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Reconfigurable group robots adaptively transforming a mechanical structure

- Numerical expression of criteria for structural transformation and automatic motion planning method -

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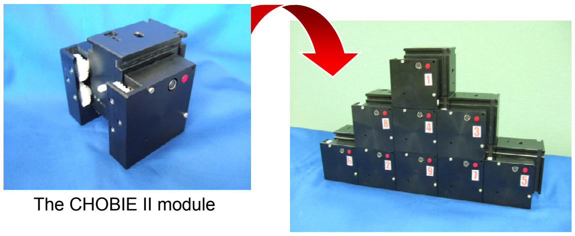
Abstract **– This study describes a group robot system "CHOBIE II". The feature of the CHOBIE II is a function to form a reconfigurable structure. In the previous paper, we introduced a control method of the robots and realized transformation of the structure. In this paper, we focus on a motion planning method to obtain control algorithms. For this purpose, we introduce a numerical criterion for generating transformations. The criterion is expressed with matrix form of 32 parameters. This paper demonstrates the criteria generate various motions of the CHOBIE II, and proposes a new method to obtain the appropriate parameters for objective motions.**

Index Terms – group robots, modular robots, structural transformation, distributed autonomous systems, adaptive transformation

I. INTRODUCTION

There have been many studies on modular robotic systems that are composed of multiple independent modules and have abilities of self-reconfiguration [1]-[7]. If the systems are equipped with well-designed organizational frameworks, modular robots achieve abilities such as multi-functionality, adaptability and fault-tolerance. With these abilities, modular robots will realize a highly organized structure like living creatures: It will maintain an optimal shape adaptively to various purposes or environments. It is expected to be useful for human environments and extreme environments such as deep sea or cosmic space. From such a point of view, we have developed a modular robot called "CHOBIE" forming a mechanical structure which has adaptability for mechanical environment [8]-[10]. The "CHOBIE II" has following properties.

- The CHOBIE II consists of identical modules in block-like shape as shown in Fig. 1.
- The modules connect each other and construct structures.
- The structural transformation is performed by cooperative movements of the modules.
- Each module determines its action by the internal microcomputer communicating with adjacent modules.
- The same control program is installed in all of them.
- With the autonomous distributed modules, the whole structure transforms to an objective configuration.


The CHOBIE II module

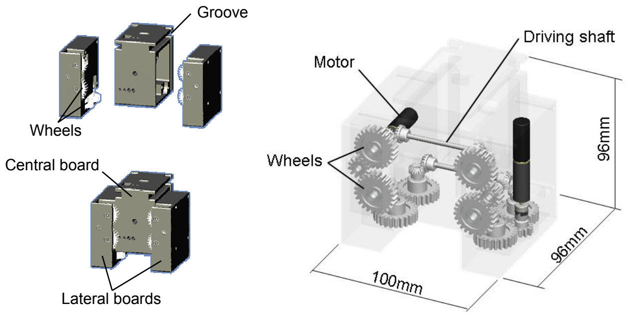
The CHOBIE II structure

Fig. 1 The module and the structure of the CHOBIE II

In the previous paper [10], we introduced a new control method for group robots and showed that the CHOBIE II modules cooperatively achieve transformation of the structure with simple rules called "temporary leader scheme". This paper discusses a motion planning method to obtain control algorithms for accomplishment of goal configuration of the CHOBIE II structure. First of all, the mechanism of the module and characteristics of the structural transformation are described. Second, the control method with numerical expression to perform transformations is explained. And third, an automatic method for obtaining control algorithms to achieve objective motions is introduced.

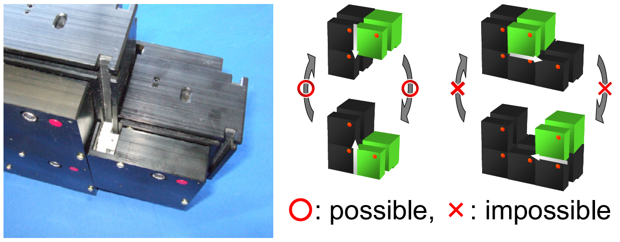
II. MECHANICAL FEATURES OF CHOBIE II

We briefly describe the hardware of the CHOBIE II because it is related to the control algorithm as stated below. Figure 2(a) shows the proposed slide motion mechanism of a CHOBIE II module. It consists of two lateral boards and a central board. The two lateral boards include symmetrical motion mechanisms that consist of two sets of wheels as shown in Fig. 2(b). They are allocated in vertical and horizontal directions, which enable the two directional motions of modules. On the other hand, the central board has grooves as sliding guides, which maintains high rigidity even in transformation as shown in Fig. 3(a). Due to this motion mechanism, modules successfully connect to other robots but cannot get joined or separated as shown in Fig. 3(b).



