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Development of Three-legged Modular Robots and Demonstration of Collaborative Task Execution

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***Abstract*— Our research perspective is to develop mechanisms for gathering information efficiently in disaster sites. Ideally this requires mechanisms with capabilities of flexible, on-site, adaptation of the overall shape and of the locomotion strategy to unknown and unstable environments. We have been developing three-legged modular robots which can be inter-connected to cooperatively achieve multiple locomotion modes and collaboratively perform tasks that cannot be done by a single module. In this paper, we report the development of experimental modular robots and experimentations with their cooperative activities which evolve out of their various inter-connectivity options.**

I. INTRODUCTION

In recent years, we witnessed many large-scale natural and man-made disasters such as Hanshin-Awaji (Kobe) Earthquake in 1995, New York WTC terrorism in 2001, Chuetsu earthquakes(Japan), the Sumatra coast earthquakes in 2004, etc.The importance of information collection task by remotely operable rescue robots in such disaster environments is undisputable and researches of the rescue infrastructures involving rescue robots are being actively advanced by various research groups. Applications in the context of planetary explorations also need to address very similar locomotion and task planning issues while trying to navigate in unknown and unstable environments. Performing efficiently in such situations ideally demand on-site locomotion adaptation, shape adaptation and task planning.

For locomotion in unpredictable environments adaptation of the overall shape and structure out of relatively small modular robot platforms are expected to be more efficient over pre-decided structures which are designed based on a pre-decided set of environmental possibilities. In this paper, we discuss about leg type modular robot named ”ASHIGARU”. Though man made vehicles offer much higher speed in stable pre-designed terrain compared to natural biological systems, the applicability of wheeled or crawler belt based locomotion become less and less suitable as the structure and stability of the environment deteriorates. Where as legged animals including humans are found to perform exceptional feats including crawling, climbing, walking, jumping, running, rolling, sliding etc. with two or four limbs and use whichever is most suitable for given environmental context. Thus we aimed at the development of the leg type robot modules which would collaboratively be able to navigate in uneven terrain by planning and composing the optimal number and the relative positions of the limbs, on-site, based on the task being faced. Instead of using a pre-structured robot, a team of robots which are able to form the optimal possible functional structure as and when required and maintain it only for a duration which justifies its utility, would be a more effective and efficient approach for integrated and interactive rescue operation planning and execution.

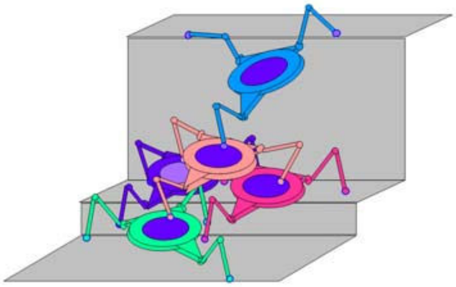

Fig. 1. Image of cooperating legged modular robots

The modular robot was advocated for the first time as a robot system that can compose form according to environment or tasks by Fukuda[1] in 1987. In the 90’s, researches in the field of modular robotics witnessed remarkable progress through efforts of various research laboratories[2],[3],[4].

The modular robots are usually classified broadly under two categories, the lattice type and non-lattice type. The lattice type robots have the structure composed of the space filling polyhedron, and the self re-composition can be done relatively easily as it is possible to move along the lattice points. However, a lot of degree of freedom is necessary for one module. The non-lattice type robot designs do not construct a robot shape from basic structural building blocks. These focus on integrating modules with certain degree of functional independence. However, the self re-composition is difficult and constrained from structural and functional point of view compared to lattice type modularity.

Some examples of major works in lattice type robots include the followings. Fracta[5] developed by Murata has three symmetric axes with twelve degrees of freedom. This robot is able to do self reconfiguration by means of rotating the arms and an automatic connection mechanism. I-Cube[6] is composed of the link and the cube. The link can be moved by uniting with the cube. A metamorphic robot, Proteo[7] has twelve identical connection faces which can connect with other modules, and Electromagnets are used for module

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connection.

On the other side, examples of major non-lattice type robots include, the PolyBot developed Yim[8] which has two types of modules, node type module and the segment type module, and various forms can be taken by combinations of them. Shen's robot[9] named CONRO is able to do separation and re-composition by the automatically and can transform into leg type, snake type and so on. Kurokawa[10] has developed the modular robot named M-TRAN(Modular Transformer). This robot also can change the form into legged robot, snake like robot etc. using pre-decided group of modules.

