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Reconfigurable group robots adaptively transforming a mechanical structure
- Crawl motion and adaptive transformation with new algorithms -

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***Abstract* - This paper describes group robots adaptively construct a mechanical structure. The feature of the robots is high rigidity by adopting sliding mechanisms. This study discusses algorithms of crawl motion and adaptive construction considering mechanical constraints of the robots. The proposed algorithm is based on local communication of the robots. We introduce a scheme of a temporary leader which is autonomously specified by form of the structure. The scheme decreases amount of information in communication between the robots. The experimental demonstrations are also shown in this paper.**

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

I. INTRODUCTION

Reconfigurable group robots have potential to fulfill various missions such as cooperative transportation, collection and construction [1]. To realize the group robots, a variety of mechanisms has been developed [2]-[7]. However, there are very few robots designed for supporting large external forces. It is because the almost developed robots are designed for a mobile function than a supporting function.

Our study focuses on group robots forming a mechanical structure. The group robots consist of cellular robots. Each cellular robot communicates with adjacent robots and determines its position where it should be taken. They form the structure by successive cooperative movements. We call the cellular robots "CHOBIE" (Cooperative Hexahedral Objects for Building with Intelligent Enhancement).

Figure 1 shows the concept of our study that CHOBIE cooperatively adapt to load condition. When a load acts on the structure of the robots, they change it so as to avoid concentration of stress.

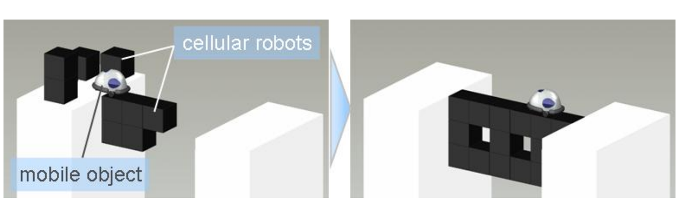


Fig. 1 Idea of cellular robots "CHOBIE" forming a structure

In our previous studies, we proposed an automated motion of the cellular robots. The robots (we call them "CHOBIE II") demonstrated that they adaptively changed the structure by a preprogrammed control with local communication between adjacent robots [8][9].

This paper discusses efficient algorithms to produce crawl motion and adaptive bridge construction considering mechanical constraints of CHOBIE II. First we introduce a scheme of a temporary leader that enables to decrease amount of information in communication between the robots in crawl motion. Next we show that the scheme is applicable to adaptive bridge construction as well as the crawl motion. The experimental demonstration is also presented.

II. STRUCTURE OF A CELLULAR ROBOT

Figure 2(a) shows the proposed slide motion mechanism of CHOBIE II. 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 cellular robots. 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, cellular robots successfully connect to other robots but cannot get joined or separated as shown in Fig. 3(b).

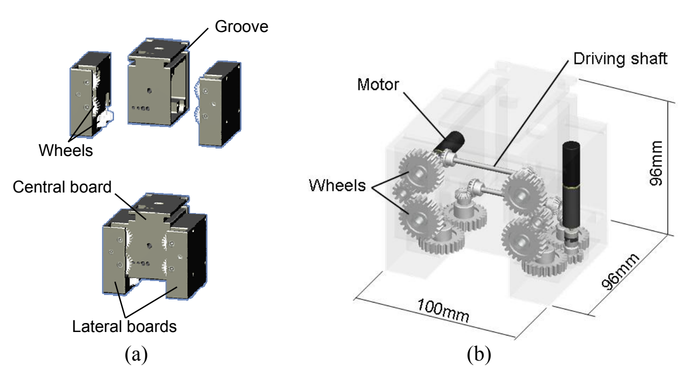
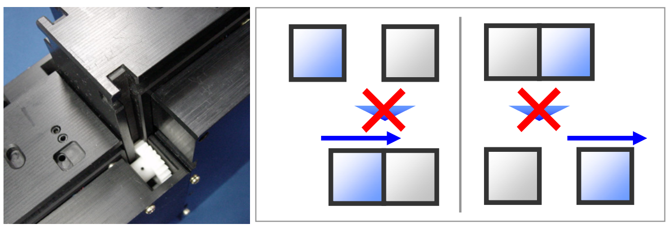