(a) (b)

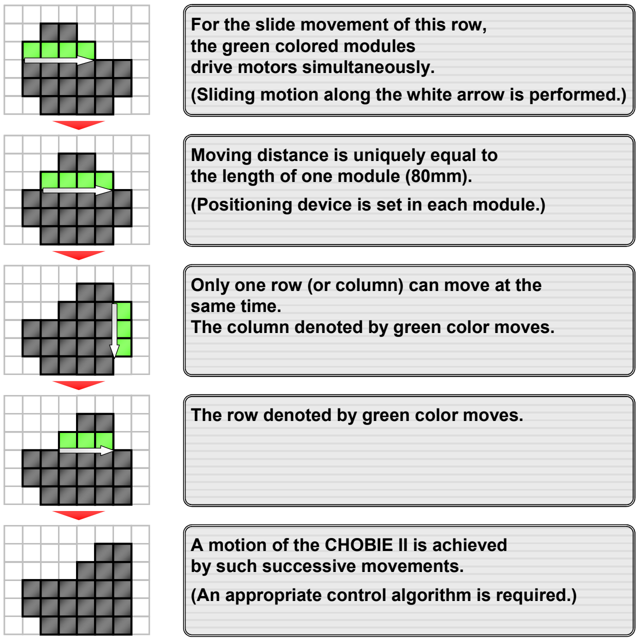
Fig. 2 Slide motion mechanism of the CHOBIE II ((a): composition of the module, (b): position of the driving mechanism)



(a) (b)

Fig. 3 Mechanical constraint between adjacent modules ((a): connection of modules, (b): possible/impossible transformation)

These mechanisms enable adjacent modules to keep joining each other strictly. In addition, the block-like shape of the module has high space-filling property. Due to the motion mechanism, the CHOBIE II constructs a sturdy 2-dimentional lattice structure. Transformations of the structure are carried out by simultaneous slide movements of modules which in a straight-line, that is, a specific "row" or "column" as shown in Fig. 4.



For the slide movement of this row, the green colored modules drive motors simultaneously.

(Sliding motion along the white arrow is performed.)

Moving distance is uniquely equal to the length of one module (80mm).

(Positioning device is set in each module.)

Only one row (or column) can move at the same time.
The column denoted by green color moves.

The row denoted by green color moves.

A motion of the CHOBIE II is achieved by such successive movements.

(An appropriate control algorithm is required.)

Fig. 4 Transformation of the CHOBIE II structure

III. CONTROL METHOD FOR STRUCTURAL TRANSFORMATION

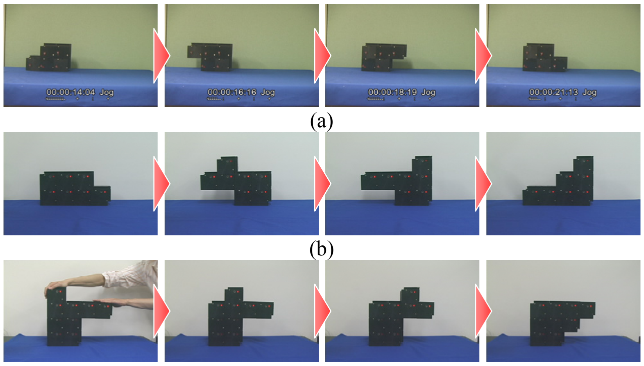
First we explain the control method of the CHOBIE II. In structural transformations of the CHOBIE II, it is necessary that the modules act cooperatively because of the mechanical constraints. That is, only modules on a specific row or column must move in the same direction at the same time. For such a synchronous action, it is efficient that there is a leader module which plays a special role in the modules. However, a system governed by a definitive leader may have some problems: The capability of the leader limits performance of the whole system, failure of the leader may cause the whole system down. Such a centralized system is not good for group robots.

