without positioning. This connecting process only took approximately 1 s, and a connector essential for the high-speed assembly that this study aims to achieve was developed. This assembly achieved high-speed assembly in a few seconds, which was not possible in previous studies. We have also been examining the assembly by robots without proposed connectors, and as shown in Figure 9, robots assembled straight-line and triangular shapes in less than 10 seconds from a connecting in all directions. The movements of the swarm in Figure 9 were generated by multi-agent deep reinforcement learning.

This time, the materials were selected based on the friction required for merging and the degree of sagging of the sponge sheet. The chloroprene rubber used in this test has a durability of about 20 years, but in the future, it will be necessary to verify whether this connector can withstand long-term wear and tear and a variety of environments.

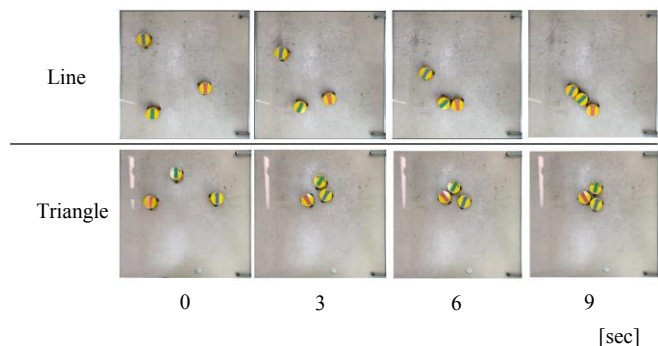


Fig. 9. Assembly with omni-directional robots

In the future, we aim to achieve assembly of any shape by self-assembling robots using these connectors. To assemble the robots into arbitrary shapes, no positioning is required to connect them. However, rough positioning of the robots is necessary to create the shape of the assembly. This assembly requires a method for determining the relative positions of the surrounding robots. An infrared device [19-20] developed by the authors was used for sensing. This infrared device was mounted by integrating the local communication and position sensing between the robots. Because this infrared device achieves seamless omni-directional communication/sensing, it was suitable for the seamless omni-directional connectors developed in this study. Combining this infrared device with the proposed connector further enhanced the feasibility of the high-speed assembly.

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