Fig. 2 Slide motion mechanism of CHOBIE II

The central board also contains locking mechanisms, communication devices, an electric controller, and two lithium ion batteries. The locking mechanism is composed of rods and holes as shown in Fig. 4(a). It enables the robot to hold a precise position with large stiffness in the sliding direction. The optical communication between the adjacent robots is performed by LED and photo-transistor embedded in four surfaces of the robot. Each robot has a microcomputer H8/3664F as the electric controller. The same control program is installed in microcomputers of all robots. With the two lithium ion batteries, the robot can operate for at least 20 consecutive minutes or more.

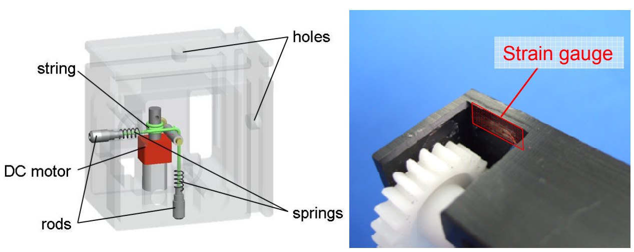
In order to perform adaptive transformation, strain gauge sensors are used for getting load information. They are attached to the position as shown in Fig. 4(b).

The overview of the whole structure is shown in Fig. 5.



(a) (b)

Fig. 3 Mechanical constraint between adjacent robots



(a) (b)

Fig. 4 Locking mechanism and position of strain gauge

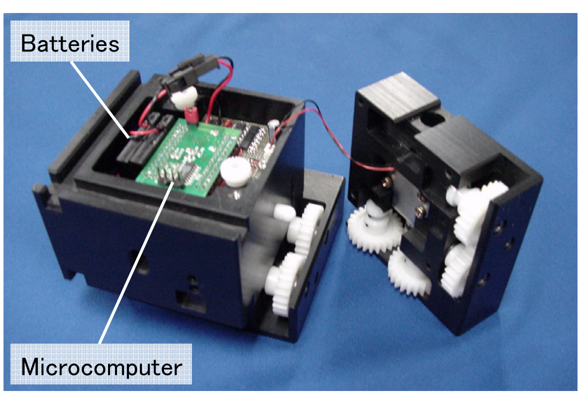


Fig. 5 Overview of a cellular robot

III. Control Algorithms

3.1. Transformation Algorithm

Performance of CHOBIE II is achieved by succession of structural transformations. In each transformation process, some robots drive their motors and the other don't drive, and we call the former "D" as meaning of "driving robot" and the later "R" as meaning of "resting robot". It is necessary to determine D from whole robots, and each robot needs the algorithm for judging whether it would be D or not. Although the algorithm changes according to target performance, it has a common fundamental flow of the judgment as explained bellow.

Each robot communicates with surrounding robots and acquires the information about the state of the structure. But it cannot process complicated data because it doesn't have powerful calculation function. On the other hand, because of the mechanical constraint mentioned above, all the robots connected horizontally must drive simultaneously in horizontal movement, and the same is true on versatile movement. It is difficult for each robot to observe such geometrical arrangements without complicated communication.

This paper proposes a scheme to accomplish the cooperative movements focusing on a characteristic position which enables simultaneous driving. The position is suitable as a starting point of a command and can be pinpointed by local communication. A robot which is located in the position becomes a temporary leader, and sends a drive command to the "line" which should drive. Using this technique, it is possible to determine a leader by local communication and to specify the robots on the line to drive by a simple algorithm without depending on the number of robots. The rough scheme of determining D is as shown in Fig. 6.

Here, it is important that the leader is temporary and is newly decided after each transformation because the robots should be an autonomous distributed system. Someone may think that a permanent leader could operate in an easier way. However, in order to treat the large amount of information, it would require high intelligence for each robot.