As a control method for distributed autonomous systems, we proposed "temporary leader scheme" in the previous paper [10]. The concept of the scheme is as follows.

1) All the modules communicate in a distributed manner according to rules prescribed in advance.
2) They search a row or column which should be transformed.
3) A module near the row or column becomes a leader by local information processing.
4) The leader can once conduct all modules and execute a partial transformation.
5) After the transformation, the next leader is selected with the same rule.

According to the scheme, the modules generate sequential transformations. Any module equally has possibility to become a temporary leader, and a module which satisfies a specific condition in each situation becomes a leader. By setting the control algorithm appropriately, the CHOBIE II performs various motions.

For example, the CHOBIE II can demonstrate "crawl motion" (locomotion of the whole structure on flat ground), "bridge construction" (motion of extending a beam from a cliff), "stairs construction" (motion of forming stairs-like structure) and "load adaptation" (motion of reinforcing a stress concentration position of the structure). Fig. 5 shows experimental results of the motions.



(a)

(b)

(c)

Fig. 5 Motions of the CHOBIE II ((a) crawl motion, (b) stairs construction, (c) load adaptation)

When we developed the control algorithms of such motions, we had to determine transformation processes of the whole structure, and then we set “criteria” for generating transformations so that the structure traces the processes. But it is difficult to apply this method in cases of complicated motions. In order to realize various motions of the CHOBIE II, we propose a motion planning method to automatically obtain an appropriate control algorithm.

IV. NUMERICAL CRITERION FOR GENERATING TRANSFORMATIONS

For auto-development of control algorithms, we introduce a numerical expression of criteria for generating transformations. Here, a criterion regulates what kinds of transformations should be carried out in each condition. If the criterion is expressed by a set of parameters, we can numerically describe induced tendencies of generating transformations of the structure. Therefore, it becomes possible to obtain control algorithms automatically by deriving a numerical solution.

4.1. Generalized expression of criteria

As a fundamental concept, the CHOBIE II generates a transformation when an undesirable local characteristic exists in the structure, and the transformation is generated so as to remove the characteristic. Therefore, it is important to define what kinds of characteristics are undesirable. For each module, characteristics in the row and column of the module are remarkable for generating transformation, because transformation is cooperative action of a row or column. So we propose a setting method of criterion for generating transformations as follows.

First, each module gathers 8-bit information focusing on the states of its row and column. The information is treated as two sets of 4-bit information: One is about four states whether both ends of the row are top-end or bottom-end, and the other is about four states whether both ends of the column are left-end or right-end. An example case is shown in Fig.6.

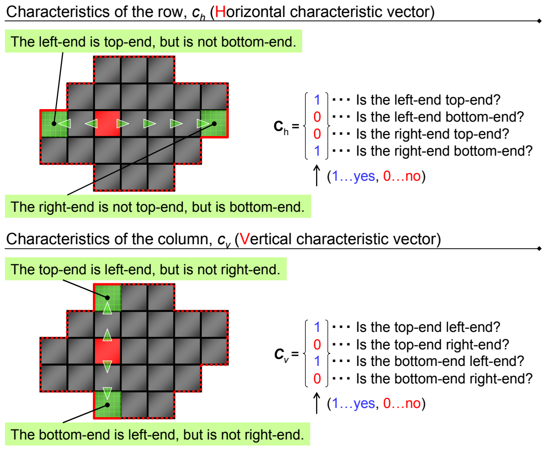


Fig. 6 Definition of c_h and c_v

Second, using combinations of these characteristics, undesirability of the both characteristics in each combination is numerically estimated. Each module calculates the undesirability of the state of its row and column with the following equation,