Our development of three-legged module, called ASHIGARU, also belongs to the non-lattice type modularity category. The common purpose of all modular robots is to be able to act by adjusting to the various environment by using the multitude of interconnection possibilities and changing the overall shape. However, most of the modular robots hardly have the ability to move only by a single module and the locomotion abilities emerge only when a number of modules are interconnected. Not many moduler robot designs are available, where each module can move arround indipendently. In the case of ASHIGARU, each three-legged module has some indipendent locomotion capabilities. In the context, for target applications in disaster environments, it is essential that each module posses as a minimal locomotion capability without external assistance, to make the on-site structural re-composition possible and to rescue itself in critical situations.

II. CONCEPT OF ASHIGARU

The purpose of the mechanism is to collaboratively adapt to various environments. ASHIGARU doesn't have very high degree of mobility by only one module as it has only three legs[11]. However, the concept of this robot is that two or more modules interconnect and cooperate to surmount obstacles in unpredictable environments where locomotion may be difficult with pre-structured robots (Fig.1 shows a schematic (futuristic) image of the three legged modular robot functionality of performing a collaborative wall climbing task).

In the natural world, a lot of living things with the legs of the even number exist, two leg, four leg, six leg. However, the living things which have only three legs do not exist. That is, in the viewpoint of biology, three-leg is not reasonable number for locomotion.

Then, why was three legged robot adopted? To have legged robot modules it is desired that each modules be light in weight, small in size and cost-effective while capable of minimal autonomous locomotion, and having connecting capability to be part a complex assemblage of similar modules. These added with the consideration of static stability with narrow footprint the three leg module seemed preferable over one and two leg module options. The three-leg also offer the convenience and symmetry of using any leg for connecting with other modules and use the other two legs for contributing to the support or locomotion of the overall assembly. When required these three legged modules can be efficiently composed to mimic most of the biologically available legged structures so far leg counts are concerned.

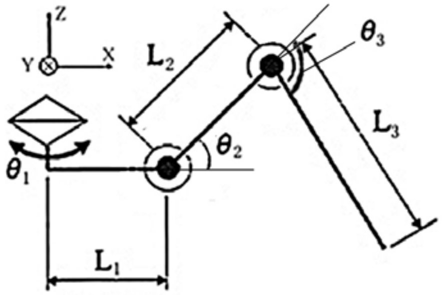

Fig. 2. Mechanics model of a leg of the robot modules

TABLE I

MECHANICAL DETAILS OF THE ROBOT MODULE

Weight of a module	920[g]
Maximum hight of a module	210[mm]
Radius of body (excluding the legs)	60[mm]
Thickness of the body	38[mm]
Weight of each motor	55[g]
Motor torque	16.5(9.6V)[kgf·cm]
Maximum rotational velocity	70[rpm]

In the current work, we intend to study the possibilities and benefits of collaborative task execution which emerge out of different structural interconnections of the multiple robot modules. Thus, in the experiments discussed in section 5, the movements and the motion plans of each module are currently preprogrammed. In the next stage of development, the individual modules are expected to communicate the sensory date about their orientations and environments to a host computer and have the motion plan generated centrally by that host computer.

III. CONFIGURATION OF THE ROBOT

We made four experimental modules and tried experiments with their inter-connected operations. The legs are arranged at intervals of 120 degrees and each leg has three degrees of freedom like that of most common insect's legs. We show the leg's structure and degrees of freedom in Fig.2. Length of the three constituting links (as shown in Fig.2) are L_1=67mm| L_2=67mm| L_3=120mm. The first joint rotates in the direction of the yaw axis, the second and the third joint in the pitch axis. The movable ranges of each joint are $-90^\circ \leq \theta_1 \leq 90^\circ$, $-90^\circ \leq \theta_2 \leq 90^\circ$, $0^\circ \leq \theta_3 \leq 180^\circ$.

Servo motors are used to drive the joints. Each joint is equipped with one servo motor. Thus, each module has nine servo motors. Each module is equipped with a microcomputer which is used to control the servo motors. Fig.3 shows an the top view of ASHIGARU in (a), the side view in (b), the comparison with 500ml PET bottle in (c) and the view of the inter-connection between two modules in (d).