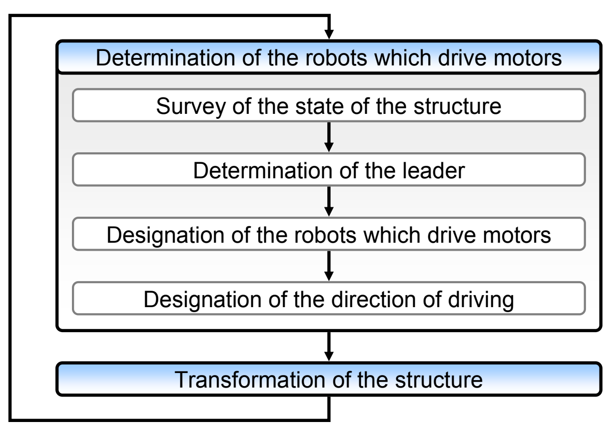


Fig. 6 Flow of transformation

Moreover, a leader becomes the starting point of a drive command signal. Thus, if the leader sent a drive command to a line far from itself, the rule of communication would be also complicated. In short, it is not enough that a leader only exists, but requires that the robot at a suitable position should be chosen as a leader.

The prime feature of the temporary leader scheme is to fulfillment of transformation by only local communication based on a simple rule. Of course, superior communication devices and microcomputers could perform an equivalent task using global information by more complicated rules. But it will be less flexibility for a scale of a structure. In contrast, the temporary leader scheme is independent of the scale because it follows a simple local rule. The scheme is also applicable to other systems if they are composed of autonomous, distributed and synchronous units.

3.2. Communication between robots

To start structural transformation of the robots, the leader informs the whole robots that a leader has been determined, and starts transfer of a drive command.

All information including a drive command is transmitted by the optical communication device through adjacent robots. The information is represented by signals with ON/OFF states. If the information that the robots communicate were complex, the processing would become complicated. This leads to decrease efficiency of communication. In order to raise the efficiency, we design a protocol that enables the robots to interpret a signal received in certain time zone. That is, all robots get synchronized, provide time steps at regular time intervals, and define the meaning of the situation whether a robot receives a signal in each time step. This technique makes the amount of data in communication small, and shortens time for the communication. In the transfer of a drive command, for example, robots get synchronized using a signal of determination of the leader. Then, a signal to specify the route of successive signals is transmitted in the first time step, a signal to specify D is in the second time step, and a signal to specify the direction of driving is in the third step.

It spends about 10 microseconds to send a signal to adjacent robot. Therefore, there is about 10 microseconds of time lag between adjacent robots in synchronization. In a large structure, the whole time lag also becomes large, and it may require a long interval in each time step. In order that each communication can be accurately performed in a specified time step, the interval of each time step must be longer than the amount of time that a signal goes and returns between both ends of the structure. There is no need to pay attention to the time lag as long as this condition is satisfied.

The time lag also produces a gap between adjacent robots when they start driving their motors. The gap is equal to a distance which a robot moves in 10 microseconds, and is uniformly about 0.6 micrometers. The distance can be easily absorbed by rubber material used for the driving mechanism and so the gap does not become a problem independent of the scale of the structure.

3.3. Crawl motion

As an example performance of robots using the temporary leader scheme, we describe crawl motion as shown in Fig. 7. The crawl motion consists of four sequential forms (From 1, 2, 3 and 4).

In this case, seven robots take the forms in order of the number. The whole structure moves by unit length of the robot. The robots which should drive in each form are indicated by blue color. To send a drive command to these robots, we introduce a procedure that the robot denoted by a star mark becomes a temporary leader. The procedure is shown below.

1. All robots send signals to all direction.
2. If a robot receives a signal from top or bottom, it stops sending signals to left and right directions.
3. If a robot has received signals from vertical and horizontal direction, it becomes the temporary leader at the present configuration of the robots.

Figure 8 shows the procedure to determine a temporary leader in case of the Form 1.