$$
\begin{aligned}
L &= c_v{}^t(\mathrm{A}_v + \mathrm{A}_h)c_h = c_v{}^t\mathrm{A}_v c_h + c_v{}^t\mathrm{A}_h c_h \\
&= \{c_{v1} \quad c_{v2} \quad c_{v3} \quad c_{v4}\}\begin{bmatrix} \alpha_{v11} & \alpha_{v12} & \alpha_{v13} & \alpha_{v14} \\ \alpha_{v21} & \alpha_{v22} & \alpha_{v23} & \alpha_{v24} \\ \alpha_{v31} & \alpha_{v32} & \alpha_{v33} & \alpha_{v34} \\ \alpha_{v41} & \alpha_{v42} & \alpha_{v43} & \alpha_{v44} \end{bmatrix}\begin{Bmatrix} c_{h1} \\ c_{h2} \\ c_{h3} \\ c_{h4} \end{Bmatrix} \\
&+ \{c_{v1} \quad c_{v2} \quad c_{v3} \quad c_{v4}\}\begin{bmatrix} \alpha_{h11} & \alpha_{h12} & \alpha_{h13} & \alpha_{h14} \\ \alpha_{h21} & \alpha_{h22} & \alpha_{h23} & \alpha_{h24} \\ \alpha_{h31} & \alpha_{h32} & \alpha_{h33} & \alpha_{h34} \\ \alpha_{h41} & \alpha_{h42} & \alpha_{h43} & \alpha_{h44} \end{bmatrix}\begin{Bmatrix} c_{h1} \\ c_{h2} \\ c_{h3} \\ c_{h4} \end{Bmatrix}
\end{aligned}
\tag{1}
$$

where, “c_h” and “c_v” are four dimensional vectors which express the existence of four characteristics in the row and column. “A_h” and “A_v” are 4×4 matrices which estimate the undesirability of the 16 combinations of the characteristics as shown in Fig.7. It is possible to set a criterion for generating transformations of the CHOBIE II with the 32 parameters. And “L”, which is calculated by them, gives the undesirability of each position of modules.

Third, the module which has the largest value of L becomes a leader. Then, the leader generates transformation to remove the most undesirable characteristic around itself, which mostly contributed in the determination of the leader.

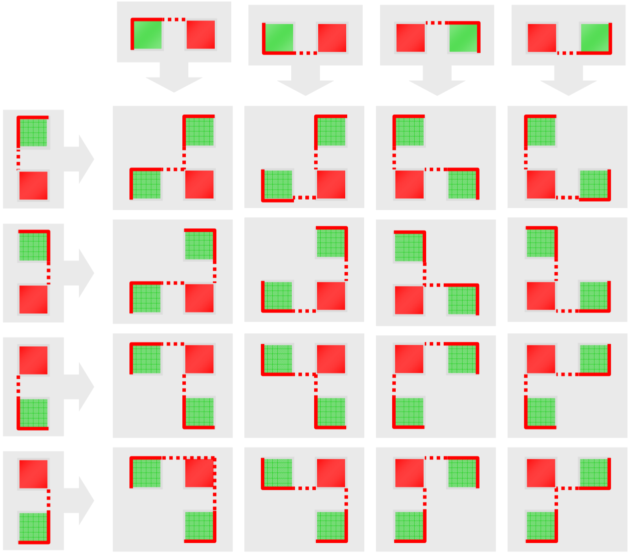


Fig. 7 Combinations of characteristics indicated by the parameters (Each column of the matrix corresponds to the four characteristics in the column which the red module exists. Likewise each row of the matrix corresponds to the four characteristics in the row which the red module exists. For example, the (1, 1) element indicates the combination of states that the top-end of the column is left-end and that the left-end of the row is top-end.)

4.2. Motions generated by numerical criteria

A set of 32 parameters expresses a criterion to generate a motion of the CHOBIE II. We show two examples. The first example is crawl motion. Crawl motion is generated by the following set,

$$A_v = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_h = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{2}$$

where, four matrix elements set in “1” generate four patterns of transformations. They produce a locomotive motion that the whole structure forms four configurations repeatedly as shown in Fig. 8.

