A Self-Reconfigurable Modular Robot: Reconfiguration Planning and Experiments

Eiichi Yoshida, Satoshi Murata, Akiya Kamimura,
Kohji Tomita, Haruhisa Kurokawa, and Shigeru Kokaji
Distributed System Design Research Group, Intelligent Systems Institute,
National Institute of Advanced Industrial Science and Technology (AIST)
1-2-1 Namiki, Tsukuba-shi, Ibaraki 305-8564 Japan
e.yoshida@aist.go.jp

Abstract

This paper addresses a reconfiguration planning method for locomotion of a homogeneous modular robotic system and conducts an experiment to verify that the planned locomotion can be realized by hardware. Our recently developed module is self-reconfigurable. A group of the modules can thus generate various three-dimensional robotic structures and motions. Although the module itself is a simple mechanism, self-reconfiguration planning for locomotion presents a computationally difficult problem due to the many combinatorial possibilities of modular configurations. In this paper, we develop a two-layered planning method for locomotion of a class of regular structures. This locomotion mode is based on multi-module blocks. The upper layer plans the overall cluster motion called flow to realize locomotion along a given desired trajectory; the lower layer determines locally cooperative module motions, called motion schemes, based on a rule database. A planning simulation demonstrates that this approach effectively solves the complicated planning problem. Besides the fundamental motion capacity of the module, the hardware feasibility of the planning locomotion is verified through a self-reconfiguration experiment using the prototype modules we have developed.

1 Introduction

In recent years, the feasibility of reconfigurable robotic systems has been examined through hardware and software experiments in two dimensions [1]–[8] and three dimensions [9]–[16]. Specifically, a self-reconfigurable robot can adapt itself to the external environments. It can also repair itself by using spare modules owing to the homogeneity of the module. This paper focuses on the reconfiguration planning for a new type homogeneous, self-reconfigurable modular robot that enables movement in three dimensions by changing the configuration. Its various potential applications include structures or robots that operate in extreme environments inaccessible to humans, for example, in space, deep sea, or nuclear plants.

Hardware of three-dimensional self-reconfigurable modular robots is classified into two types, the lattice type [9, 10, 17, 19, 18] and the linear type [13, 16]. The former corresponds to a system where each module has several fixed connection directions, and a group of them can construct various static structures like a jungle gym. However, it is difficult for such a system to generate wave-like motions involving many modules at the same time. In contrast, the latter (linear type) has a shape that can generate various robotic motions like a snake or a caterpillar, but self-reconfiguration is difficult.

There have been a number of studies on the software of lattice-type reconfigurable modular robots. Distributed self-reconfiguration methods have also been developed for two- and three-dimensional homogeneous modular robots [5]–[7],[14],[18]. The first method [5] has already been implemented in a two-dimensional hardware system with more than ten modules to demonstrate the self-assembly and self-repair capacity. The others have been investigated in simulations to be implemented in hardware in future developments. There are also other methods based on centralized planning. Kotay et al. [11, 22] developed robotic modules and described a global motion synthesis method for a class of module groups to move in arbitrary directions. Ünsal et al. [17] reported two-level motion planners for a bipartite module composed of cubes and links, based on a heuristic graph search among module configurations.

We have recently developed a new type of modular robotic system that has both lattice type and linear type features [15]. The module has a simple bipartite structure in which each part rotates about an axis parallel to the other's by a servomotor and has three magnetic connecting faces. This recent module can form various shapes, such as a legged walking robot or a crawler-type robot (see Multimedia Extension 4 [M4] for an example of transformation between these locomotion modes). However, its reconfiguration planning is not straightforward because of restricted degrees of freedom and non-isotropic geometrical properties of mobility of a module unlike lattice-type modules in previous research. When a module moves from one position to another, a sequence of necessary motions must be duly planned for each individual local configuration. In addition, a vast search space must be explored to examine the interchangeability between two arbitrary module configurations and avoid collisions between modules in three-dimensional space. These properties of the module make it difficult to identify generic laws of motion planning and to apply our distributed methods directly.

This paper therefore concentrates on developing feasible reconfiguration planning for locomotion of a particular class of lattice-type module clusters by narrowing the motion search space as the first step to a more general planning method. The module cluster to be investigated is a serial collection of cube-like blocks, each of which is composed of four modules. Using this locomotion mode, the self-reconfigurable robot can surmount large obstacles and gaps that are difficult for wheeled or legged mobile robots to handle, although it has a disadvantage of low velocity. Another advantage over other robot types is its versatility, which simplifies the structure of the robot since various functions can be realized without adding supplementary parts.

In this paper, we propose a two-layered planner that consists of global and local planners to guide a class of module clusters along a desired trajectory. The former part of the planner provides the *flow* of the cluster, which corresponds to a global movement that enables locomotion along the trajectory. The latter generates local cooperative motions called *motion schemes* based on a rule database. The rules take into account the non-isotropic geometrical properties of module mobility by associating an appropriate pre-planned motion scheme with each different local configuration. This method is classified as a centralized method.

After introducing the design and basic motion of the module in Section 2, we provide detailed descriptions of the planning method in Sections 3 to 5. In Section 6, fundamental module motions are experimentally confirmed using the prototype modules. The feasibility of the motion plan is then verified through a many-module experiment. Improvements required for the hardware prototype and planning software are also discussed.

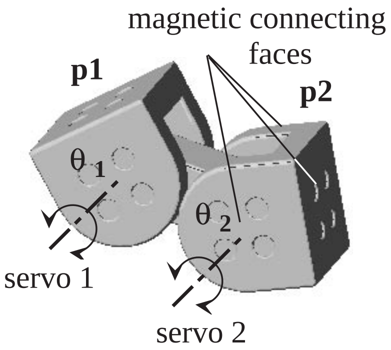


Fig. 1: A robotic module [M1].