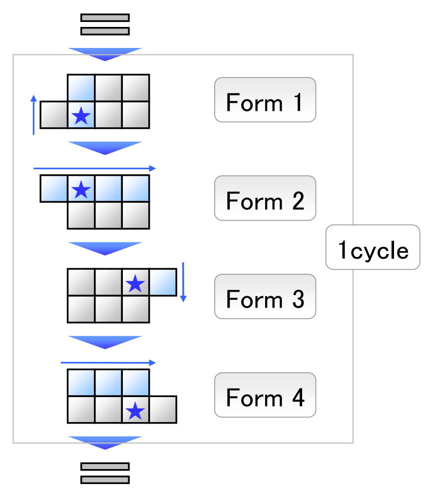


Fig. 7 Crawl motion

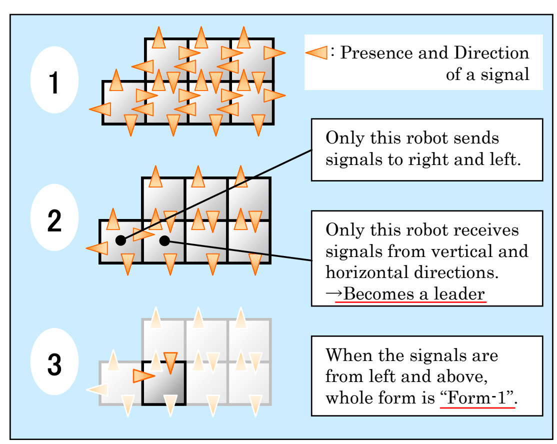


Fig. 8 Procedure of determining a Leader

The temporary leader is classified into four kinds by combination of two signals, and it corresponds to the four patterns of form respectively. Thus, when a robot becomes a leader, it recognizes the present pattern of form. Furthermore, since the positional relationship between the leader and the line which should drive is determined uniquely in the each form, the leader can judge the line to which it should send a drive command.

On the other hand, the robots which have received the command drive their motors with synchronization. And then, if they check that all of them have completed fixation by rods, they send the signal of completion of transformation to the whole robots. Using this signal, all robots get synchronized and start communication to determine the next leader. In this way, crawl motion is performed.

We made the program which operates with the algorithm described above, and carried out experiments of crawl motion with 3, 5, 7 and 9 robots. In all cases, the crawl motion was successfully demonstrated. The crawl motions with 3 and 5 robots are shown in fig. 9 and fig. 10.