The second example is upper growth motion. The matrices A_h and A_v are expressed by the formula (3). Figure 9 shows the simulation result.

$$A_v = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, A_h = \begin{bmatrix} 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 8 \end{bmatrix}. \tag{3}$$

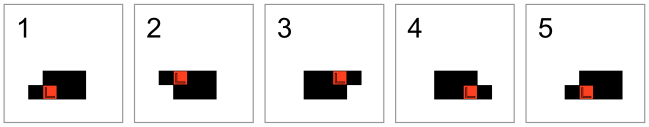


Fig. 8 Simulation result of generated crawl motion with six modules (The larger the value of *L* is, the redder the module is colored. The leader modules, which have the maximum value of *L* in each step, are marked with “L”)

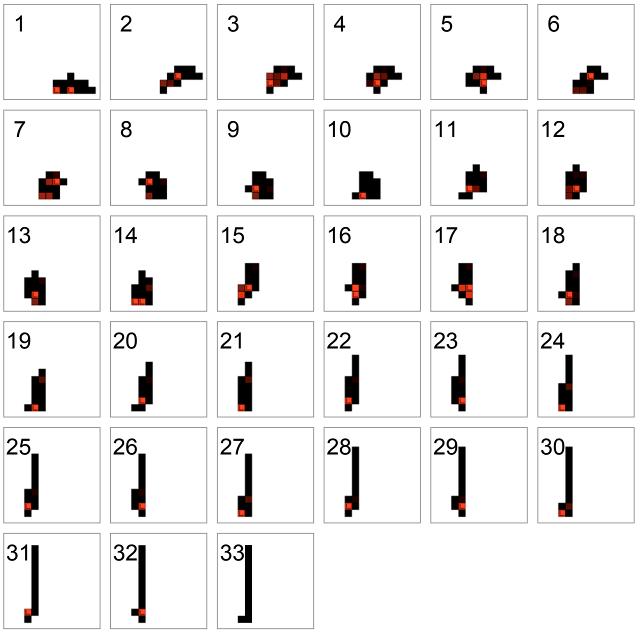


Fig. 9 Simulation result of generated upper growth motion with twelve modules

V. MOTION PLANNING METHOD

The proposed method enables the CHOBIE II to have various tendencies of transformation by use of the 32 parameters. We can manually set the parameters if motions are generated by simple criteria such as crawl motion or growing up motion. However, it is difficult to find the parameters to generate a complicated motion by an analytical method. In this section, we discuss motion planning method for automatic search of parameters which generates any given objective configuration. The subject is related to a constraint satisfaction problem (CSP).

5.1. Transformation from specific initial configuration to specific goal configuration

First we examine how to obtain parameters for transformation from a specific initial configuration to a specific goal configuration. If even one set of parameters is found, the CHOBIE II can perform the transformation anytime by using it. By making a database of obtained sets of parameters about various pairs of initial configurations and goal configurations, we can provide various transformation processes. In this paper, we describe the case of the pair of initial configuration and goal configuration as shown in Fig. 10 as an example.

Fundamentally, a large parameter means that the characteristic indicated by the parameter is undesirable, and contrary, a small parameter means that the characteristic is desirable. Therefore, if we set small values to the parameters about characteristics in a goal configuration, we can express a criterion that configurations near the goal configuration are desirable. In addition, if we want to express a criterion that configurations near the initial configuration are undesirable, we set large values to the parameters about characteristics in the initial configuration. These methods provide the parameters with a tendency against the initial configuration and for the goal configuration. We call them “standard parameters”. But since a concrete transformation process is not given, the parameters may lead the CHOBIE II to a configuration different from the goal configuration or, what is worse, the CHOBIE II may not become a stable configuration.

Then, we search parameters which insure accurate convergence with a simulation method according to the flow chart as shown in Fig. 11. A set of parameters is randomly selected around the standard parameters given above and the transformation is simulated. The procedure continues until a solution is found. Fig. 11 shows the flow chart of the procedure.