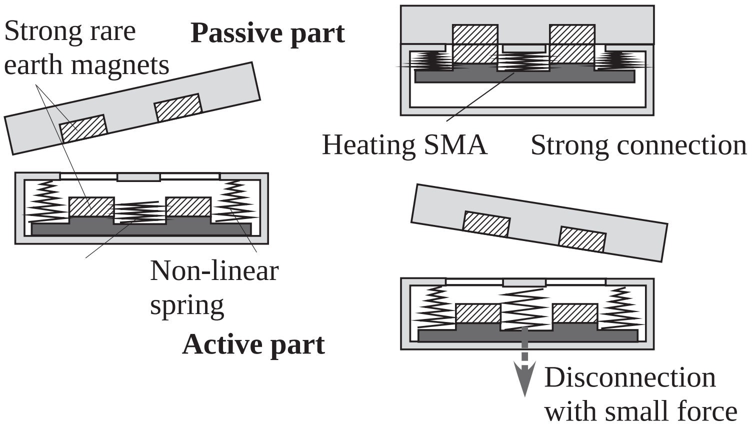


Fig. 2: Connection mechanism [M1].

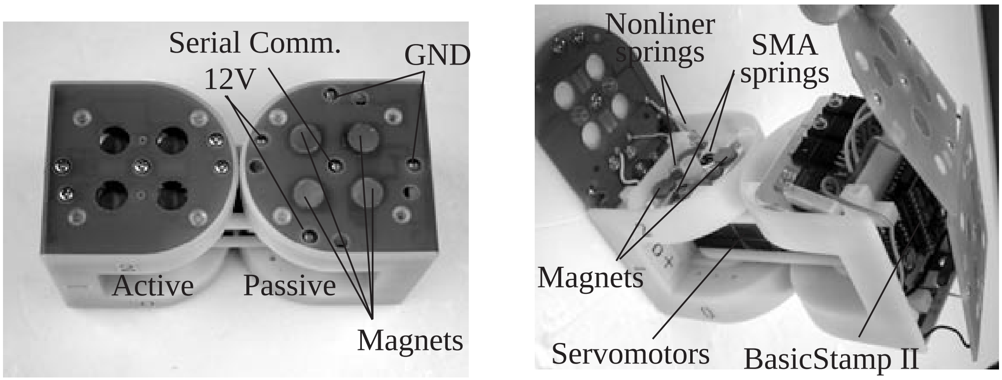
2 Hardware Design and Basic Motions

2.1 Hardware Overview

The developed module consists of two semi-cylindrical parts connected by a link part (Fig. 1). Servomotors are embedded in the link part so that each part can rotate by 180°. The semi-cylindrical parts of the module are labeled p1 and p2. The rotational angles of these parts (θ_1, θ_2) are limited to either 0° or ±90° for simplicity. The unit length of the lattice grid is defined as the length between the two rotational axes of the module. A module therefore occupies two adjacent points in the grid.

Figure 3a shows the hardware of the prototype module. Each module has three surfaces to connect with other modules, and the connecting mechanism is based on an “Internally-Balanced Magnetic Unit” [20]. An *active* semi-cylindrical part (p1), which can be connected to only *passive* parts (p2) of other modules, has nonlinear springs and shape memory alloy (SMA) springs whose compression force is made slightly less than the magnetic force. By electrically heating the SMA springs, the total force of springs becomes larger than the magnetic force and the connection is released, as shown in Fig. 2 [15]. Figure 3b shows the internal structure of the module. The connecting surfaces also have electrodes for power supply and serial communication. All the connected modules can be supplied power from one module connected to the power source. This eliminates the tether entanglement that becomes significant in three-dimensional configurations.

Each module is equipped with a PIC microprocessor BasicStamp II that drives servomotors and SMA actuators. In the current development, all the modules are controlled from a host PC that provides motion commands through serial communication bus lines. One semi-cylindrical part is 6cm cube, and a module weighs approximately 400g. The SMA actuator is controlled by 200Hz PWM with a 60% duty ratio, 12V voltage and 2A average current.



(a) Hardware overview (b) Internal structure.

Fig. 3: Hardware module [M1].

2.2 Atomic Motion

Before introducing the reconfiguration planner, it is helpful to explain the *atomic motions* that are the simplest module motions of one or two modules. There are mainly three types of atomic motion, *pivot motion*, *forward-roll motion* and *mode conversion*.

Figures 4 and 5 show two different atomic motions on a plane, forward-roll and pivot motions, where the orientation of the rotational axes are different.

When a module makes a motion, one of the parts must be attached to another module, or fixed part, to maintain connectivity. This fixed part is called a *base part*. Atomic motions are achieved by alternating the base part properly. Here, the plane is also assumed to be filled by the connecting faces of the module that performs appropriate connection and disconnection operations to realize these motions. The module is said to be in *pivot mode* or *forward-roll mode* if it can perform one of these motions. Mode conversion is a two-module motion to convert from one mode to the other, where a

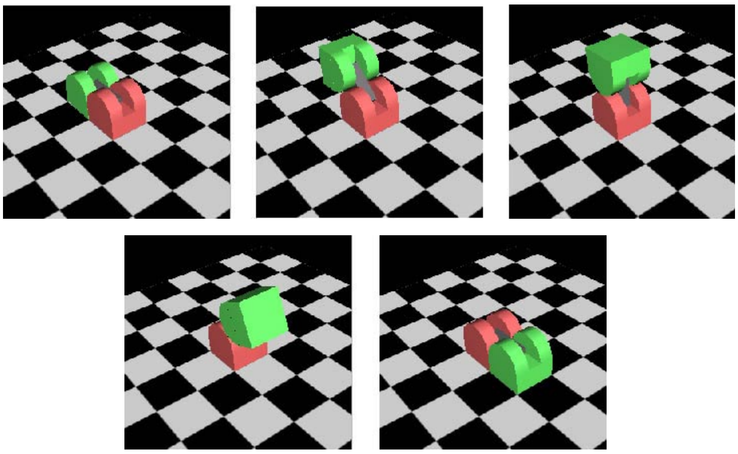


Fig. 4: Forward-roll motion [M1].