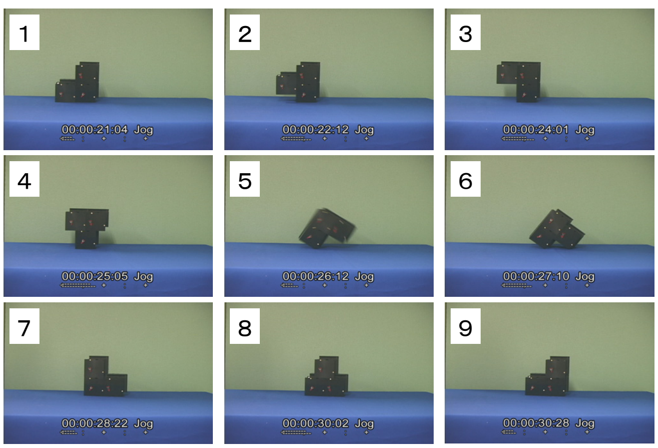


Fig. 9 Crawl motion with three robots

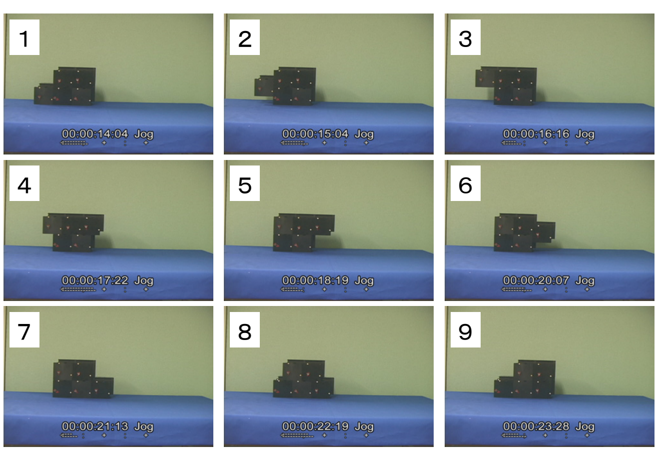


Fig. 10 Crawl motion with five robots

3.4. Load adaptation

Next, we describe a method that robots build a bridge structure adapting to a loading force. The basic idea of load adaptation is to equalize stressed states of all robots by changing the structure. To build the adaptive bridge, the robots need a scheme of bridge construction. That is, they continue bridge construction with permitting a certain amount of stress. When the stress becomes over the threshold level, they perform load adaptation. We call each of them bridge construction mode and load adaptation mode. CHOBIE II performs bridge construction in the first stage.

Figure 11 shows an example process of the bridge construction extending the structure from the cliff. In the process, overloaded states occur at some robots because of the weight of the robots. The overloaded robots are indicated by red color. To help such robots, some robots change the structure so that such parts become thick. In the initial form (No. 1), robots take a two-tiered structure on the flat part. Most robots are arranged at the lower tier, and the other robots are located at left side of the upper tier. The lower tier slides to the right on the flat part of the base, and constructs the bridge structure. The robots on the upper tier are used for load adaptation. When overload occurs, these robots move and reinforce the overloaded position. They are usually located at left side not to interfere with the bridge construction.

In crawl motion, only the algorithm for crawl motion was prepared and robots always operated with this algorithm. But in the bridge construction, the two algorithms for bridge construction mode and load adaptation mode are prepared, and robots use both algorithms as situation demands. Therefore, unless there is a robot which detects an excessive amount of stress, the robots carry on bridge construction with the algorithm. When the stress becomes over the threshold level in the process, they switch to the algorithm for load adaptation mode. Then, when the overload is done away with, they switch to bridge construction mode again.

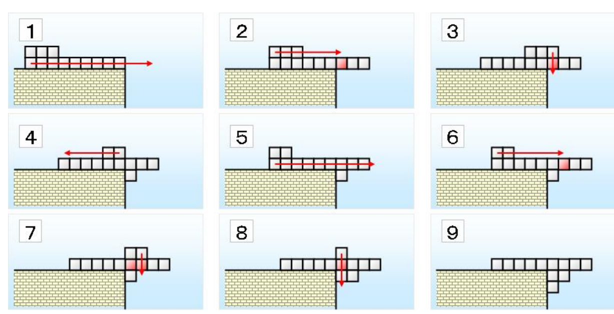


Fig. 11 Bridge construction

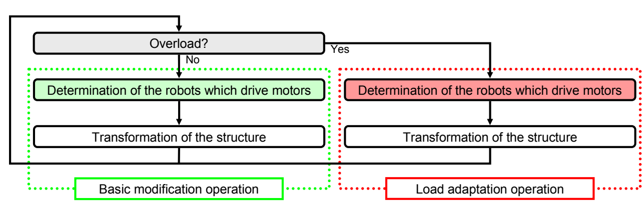


Fig. 12 Flow chart of switching the algorithms

Figure 12 shows the flow chart of the adaptive bridge construction. The switching of the algorithm must be done before the robots begin to determine the next leader. So each robot checks its load condition right after each transformation, and communicates about the condition in the first time step after synchronization by the signal of completion of the transformation. The robots decide which algorithm to use examining whether they have received a signal or not.

To realize the load adaptation mode, we use strain gauges to obtain load information. In order to verify validity of the sensors, we demonstrated the performance of load adaptation mode. Figure 13 shows the outline of the adaptive transformation. When a load acts at the end of the cantilever structure, robot B around the root detects a high stress. Then the robot A moves so that the stressed part becomes thick. The algorithm is described as following steps.