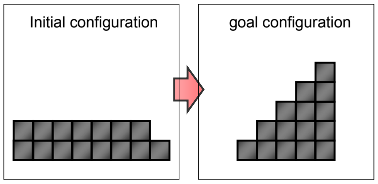


Fig. 10 Considered initial configuration and goal configuration

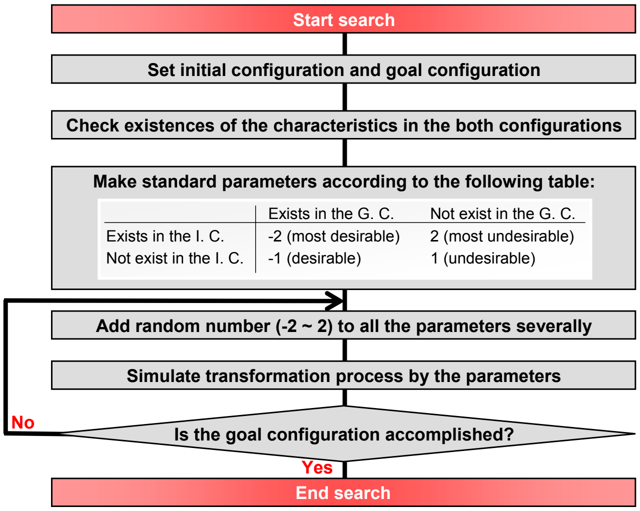


Fig. 11 Flow chart of the searching method

In the case of the setting as shown in Fig. 10, the following parameters are obtained by the searching method. It took 20-30 minutes to find the parameters on a personal computer (CPU: Intel Pentium 4, 3.4GHz). The simulation result of transformation process with the parameters is shown in Fig.12.

$$A_v = \begin{bmatrix} -1 & 0 & 3 & 0 \\ 0 & -1 & 2 & 2 \\ 3 & 0 & 0 & 1 \\ -2 & 1 & 1 & 2 \end{bmatrix}, A_h = \begin{bmatrix} -3 & -3 & 3 & -1 \\ -3 & -2 & 1 & 4 \\ 0 & 3 & 4 & 1 \\ -2 & -1 & 1 & 1 \end{bmatrix}. \qquad (4)$$

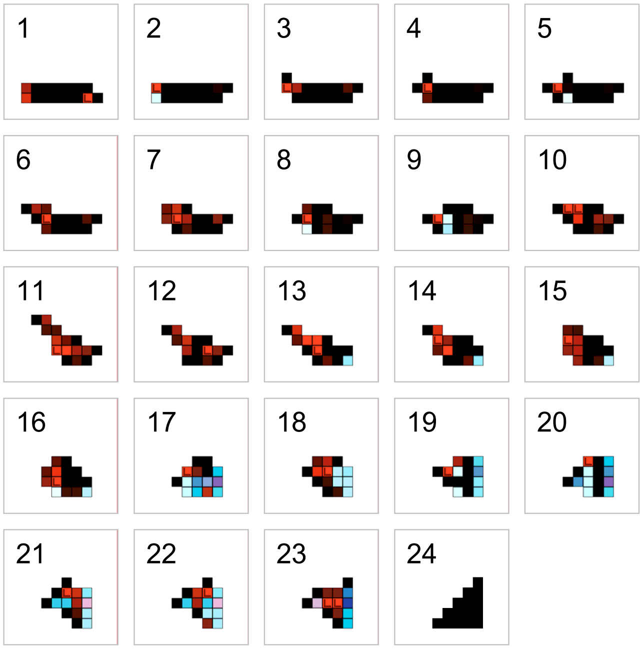


Fig. 12 Simulation result of stairs construction motion from the initial configuration in Fig. 10 using the parameters of formula (4) obtained by the searching method (There are blue colored modules because they have minus values of *L*.)

5.2. Transformation from arbitrary initial configuration to specific goal configuration

Next, we discuss a problem of obtaining parameters for transformation from any initial configuration to specific goal configuration. As described in section 5.1, the 32 parameters express a transformation process from an initial configuration to a goal configuration, and they cannot be defined by only a goal configuration except some distinctive configurations. Therefore it is difficult to obtain one set of parameters which achieves a specific goal configuration independent of an initial configuration.

We introduce a method of dimidiating the transformation process by setting an intermediate configuration between the initial configurations and the goal configuration. That is, we provide two sets of parameters. One generates transformation from the initial configurations to the intermediate configuration in the first step, and the other is from the intermediate configuration to the goal configuration in the second step. In the first step, if the intermediate configuration is distinctive, we can provide parameters for making the configuration from various initial configurations. Then, the second step is assumed to be same as the problem mentioned in section 5.1. Therefore the proposed searching method is applicable to more complicated transformations.

VI. MOTION EXPERIMENT

We demonstrated an experiment of structural transformation using a parameter set obtained by the proposed method. Table 1 shows the specification of the CHOBIE II module.