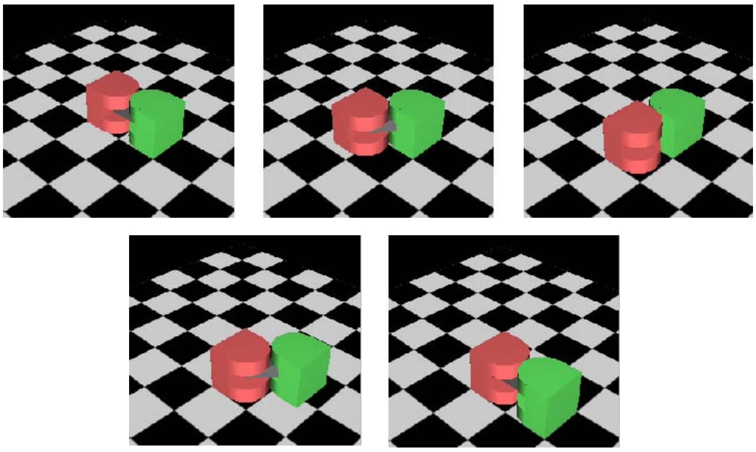


Fig. 5: Pivot motion.

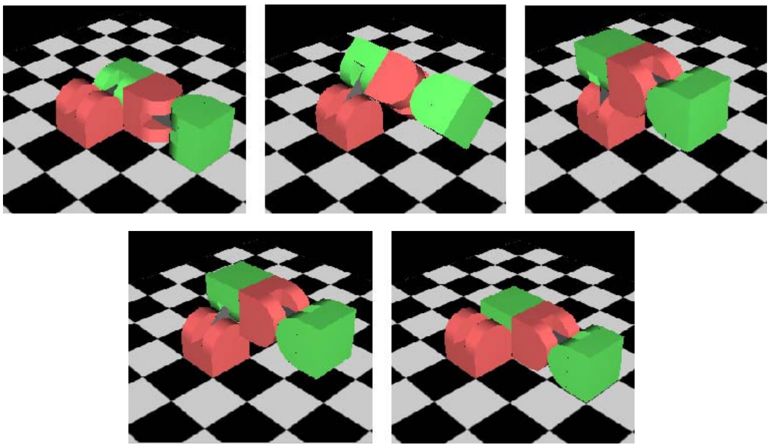


Fig. 6: Mode conversion from pivot to forward-roll.

helper module is required as illustrated in Fig. 6. Using modules in both forward-roll mode and pivot mode makes possible a variety of three-dimensional structures. Reconfiguration is performed by a *motion sequence*, which is a series of these basic module motions.

3 Planner Architecture for Block-based Locomotion

The goal of planning is to enable a class of a module cluster to trace a given three-dimensional trajectory in the lattice grid (Fig. 7). The trajectory corresponds to a path that the robot would traverse. Reconfiguration planning enables the module cluster to move in various environments as mentioned in Section 1. One of the examples of its application is a rescue robot. If external sensors are available, the robot can go into a narrow space, move around, and search for survivors in rubble by adapting its configuration to unstructured environments. Other examples include a planetary exploration robot and a plant inspection robot that are also required to go through environments with many obstacles.

The planner must generate an appropriate motion sequence so that the cluster motion can be guided along the desired trajectory.

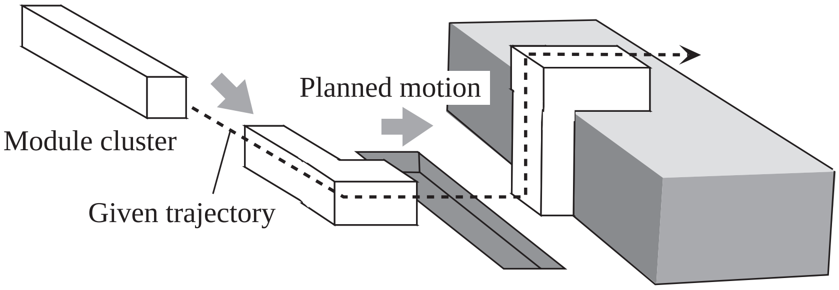
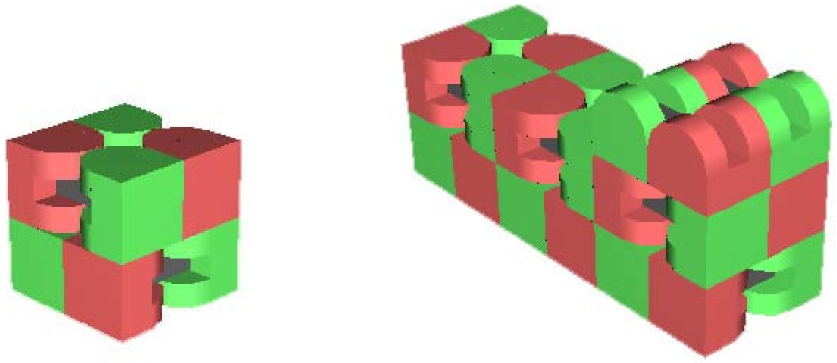


Fig. 7: Planning of cluster motion.



Block of 4 modules. Cluster of 14 modules with two converters.

Fig. 8: A cluster composed of two layers with two converter modules.

3.1 Locomotion by block-based cluster

The search space grows exponentially with the number of modules and the motion sequence length[1] when generating an arbitrary motion for an arbitrary configuration. To develop a feasible motion generator, we consider a particular class of module clusters (Fig. 8) composed of four-module *blocks* that resemble large cubes. All the rotation axes of the modules in a block are oriented in the same direction, while the directions of the link part in different layers are orthogonally placed.