In the current design any of the three legs can be used for connecting with other modules. While connecting, to reduce

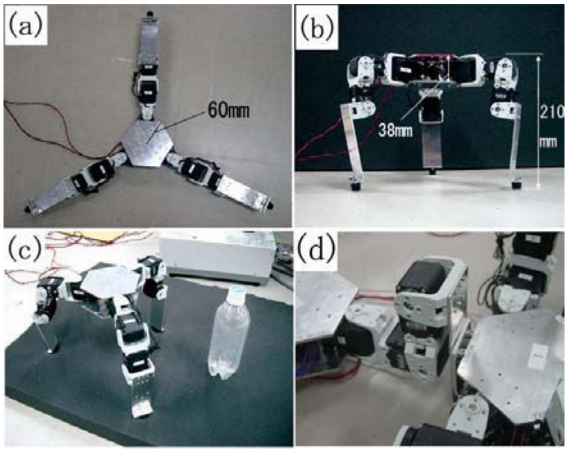

Fig. 3. (a)The top view of the robot (b)Side view of the robot (c)Comparison with 500ml PET bottle (d)Connecting part

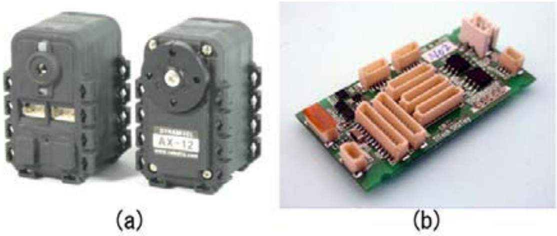

Fig. 4. (a)Dynamixel AX-12 (b)TITech SH2 tiny controller

the load of the connecting part as much as possible, the connecting leg is folded like Fig.3(d).

The modules are intended to be capable of interconnecting and disconnecting autonomously at a later stage of development. In the current work, we focus on the collaborative operational features and possibilities of three-legged modules. Thus, corrently the modules are interconnected manually to construct various configurations.

IV. SYSTEM CONFIGURATION

Dynamixel AX-12, made by the ROBOTIS company, is used as the joint actuators (Fig.4(a)). The basis of selection of this actuator was the high weight to torque ratio at a relatively low cost compared to other available options for the target size. Unlike usual radio-controlled servos it has the feature of transmitting the commands by serial communications instead of PWM based settings. Thus, it is possible to control multiple motors at the same time by connecting them in series and there is also the advantage that information of the current angle and the temperature of the motor are available to read out.

The TITech SH2 tiny Controller, made by the HiBot company, is adopted as the on-board microcontroller (Fig.4(b)). This is of a miniature size of 25mm∑ 50mm, and it comes with three serial ports(RS-485). The CAN bus option is also available for communicating with other microcontrollers.

As for this robot, each module is equipped with one microcontroller board and information is sent via the three serial ports of the microcontroller board to three legs respectively. External input for the driving motors is transmitted from PC through a serial communications port which is subsequently converted to CAN bus by a microcontroller dedicated to perform the protocol conversion. When two or more modules mechanically interconnect to form a composite structure, the microcomputers of the modules are connected by CAN bus to exchange controller level information. Each leg has three motors connected in series and this structure allows operating three motors through a single serial port. The motors connected over the same bus can be addressed uniquely by referring their pre-allotted unique IDs. In the current version the power supply of each module is externally supplied by cables and the sensors for environment recognition are not installed yet. The communication structure of the entire system is shown in Fig.5 and details of the communication structure of a module are shown in Fig.6.