First, we ran the search program on a personal computer and derived parameters which can generate structural transformation shown in Fig. 13. Because of constraint of the maximum driving torque of the module, there is a risk that modules cannot carry out heavy loaded slide movements if the number of modules is too much. So we chose these simple initial/goal configurations. Furthermore, it is favoring for the searching method that there is a clear difference in terms of shape between the initial/goal configurations. The search program derived the following parameter set in a few seconds,

$$A_v = \begin{bmatrix} -2 & -2 & 2 & -2 \\ 0 & 0 & 1 & 0 \\ 2 & -1 & 2 & -1 \\ 0 & -1 & 2 & -1 \end{bmatrix}, A_h = \begin{bmatrix} -2 & -1 & -1 & 0 \\ -1 & -2 & 2 & 1 \\ 3 & -1 & 2 & -1 \\ -4 & 0 & 0 & 3 \end{bmatrix}. \qquad (5)$$

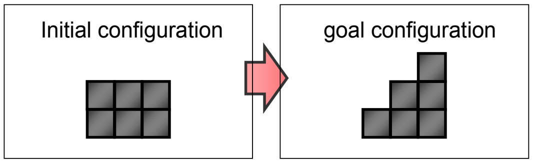


Fig. 13 Initial configuration and goal configuration of the motion experiment

Table 1 Specification of the CHOBIE II module

main material	ABS resin
size	$96 \times 96 \times 100$[mm]
mass	0.59[kg]
driving force	20[N]
moving verocity	upward…44.4[mm/s] downward…57.1[mm/s] sideways…53.3[mm/s]
MPU	H8/3664F (16[MHz])
battery	Li-355SP × 2 (serial) (7.4[V], 550[mAh])

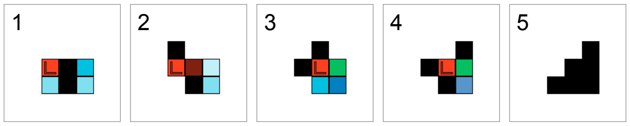


Fig. 14 Simulation result of the transformation process using the parameters in formula (5)

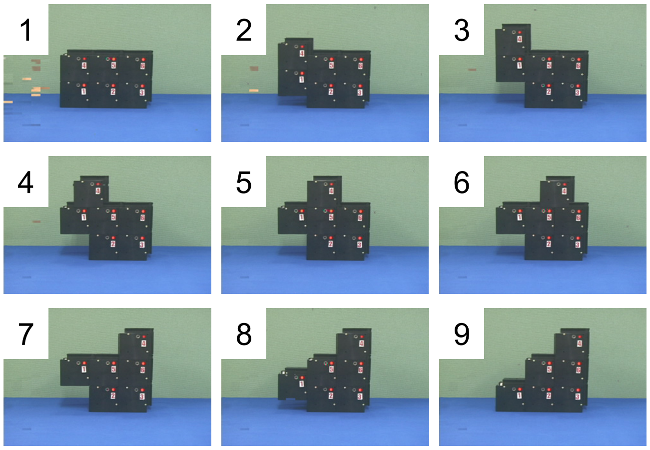


Fig. 15 Experimental result with the control program coded by the parameters

We checked the transformation process by the simulator (Fig. 14). It showed that the structure reached the goal configuration after four times of slide movements.

Then, we code a control program using the parameters. The same control program is implemented in micro-computers of all the modules. It makes actions in following steps:

1) Collection of information about characteristics in the row and column by communication with adjacent modules
2) Calculation of L using the preset parameters (formula (5))
3) Search for a module which has the largest value of L and determination of a leader
4) Transmission of drive command from the leader
5) Execution of the slide movement by the modules which received the command

While all the modules keep synchronization, each module does these actions in distributed manner. Figure 15 shows the experimental result demonstrating that the proposed method is available for providing control programs to carry out requested transformations.

VII. DISCUSSION

7.1. Transformations generated by "desirability"

In the criterion proposed at section IV, we paid attention to only undesirable characteristics in the structure and obtained transformations to remove the characteristics which have large values of undesirability. Therefore a leader occurs in case that $L > 0$ (The value of L is calculated by the equation (1) by each module). Considering transformations generated by states that $L < 0$, that is, "desirability" of characteristics, we can make the CHOBIE II perform motions to emphasize such desirable characteristics. By this method, for example, it is possible to set goal configurations with distinctive characteristics such as bridge-like configuration shown in Fig. 16.