We adopted this cube-like block from among several possibilities since it is the smallest block that has an isotropic shape that can be connected at any of its faces. This isotropic geometry enables easily configuring various sizes of 3D structures and maintaining the connectivity of all the modules in a cluster composed of these blocks. This block also has the advantage that it is simple to plan a global motion along a three-dimensional trajectory. Similar approaches using “metamodules” have also been reported to simplify planning of large-scale modular robots [21, 22].

A couple of modules that have different rotation axis directions, called converters, are attached to the top of the cluster. The converter modules are used to change the direction of the rotation axis of the modules in the chain cluster.

3.2 Planner architecture

Given the block-based trajectory of locomotion as the input, the motion of each module must be planned. However, the module’s non-isotropic geometrical properties make it difficult to obtain the motion sequence in a straightforward manner. Since a module has only two parallel rotation axes,

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[1] For N modules, $2^N - 1$ possibilities at maximum to determine which module to move every time they make motions. For each case, each module can take at most nine possible states for angles (θ_1, θ_2), even using discrete angle 0° and $\pm 90^\circ$. The fixed part selection has also two possibilities. The search space increases exponentially in the length of motion sequence as well.

its three-dimensional motion usually requires a combined cooperative motion sequence with other surrounding modules. The cooperative motion sequence must be carefully chosen in each individual local configuration to avoid collisions between modules or loss of connectivity during the motion. Since generally applicable laws have not been determined yet for planning these motion sequences, an available database of rules is necessary.

This paper proposes a two-layered motion planner consisting of the *global flow planner* and the local *motion scheme selector*. As shown in Fig. 9, the global flow planner searches possible module *paths* and *motion orders* to provide the global cluster movement, called *flow*, according to the desired trajectory. This is realized as the motion of a block such that the tail block is transferred toward the given heading direction. The local motion scheme selector verifies that the paths generated by the global planner are valid for each *member* module of the block according to the possible motion orders, by repeatedly applying *rules* from the database. The rule includes a local reconfiguration motion sequence, called a *motion scheme*, associated with an individual initial local configuration. If the given paths are validly determined for all the member modules in one of the motion orders, the selector updates the reconfiguration plan by adding selected motion schemes from the database. Otherwise, the selector tries the other possibilities generated by the global planner until a feasible plan is determined. The selector copes with the non-isotropic properties of module mobility by associating the cooperative motion with the corresponding local configuration in the form of rules. Note that this is a centralized planning method that assumes all the information about the modules in the cluster is available.

The method is scalable in the sense that planning of various length of cluster can be treated in the same framework, although it applies only to these particular serial clusters composed of four-module

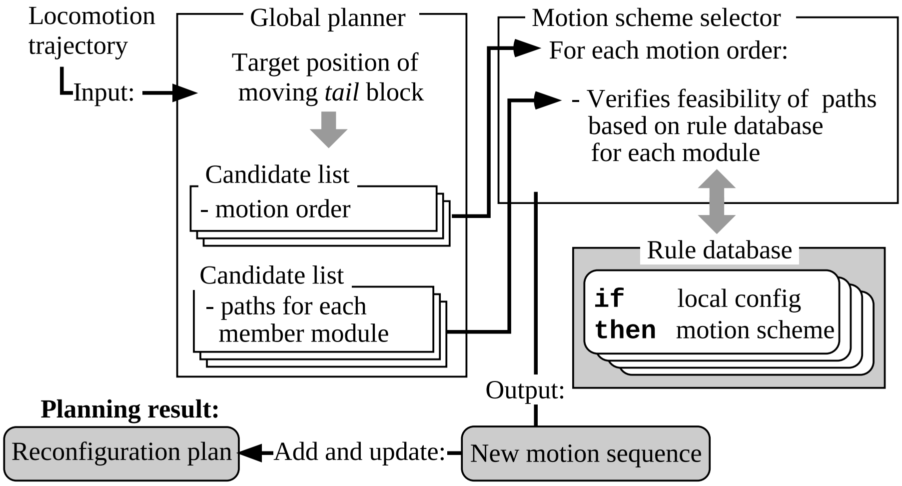


Fig. 9: Reconfiguration planner architecture.

cubic blocks.

In the planning described below, we assume for simplicity that only one motion scheme is allowed at a time and that the flow direction does not self-intersect and runs straight for at least two unit lengths during the cluster flow. We also assume in the planning that one module can lift only one other module, which comes from the limited torque capacity of the hardware.

4 Cluster Flow and Global Planner

The input to the global planner is the desired trajectory of the cluster. The cluster *flow* is defined as the trace of block motion, where the *tail* block is transferred to the other end as the new *head*, as shown in Fig. 10. While there are several ways of generating the cluster motion, we adopt a simple motion that sends modules individually toward the head. More practically, they move primarily by the forward-roll motion on the side of the cluster (Fig. 10).

