The Thirteenth International Symposium on Artificial Life and Robotics 2008(AROB 13th '08),
B-Con Plaza, Beppu, Oita, Japan, January 31-February 2, 2008

Fault-tolerance of Modular Robots Adaptively Transforming a Mechanical Structure

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Abstract: This paper describes fault-tolerance of our modular robots, "CHOBIE II." There are generally two important issues for realization of fault-tolerance of modular robots. One is that the system needs a function to detect troubled states, and the other is that the system also has to have a control algorithm to respond to such troubles. First, we categorize trouble patterns of CHOBIE II about its components such as driving mechanism and communication devices. Although there are a variety of situations, it is certified that the troubled states induce strange signs when the troubled part takes an action. Therefore, any trouble can be found by checking the signs. From the viewpoint, we examine strategies of solving the troubles and discuss implementation of fault-tolerance of CHOBIE II.

Keywords: Modular robots, Fault-tolerance, Distributed autonomous system

I. INTRODUCTION

A modular robotic system is composed of a group of modules and is able to customize its function or configuration flexibly [1]-[3]. It is called "dynamic self-reconfiguration capability." On behalf of the capability, modular robots have abilities of assembling themselves according to their objectives and changing the internal states to adapt to their surrounding environments. Furthermore, they also have a function of fault-tolerance. That is, even if there are troubles in some modules of the system, by setting algorithm so that other modules support them, the whole system can keep its application.

We have developed modular robots "CHOBIE II." The CHOBIE II consists of identical modules which have block-like shape. The modules can connect each other and construct a lattice structure. The structural transformations are performed by slide movements of the modules along lattice lines. Each module has an internal microcomputer and determines its action by optical communication with adjacent modules.

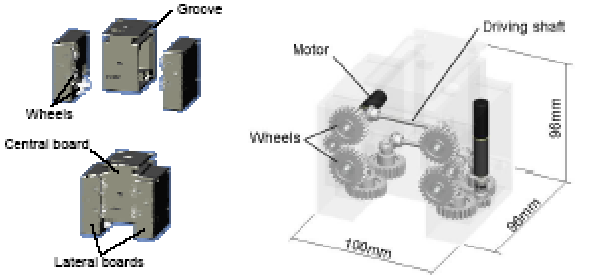
In our previous study, we introduced a method of implementation of criteria for generating slide movements and enabled CHOBIE II to transform to formations indicated by the criteria [4]. Furthermore, we also succeeded in load adaptive motion of CHOBIE II [5]. That is, when large stress acts on a part of the structure, the system detects the existence of the states and its position and generates transformations in order to reinforce the overstressed part.

This paper deals with fault-tolerant design of CHOBIE II. In general, there are two important factors to achieve fault-tolerance in modular robotic systems. One is an implementation of a function to recognize various mechanical accidents in each module. The other is a design of an operation algorithm with flexibility to adapt transitions of states on the whole systems. We first describe the mechanism and the control algorithm of CHOBIE II in chapter II, and examine possible trouble patterns and detection method of them in chapter III. Then, in chapter IV, we discuss a feasibility of fault-tolerance of the system.

II. Mechanism and Control of CHOBIE II

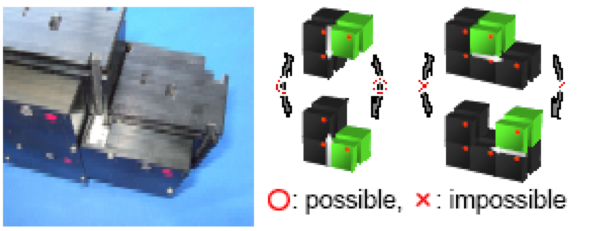
1. Mechanical Features of the Module

Figure 1(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. 1(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. 2(a). Due to this motion mechanism, modules successfully connect to other robots but cannot get joined or separated as shown in Fig. 2(b).



(a) (b)

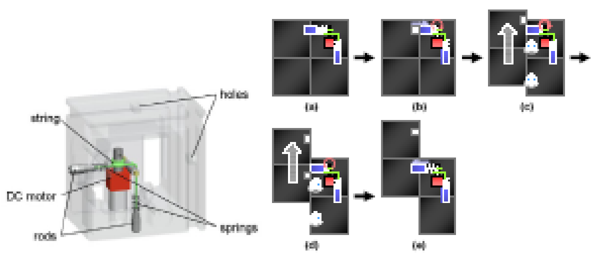
Fig. 1. Slide motion mechanism of CHOBIE II ((a): composition of the module, (b): position of the driving mechanism)



(a) (b)

Fig. 2. Mechanical constraint between adjacent modules ((a): connection of modules, (b): possible/impossible transformation)

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. 3(a). It enables the module to hold a precise position with large stiffness in the sliding direction (Fig. 3(b)). The optical communication between the adjacent modules is performed by infra-red LED and photo-transistor embedded in four surfaces of the module. Each module 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. Table 1 shows the specification of the module.