It is expected that such emphasis of desirable characteristics is effective for distinctive transformations but may detract the stability of the structure because it may cause excessive emphasis of specific characteristic. On the other hand, removal of undesirable characteristics insures the stability of the structure but there is a limit to generable configuration patterns. Therefore it is important whether and how we should place a higher priority on desirability or undesirability.

7.2. Consideration of load condition

In order to achieve adaptive motions for mechanical environment, the CHOBIE II must consider not only the configuration characteristics but also stressed states of the modules in generating transformations. We discuss a method to take into consideration of the stressed states to the proposed criterion.

An adaptive motion of the CHOBIE II is performed by gathering modules to a stress concentration position, which lead to equalization of the stress distribution. Such a transformation can be generated by a criterion to remove the characteristic which causes the stress concentration. Therefore, we propose the following method.

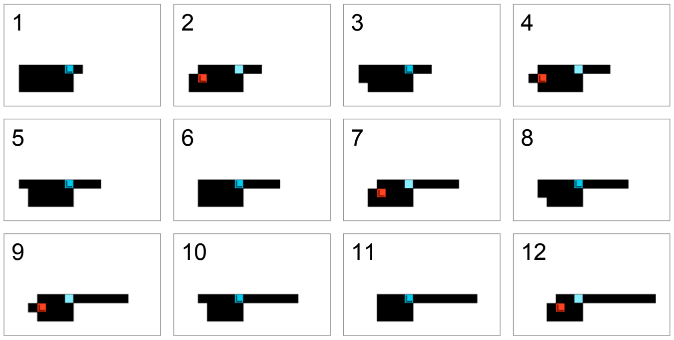


Fig. 16 Simulation result of bridge construction motion generated by both "desirability" and "undesirability" (In this simulation, the module which has the maximum absolute value of L becomes the leader. In 1, 3, 5, 6, 8, 10, 11th steps, blue colored modules, which have minus values, become leaders.)

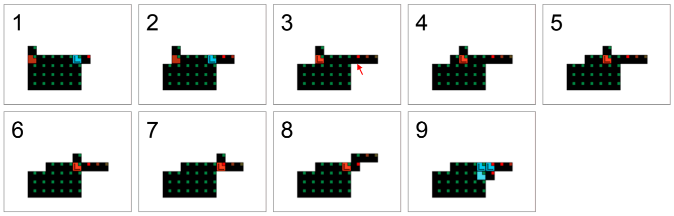


Fig. 17 Simulation result of bridge construction and load adaptation applying the method of considering stressed states (Color of small squares on upper right corners of modules shows the stressed state (Green: normal state, Red: high stressed state.) In 3rd step, the module indicated by the arrow detects a stress beyond threshold level. The weight factor is set by 5 in this simulation)

- The module which detects stress beyond threshold level sends signals to four directions: Above, below, left and right.
- The modules which receive the signals multiply weight factors (> 1) to the undesirability of the characteristics on the reception direction in calculations of L.

It is confirmed that load adaptive transformation as shown in Fig. 17 can be performed by this method. However, results of simulations suggested that there is difficulty in this method to transfer modules to target positions because it only considers gathering modules near the stress concentration positions. For more effective adaptive motions, we have to add another method which concretely generates transformations for avoidance of stress concentration near the positions.

VII. CONCLUSIONS

This paper described a motion planning method of the CHOBIE II. Transformations of the CHOBIE II structure are performed by simultaneous movements of rows or columns of the modules. So we introduced a numerical criterion for generating transformations which consists of 32 parameters corresponding to the undesirability of the characteristics on a row and a column of each module. Criteria for simple motions as crawl motion or upper growth motion were able to be generated manually. In order to obtain criteria for more complicated motions, we also introduced a searching method using a computer. By the proposed method, a problem of transforming from specific initial configuration to specific goal configuration is solved. Even if the initial configuration is not specified, we can also achieve the goal configuration by setting an intermediate configuration. In addition, we discussed two methods of diversification of criteria. It is suggested that the CHOBIE II can generate more various motions by itself.

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