The global flow planner outputs possible *paths* of each member module in the tail block and its *motion orders* in which the four member modules in a block move along the corresponding path to realize the desired flow. A *path* denotes the routing of a member module of a block. It is derived by

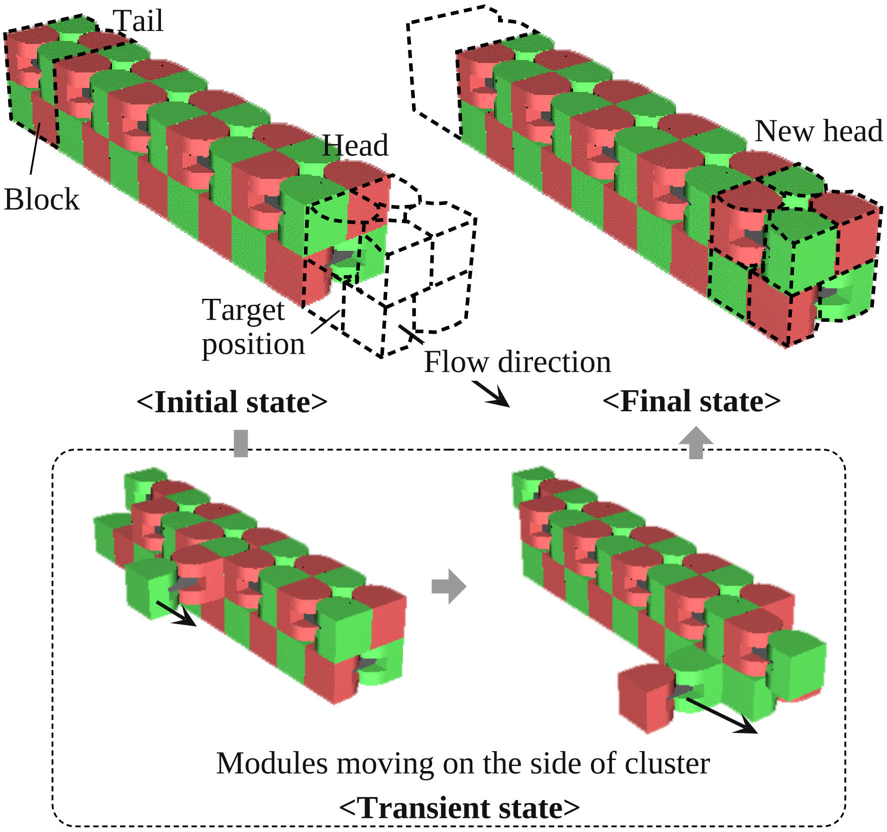


Fig. 10: Example of block motion.

tracing lattice positions on the side of the cluster, starting from the initial tail position, until the module reaches one of the target positions next to the current head block. A module may have multiple target positions and paths; their number varies depending on the cluster configuration. In Fig. 11 where module 1 is moving, there are two possible paths to the two target positions. The tail block becomes a new head block after it reaches the other end of the cluster. The next tail is then sent to the head, and so forth.

The global planner also outputs the possible *motion orders* of applying paths. These orders must be determined in such a way that the connectivity of whole cluster is maintained. For example, consecutive transportation of modules 1 and 2 in Fig. 11 is not allowed because the connectivity of the two lower modules is violated after the motion of the two modules.

5 Motion Scheme Selector

After the global planner outputs the possible motion orders and module paths, appropriate *motion schemes* must be selected for the modules to achieve the paths to generate the reconfiguration plan. The *motion scheme selector* plays this role by using the database of rules for local cooperative motion.

5.1 Selection overview

The selector outputs *a reconfiguration plan* as a unified motion sequence by collecting the motion schemes selected based on the rule database, as described below. Each rule includes a motion scheme associated with an initial configuration that is described as a connectivity graph. Here, the block

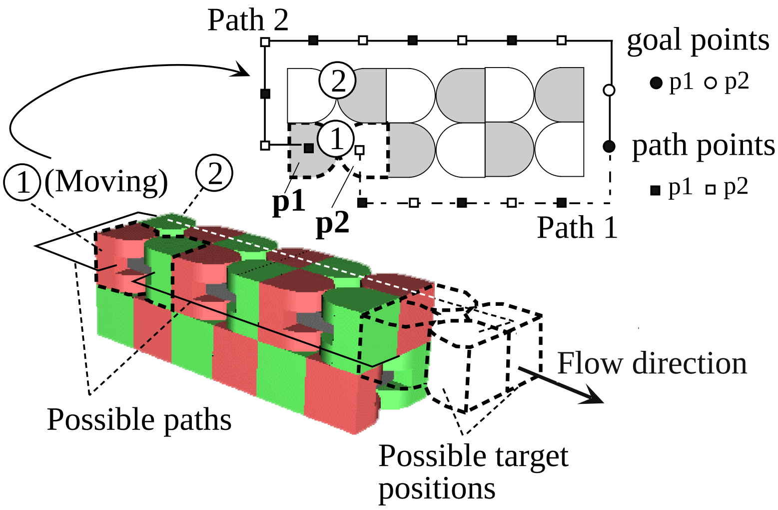


Fig. 11: Path of a module for block motion.

movement is realized by the individual motion of each member module in a valid order; one module continues to move until it reaches a target position.

(1) Selecting the motion order

A motion order in which all the member modules of the moving block have *valid paths* is selected from among the possible motion orders.

If a feasible order is found, the selector can successfully output the reconfiguration plan.

(2) Verifying the valid paths

The possible paths for the moving module are examined to determine if they are sufficiently valid to have a *unified motion sequence* that enables the module to reach the target position. This verification is performed in increasing order of the path's traveling distance; the path with the shortest length is tried first; the second shortest, next; and so on.

This verification terminates successfully if a valid path is found for the moving module.

(3) Generating the unified motion scheme

The output unified motion sequence for the path is initialized as an empty sequence. The following is repeated until the moving module reaches the target position along the examined path, starting from the initial position.

(a) A list of all the rules that match the current local configuration of the moving module is extracted from the rule database (Section 5.2).

(b) The rules in the list are screened by verifying the motion executability, taking into account connectivity and collision avoidance (Section 5.3).

(c) A rule that gives the maximum forward movement along the path is selected from among the listed rules.

The motion scheme associated with the selected rule is added to the unified motion sequence. The position of the moving module is also updated accordingly.

If no rules are found, the selection process continues by using a backtracking search.

If the module arrives at the target position, a unified motion sequence is successfully generated for the path.

If the above verification is successful, the unified motion sequence is determined for the moving block and is added to the total reconfiguration plan; otherwise the planning fails. Sufficient rules must therefore be provided to appropriately generate the reconfiguration plan.