(a) (b)

Fig. 3. Locking Mechanism of CHOBIE II ((a): inner structure, (b): motion of the locking mechanism)

Table 1. Specifications of the Module

Main material	ABS resin
Size	96x96x100[mm]
Mass	600[g]
Battery	Li-ion battery (x2) (serial) 7.4[V], 550[mAh]
Moving velocity	60[mm/s]
Communication	Infra-red LED (x4) Photo-transistor (x4)
MPU	H8/3664F (16MHz)

2. Control Algorithm of 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. As a control method for such a system, we proposed "temporary leader scheme." The concept of the scheme is as follows (Fig. 4).

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 once conducts all modules and executes a slide movement. After the transformation, the next leader is selected with the same rule.

With the control program based on the scheme, the modules generate the most demanded slide movement in each immediate formation by distributed and decentralized communication. It realizes scalability and robustness of the system. By setting criteria for generating slide movements, we can enable CHOBIE II to transform to various formations. Figure 5 shows an example of the transformation.

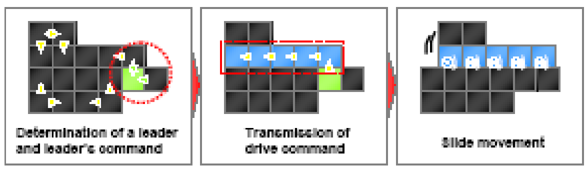


Fig. 4. Temporary leader scheme

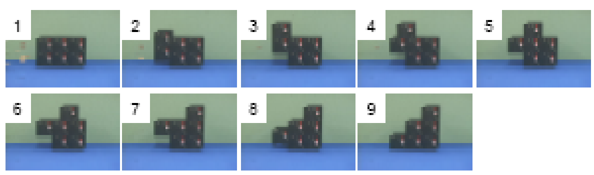


Fig. 5. Transformation to stairs structure

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III. Recognition of Troubles

1. Category of Possible Trouble Patterns

The first important issue for implementation of fault-tolerance is how the modules can recognize occurrences of troubled states. Since the modules communicate in distributed and decentralized manner, they cannot easily detect failures of other modules as well as those of themselves. For example, the modules treat the same information in either case that a neighboring module cannot communicate or that no module exists here. Therefore, in this section, we examine what kinds of problems are caused by troubles of each device.

Case 1: Trouble of Communication Device

The modules of CHOBIE II find existence of adjacent modules by receiving signals from each direction, and they determine a leader based on the information. Hence, troubles of communication devices affect the determination of leaders. But it is not so crucial situation because the distributed modules can determine an appropriate leader by usual information processing procedures without sensing the troubles, though the leader is not necessarily the most appropriate.

A fatal problem occurs in such cases that driving command from the leader cannot be rightly transmitted. Especially, as shown in Fig. 6, when only a part of modules drives the motor, the system cannot achieve the slide movement, and furthermore, driving mechanisms of the modules are damaged.

Case 2: Trouble of Driving Mechanism

A possible trouble about driving mechanism is a failure of driving motors. When modules intend to do a slide movement with which the troubled motor is engaged, the trouble becomes a break and causes large load on the other motors.

Case 3: Trouble of Locking Mechanism

There are two cases to be considered: one is a case that a module cannot lock or unlock the mechanical connection to its adjacent module, and the other is a case that a sensor for detecting the locking/unlocking state is troubled. The former can be handled by a proper program, but the latter cannot. In particular, a mechanical damage occurs when a module misidentifies that the connection has been unlocked even though it is not unlocked.

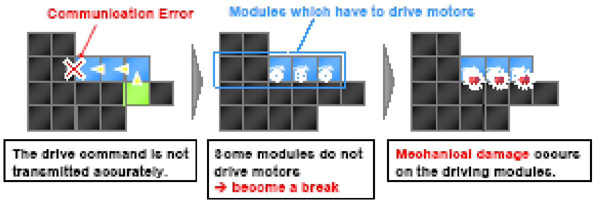

Fig. 6. An example case of communication troubles

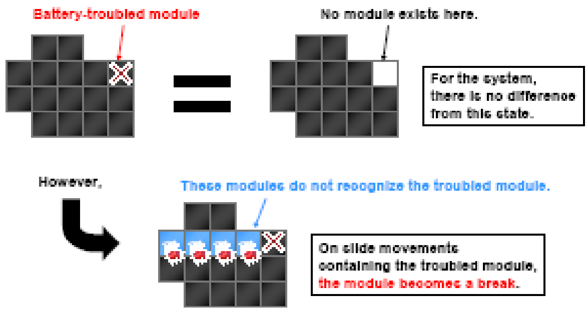

Fig. 7. A case of a trouble of electric power supply

Case 4: Trouble of Electric Power Supply

In this case, the troubled module does no action, so the surrounding modules do not recognize the existence of the module. The system acts as if there were no module in this position. The modules can determine a leader as usual. However, the troubled module becomes interruption on slide movements of the row or column which contains the troubled module (Fig. 7).