1. If a robot detects stress over the threshold level, it sends a signal, and all robots switch to load adaptation mode.
2. If a robot is on right edge, it sends a signal to bottom.
3. If the robot which detected overload at step 1 receives a signal from top, it becomes the leader 1. Then go to step 7.
4. If the robot which detected overload at step 1 doesn't receive a signal from top, it sends a signal to left.
5. If the robot which received the signal from right at step 4 also receives a signal from top, it becomes the leader 2. Then go to step 8.
6. If the robot which received the signal from right at step 4 doesn't receive a signal from top, it sends a signal to left.

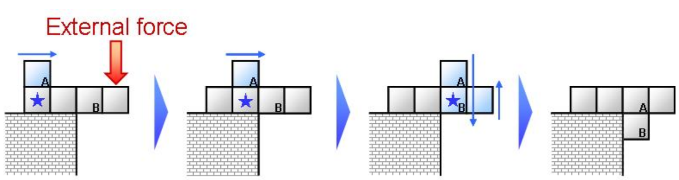


Fig.13 Load adaptation in bridge construction

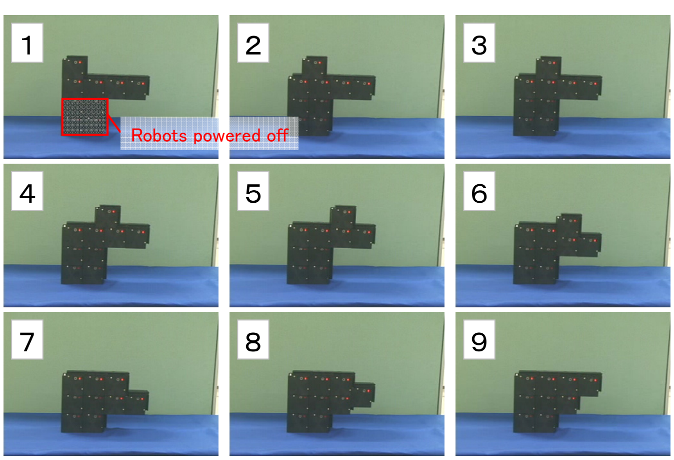


Fig.14 Load adaptation with five robots

7. The leader 1 sends drive commands so that the vertical line of itself drives to downward and the vertical line of its right-side neighbor drives to upward.
8. The leader 2 sends a drive command so that the horizontal line of its top-side neighbor drives to rightward.

The result of the experiment is shown in Fig. 14. It shows that it is successful to realize load adaptation by using load information as a trigger. In this experiment, the threshold level of stress was regulated to react to pushing force at the end of the cantilever. But considering a practical load adaptation, it should be determined based on the tensile strength of ABS resin which is main material of CHOBIE. The value of the safety factor should be enough large because several times of transformation is required till overload is removed.

This method is applicable not only to load adaptation but also to any other modes which have priority over bridge construction mode. That is, robots have several algorithms of every possible mode and switch them according to the information acquired by sensors. This method produces a flexible program which enables CHOBIE II to act accommodative to various situations.

IV. Discussion

The algorithm of crawl motion described in the chapter 3.3 is not subjected to the number of robots, but has restrictions on the initial form. It cannot achieve crawl motion without the four patterns of form shown in Fig. 7. It is because the algorithm is designed to execute the predetermined procedure presupposing that the sequential transformation forms are previously set up.

We discuss a more flexible algorithm that enables CHOBIE II to perform crawl motion in more variety of initial forms shown in the following Fig. 15. Form (a) is the initial form that we have already discussed. Form (b) and (c) have a problem that no leader is elected. On the other hand, form (d) has a problem that plural leaders are simultaneously elected.

In form (a), the robot on right-side making a horizontally protruded portion plays an important role in determination of a leader. In form (b) and (c), since there is no robot which makes a horizontally protruded portion, there is no robot which becomes a leader. To solve this problem, we propose a method that the robots use several algorithms as follows.

If there is no leader, no signal is detected in the time step when a signal of determination of a leader should be detected. So the robots recognize that this algorithm cannot determine a leader, and then the robots apply the second algorithm. This method expands the flexibility of the operation by providing several algorithms in advance. We call it "trail-and-error method".