Concerning the computational complexity, the most time-consuming part is the backtracking search during generation of the unified motion scheme. However, the search space can be sufficiently narrowed based on careful rule definition and the heuristics selecting the rules giving the maximum movement along the path. In most cases, the planner can retrieve one best-fitting rule at each position in the path. The computational time, therefore, becomes almost linear to the numbers of modules and rules.

5.2 Rule matching

A rule in the database is composed of an `if`-condition part and a `then`-action part as shown in Fig. 12. The former is a connectivity graph that describes a local connection state to be matched to the current local configuration of the moving module. The latter corresponds to a motion scheme written in the form of a motion sequence.

Figure 12 also graphically describes a local configuration. A node is assigned to each module in the connectivity graph. The node includes such data as the local identification of the module, rotation angles and the states of the six connecting faces. An arc in the connectivity graph denotes a connection to other modules and specifies the relative direction of the rotation axes and the link part.

In order to implement the motion scheme selector, we extracted several fundamental motion schemes as follows.

(1) Rolling on a side of the cluster (Fig. 12).

(2) Carrying a module by making a right angle on a plane (Fig. 13).

(3) Converting the rotational axis of a module (Fig. 14).

Figure 12 shows a rule corresponding to a simple motion scheme of rolling on the side of the cluster. Figures 13 and 14 illustrate how the module configuration changes in the latter two motion schemes. The converter modules are used when the desired cluster flow requires change of the rota-

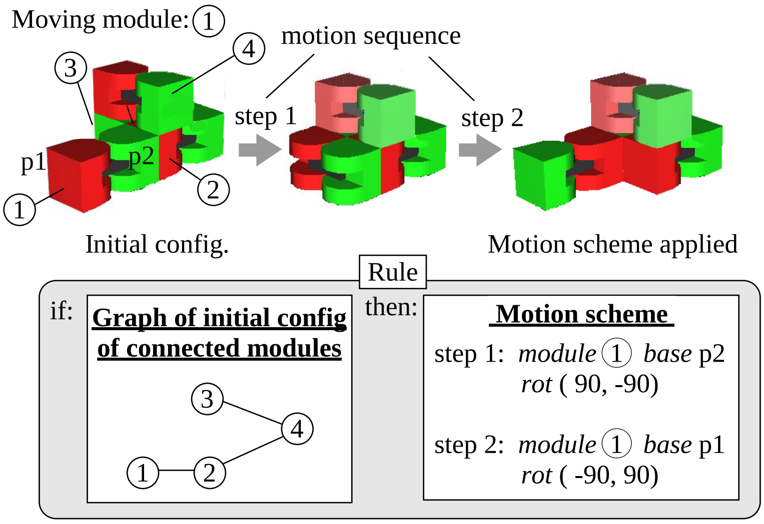


Fig. 12: Example of a rule for a rolling motion scheme

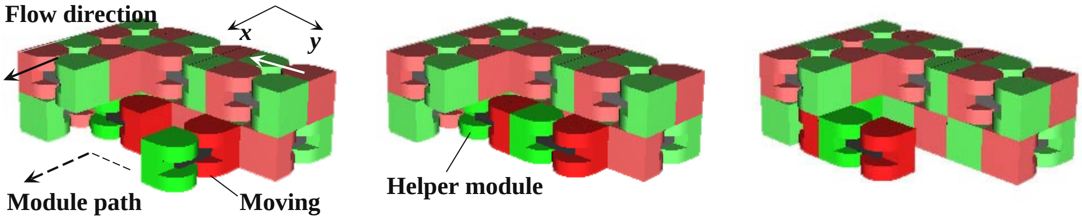


Fig. 13: Direction change of cluster on a plane.

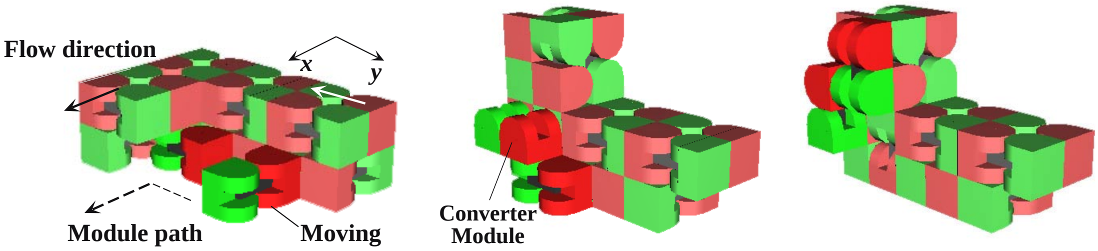


Fig. 14: Direction change to vertical direction on a plane.

tional axes of the modules (Fig. 14). The number of converter modules can be augmented if necessary. Some 30 basic rules have been extracted as basic motion schemes and are currently hand-coded.

To find a motion scheme of the moving module for the path and motion order, the selector searches for rules that match the current local configuration of the module. The selector then makes a list of all the matching rules that will be verified by the motion executability test described below.

5.3 Motion executability test

The motion executability check is performed for each matched rule from two aspects, collision avoidance and connectivity of the total cluster. If the latter is not satisfied, the cluster may be split into two or more smaller clusters, which may cut off the communication and power supply. Applying the motion scheme to the moving module enables a collision to be detected by calculating the sweeping area of its motions. Similarly, the connectivity during the motion is examined by tracing the current connectivity graph from the moving module down to connected modules.

When more than one rule is found valid, the rule that gives the maximum forward movement along the path is selected. This avoids infinite motion loops that make the modules move back and forth in the same place.