2. Detection Method of Troubles

From the above description, it can be said that troubles of every devices result in a problem of overload of driving motors in slide movements (otherwise they are not critical situations.) Therefore, by building an electric circuit to measure the electric current flowing through the motors, we can implement an algorithm to recognize troubled states from the output of the circuit.

For example, if a module detects its current over threshold in slide movement, the module immediately sends a signal to stop the motor drive. Here, if there is a module which detects no current through its motor, the module recognizes that the motor is electrically broken. Then, all modules transmit signals to find disconnected points of communication. If such a state is discovered, the modules recognize that there is a failure in infra-red LED of the sending module or photo-transistor of the receiving module. Additionally, if there is no communication trouble, the modules check operations of the locking mechanisms.

IV. Fault-tolerant Design of CHOBIE II

1. Strategy of Coping by a Robust Algorithm

Fault-tolerance of a system means that the system continues its operation or achieves its purpose even if some part of the system fails. In the CHOBIE II system, a failure of a module may cause a problem that the modules cannot carry out intended slide movements. We first discuss a way to cope with this problem by employing a flexible algorithm, which enables the system to accomplish a goal formation avoiding impossible slide movements.

In the present algorithm of CHOBIE II, the modules numerically estimate demands for partial transformations in the immediate formations of the structure, and a transformation of the largest demand is performed. Here, we introduce a method of adopting the second demanded transformation if the first demanded transformation is impracticable due to a trouble of a module (Fig. 8). This method functions well because the transformation is also available for forming the goal formation. In this method, it is important to provide appropriate criteria to estimate the demands of transformation.

2. Strategy of Separating a Troubled Module

On the other hand, there is an idea that existence of troubled modules is undesirable in order that the system may stably continue its operation. Therefore, we next examine a method to keep the system in good condition by separating the troubled modules.

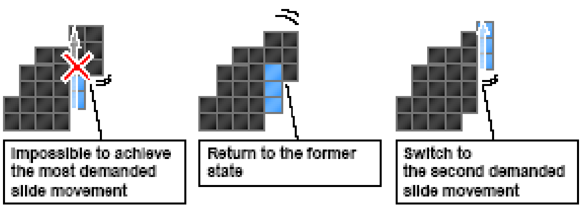

Fig. 8. A method of switching the motion pattern

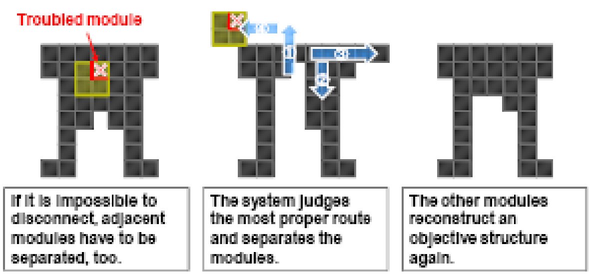

Fig. 9. A method of separating the troubled module

When the CHOBIE II system separates a module, an important issue is that the system has to separate multiple modules in response to the trouble patterns. That is, in the sequencing structure of CHOBIE II, each module manages mechanical connections with its lower and left adjacent modules. Therefore, if a troubled module cannot unlock the connections, the system may have to separate modules in positions of lower, left and lower-left adjacent of the troubled modules at the same time. In this case, the system employs a concentrated communication procedure to judge which and how to accomplish the separation. This method is also considered to be available for fault-tolerance of CHOBIE II (Fig. 9).

V. CONCLUSION

This paper described fault-tolerance of our modular robotic system, CHOBIE II. Due to the distributed algorithm, even if some of the modules are in trouble, the system can continue its objective transformation in a manner. However, when the troubled modules have to play a role in the slide movements, there are possible problems that mechanical damages occur in the driving mechanisms. We confirmed that the problems can be avoided by implementing an electric circuit to detect current through driving motors. Here, the modules can guess the trouble pattern with use of a specialized communication procedure. Then, it is expected that the system adapt to the troubles by employing flexible algorithm to transform to a goal formation without impossible slide movements, or by separating troubled modules from the structure.

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