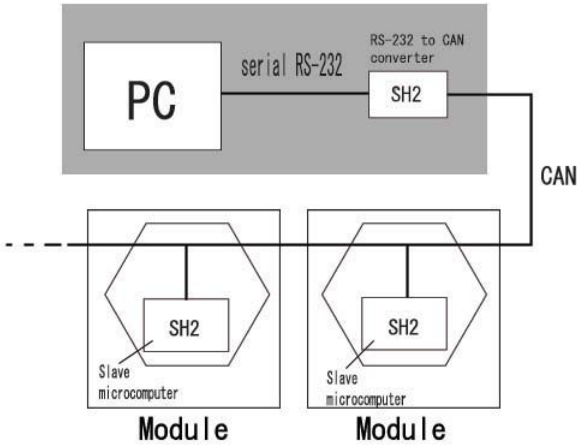

Fig. 5. Overall communication structure of a system with interconnected modules

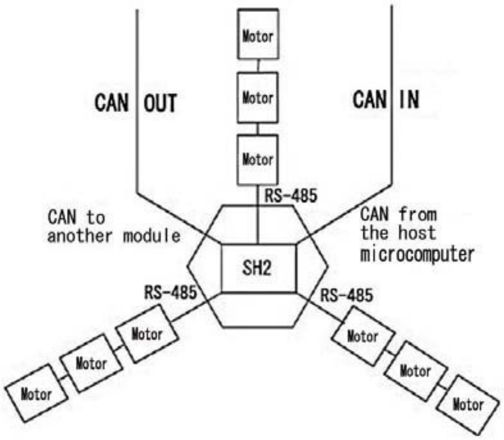

Fig. 6. Communication structure within a single module

The microcontroller on board of each module is always in the reception state waiting for incoming data through the

CAN interface. When data is received appropriate commands are sent through serial ports(RS-485) to the leg joint actuators(Fig.6). The mailbox concept is used for the sending and receiving of data by the CAN. The mailbox is the one to store the received data temporarily and transmit when appropriate. Thirty-two mailboxes are prepared in each microcontroller, and the data of eight bytes can be stored in one mailbox at a time. The protocol converter controller sets the data first in the send mail box and begins transmitting. The onboard microcontroller stores data in the receive mail box once and completes the reception. Moreover, with unique ID assignment of the mailbox of each microcontroller, different data can be sent at the same time.

V. EXPERIMENTS WITH REAL ROBOTS

In this section the operational experiments that use the implemented robot are described. First of all, the capabilities achievable only by a single module is described followed by descriptions of some of the cooperative activities performed by collaborative interactions among multiple modules. In this paper, we experimented by already-known experimental environments, and all movements are programmed beforehand by trial and error. Once the limits of the collaborative capabilities are evaluated, autonomous movement planning would be the subsequent focus of research. Thus, currently, the host computer transmits byte sequence that include the information of the target position of all the joints, at constant intervals, which are appropriately re-distributed within the composed robot body by the robot module controllers.

A. Activity by a single robot module

This robot cannot do the steady walk because it has only three legs, but it is possible to move by crawling} For example, the robot arranges the foot ahead in the traveling direction with the body put on to ground, and the body is lifted, advances, and put on the ground again as shown in Fig.7. Fig.7 also shows the number of motors and the target position of the all joints. It is possible to move forward by repeating these basic movements. We achieved 4cm/s of speed with this type of locomotion.

By operation using this movement it was confirmed that the robots are able to overcome a level difference of about 100mm. As described above, these robots have some primitive movement ability though it has only three legs. In the future, when module inter-connections will be changed in un-manned, autonomous scenario, it is necessary to act temporarily only by one module. In addition, when acting by two or more modules, the possibility of damage of a constituting module can be thought of. Consequently, it is important that individual modules has some minimal locomotion ability.

B. Walking by connecting modules

When two modules connect, it becomes a five-legged robot, and the assembly becomes capable to walk like the conventional four-legged robots. In this case, the 5th leg can be used as a supplementary leg to achieve better stability if required in some of the possible 4-leg locomotion modes.

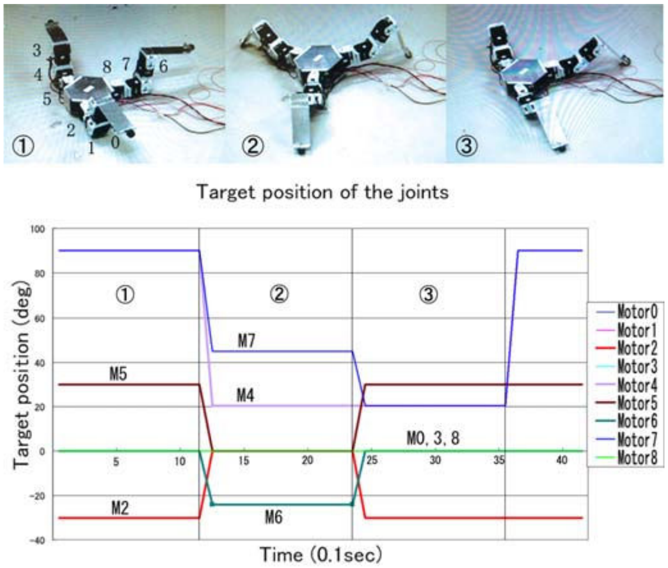

Fig. 7. Movement of a single robot module and the intermediate target positions of each joint