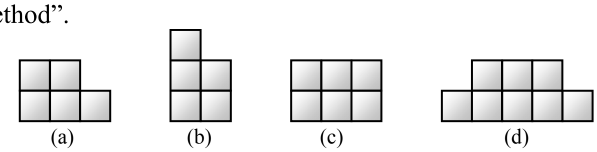


Fig. 15 Supposed initial forms

In this case, we should provide the second and the third algorithm for form (b) and (c) besides the first algorithm. Figure 16 shows the flow chart of this method.

The trail-and-error method is available for various types of initial forms, but it is not efficient because the robots must try several algorithms. In order to improve the efficiency, we propose "cautious method". In this method, the robots check characteristics of the structure at first, and they decide the algorithm to apply. The flow chart of this method is shown in Fig. 17. This method is thought to be more efficient.

In form (d), plural robots comply with the condition for leader at the same time. When there exist plural leaders, several lines of robots would receive drive commands. If the directions of both commands are the same, there is no structural problem. But, if the directions are different, it may be impossible to carry out transformation. Therefore, this situation should be avoided. To avoid the problem, we can use a method to determine priorities of the leaders as follows.

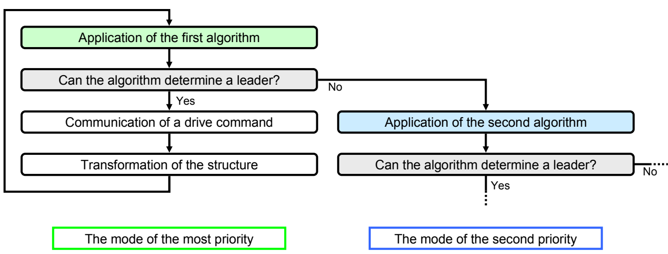


Fig. 16 Flow chart of trail-and-error method

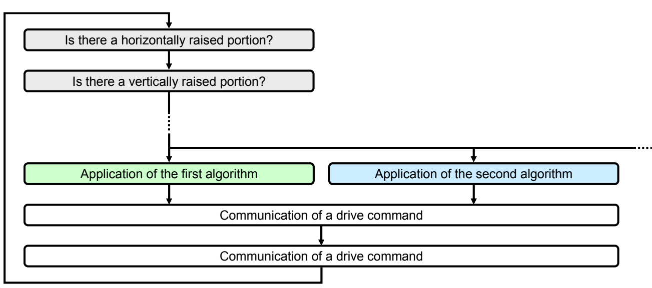


Fig. 17 Flow chart of cautious method

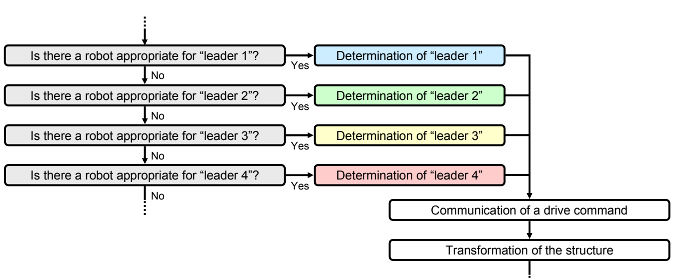


Fig. 18 Flow chart of priority sequence

In the case (d), there are two kinds of leaders and they send commands of both horizontal and vertical transformations. It can be avoided by setting priorities of leaders. That is, the existence of robot appropriate for the leader is checked by the priority sequence. The priority sequence is shown in Fig.18.

This method cannot avoid a situation that the leaders of the same kind are elected. However, in this case, the directions of commands are also the same. So the two transformations can be performed simultaneously.

V. Conclusions

The algorithms using a scheme of a temporary leader for structural transformation of CHOBIE II were discussed. We demonstrated crawl motion as an example performance using the scheme. This performance showed that the robots successfully operated with local communication by the scheme. We also demonstrated load adaptation with load information obtained from a strain gauge sensor. In this experiment, the robots performed adaptive transformation using load information as a trigger. To realize crawl motion in various initial forms, we proposed several feasible methods. The methods are available when no leader is elected or when plural leaders are simultaneously elected.

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