5.4 Planning results and discussions

The reconfiguration planner can generate three-dimensional paths for various sizes of clusters. Figure 15 shows some snapshots taken from the planned motion of a cluster of 22 modules starting from

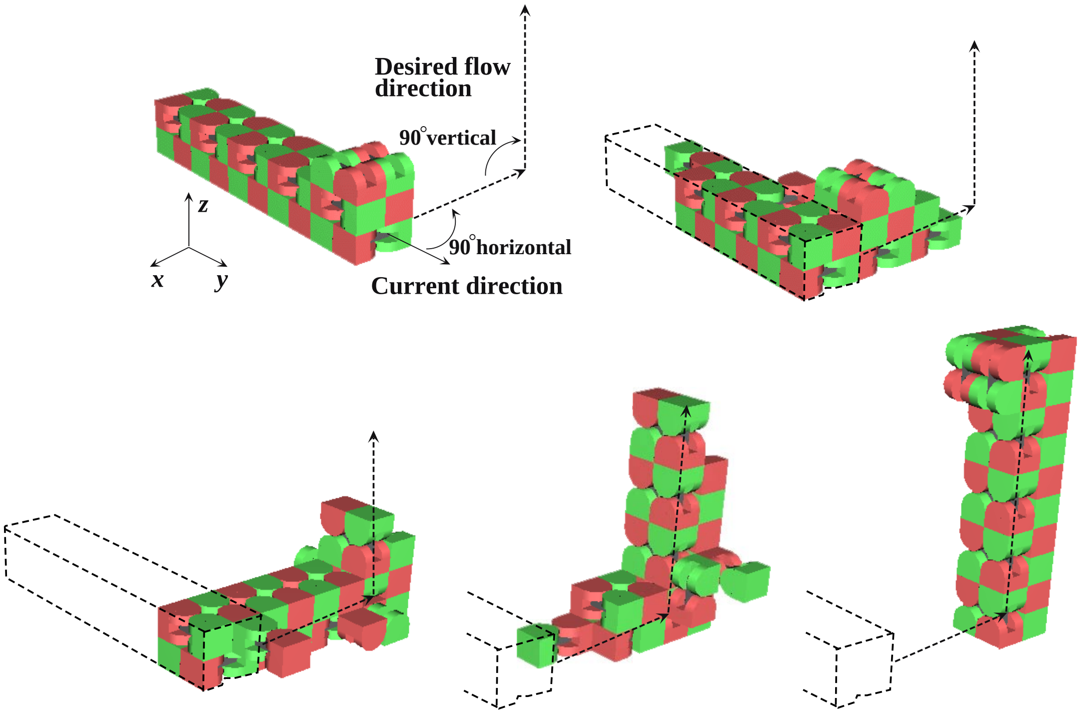


Fig. 15: Simulated plan of motions in different flow directions from initial configuration on a plane [M2].

a configuration on a plane. The cluster first changes its flow direction in the horizontal plane, then moves in a vertical direction. The cluster traveled by 16 unit lengths along the flow trajectory, and the resulting motion sequence takes 773 steps.

Although the currently developed method applies to a limited class, we believe that the basic framework of the two-layered approach is generally effective for other classes. The global planner depends largely on the application and should be designed to narrow the search space according to the task. In contrast, the motion scheme selector is less problem-dependent owing to its locality. It is applicable to various classes of module structures provided that basic rule sets that can cover sufficiently wide cases are correctly extracted. We are thinking of extending the database using an evolutionary method, and also generating more complex rules including rule hierarchy.

Simultaneous motion of several modules is another important issue for overcoming the low velocity of the cluster motion. This improvement is being implemented to increase the concurrency of motion by parallelizing several concurrent motion sequences. Future work also includes trajectory planning and extension of the planning method for more complicated paths, as well as theoretical investigation of completeness and optimality.

6 Hardware Experiments

A hardware prototype of the robotic modules is currently under development. After the basic atomic motions of modules are verified, an example of the cluster motion of a block structure will be implemented to show the planned motion can be achieved by hardware modules.

6.1 Atomic Motions

Figures 16 to 18 show the experiments of the forward-roll motion (Fig. 4), pivot motion (Fig. 5), and mode conversion (Fig. 6). In these experiments, the connecting mechanism performed reliably; it is strong enough to hold the module against gravity and detaches smoothly. It takes approximately five seconds for the connection to be completely released, mainly due to the time required to heat the SMAs. We also verified from Fig. 18 that the module has sufficient torque to conduct certain two-module motions.

Fig. 16: Experiment of forward-roll motion.

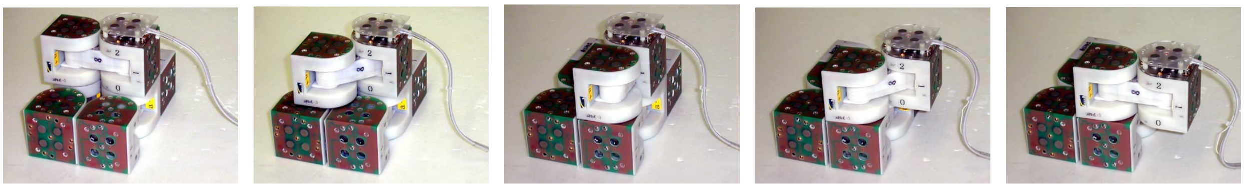


Fig. 17: Experiment of pivot motion.

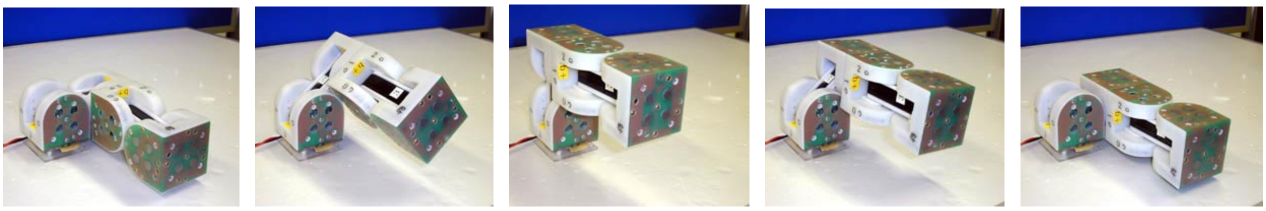


Fig. 18: Experiment of mode conversion.

6.2 Block Cluster Locomotion

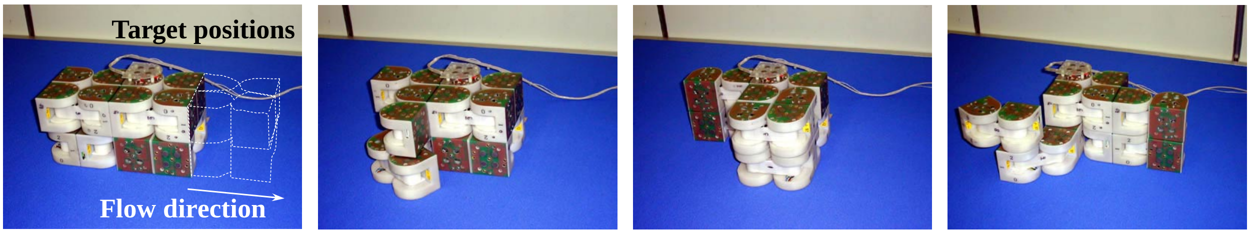
The planned cluster motion experiment described in this paper has been conducted using the hardware modules. The motion is planned in the host PC and then converted into low-level control commands of servomotors and SMA actuators by the simulator software. These control commands are distributed to the microprocessor of appropriate modules through a serial bus line by way of electrodes on the connecting faces. The commands are sent with module IDs so the indicated modules can achieve the desired motion. Power is also supplied to all the modules through inter-module connection from one module connected to the power source.

In this experiment, eight-module cluster flow motion is executed. Although the generated motion plan transfers the modules individually on the side of the cluster, the plan was modified so that some motions are carried out in parallel to reduce the execution time. There was a total of 23 motion steps. As shown in Fig. 19, cluster motion has been achieved, demonstrating the validity of the planned motion.

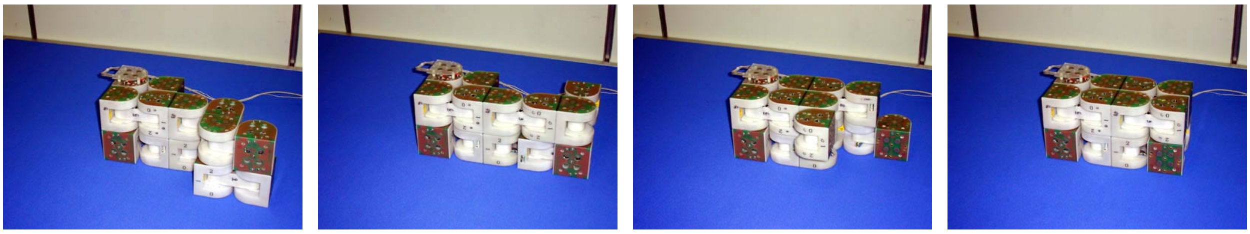
These experiments have suggested several issues to be improved in future hardware developments.

Redesigning electrodes. During the pivot motion (Fig. 5), there is sometimes an unnecessary contact between the electrodes. The next prototype model will be improved by allowing the electrodes to slide with the connecting mechanism to prevent such unfavorable effects.

Providing sensors for modules. By measuring the internal state and detecting the external environment, the group of modules will be able to adapt to various situations. For this purpose, we intend to use inclinometers and tactile sensors in the next prototype.



Initial state step 4 after step 8 step 14



after step 17 after step 18 after step 21 Final state

Fig. 19: Experiment of cluster motion of block structure using 8 modules [M3].

Planning for efficient motions. Plans that require more disconnection operations consume more time for motion, even though the difference is not apparent in the current simulator. This cost should be reflected in planning and rule definition to generate more efficient motion by the hardware module. Simultaneous module motion is another issue to be addressed for efficient module motion as previously mentioned.

7 Conclusions

This paper discussed the reconfiguration planning for locomotion of a self-reconfigurable modular robot and conducted experiments of the planned locomotion. A module was designed to generate three-dimensional structures of both the lattice and linear types. A two-layered planning method was proposed for a class of three-dimensional structures composed of multi-module blocks. The global flow planner outputs possible paths and motion orders to realize the block-based cluster flow. The local motion scheme selector determines the motion of each module according to the output from the global planner. The non-isotropic geometric properties of module mobility were properly reflected in the rules that associate appropriate pre-planned motions with corresponding local configurations. The future work concerning the reconfiguration planner includes investigation of more complete and compact rule sets applicable to wider classes of configurations. Generating simultaneous motion of many modules is also an important issue to be investigated to fully exploit the parallelism of the modular robot and to improve the locomotion velocity. Theoretical completeness and optimality of the method must also be addressed in the future work.

Several experiments were performed to verify the fundamental atomic motions and to show the feasibility of the generated plans using the prototype modules. From these experiments, we could obtain feedback to the planner in order to improve the efficiency of the motion by the hardware module. The basic module functions have now been confirmed. In the next development stage, we will seek to improve some mechanisms for motion reliability and to provide sensors for modules. This will allow the module cluster to move around in unknown environments with bumps or walls, adapting its shape to the outside world.

Multimedia Index Table

The multimedia extension page is found at `http://www.ijrr.org`.

[M1]	Extension #1	(Video) MTRAN mechanism and its basic motions
[M2]	Extension #2	(Video) Simulation of block cluster motion by 22 modules
[M3]	Extension #3	(Video) Experiment of cluster motion by 8 hardware modules
[M4]	Extension #4	(Video) Another example: reconfiguration from a crawler to 4-legged walking robot

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