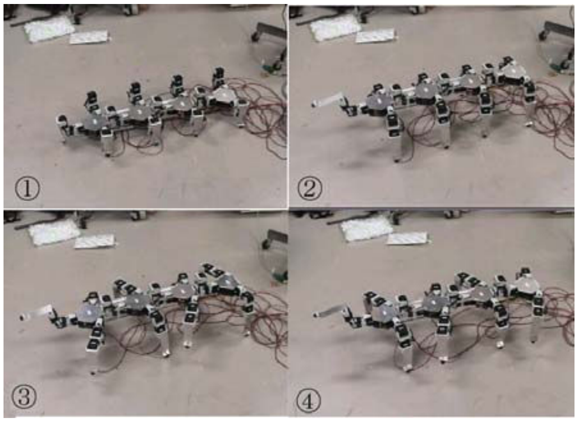

Fig. 8. Walking of four serially interconnected modules

However, as shown in Fig.8, by connecting more modules is series, more stability during walking is achieved because the center of gravity position moves to the rear side. As a result, the composite robot structure is able to use the frontmost leg for usages other than supporting walking.

For instance, if a miniature camera can be put on this leg, it is possible to use it for the information gathering by acting as a camera arm, even if no dedicated camera arm is attached.

This is an important feature of the modular robots to have redundancy of usable limbs as the number of connecting modules increases.

By such connection, the static walking became possible, and the assembly can walk with faster speed(10cm/s) than only one module.

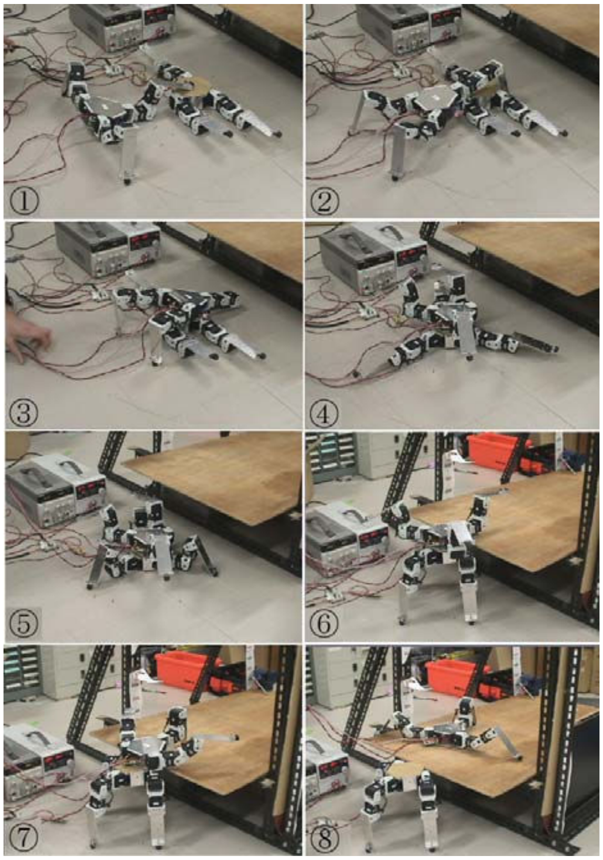

Fig. 9. Cooperative task of two independent robots units

C. Task of climbing over a step by cooperation of independent robot modules

By Using two modules and giving a different role to each module, we experimented with the cooperative step climbing task (Fig.9).

The sequence of step climbing operation is described below. First, one of the modules gets on top of a second module by using its basic locomotion capability, when the second module is in a resting state on the ground supported by the central body part with the legs spread away from the body horizontally in a way not obstructing the approaching movement of the climbing module. Once the climbing operation is completed, the module below starts moving using the basic three legged locomotion and approaches the step to be climbed, carrying the first robot on its back. Then the locomotion mode is changed and the module below stands up, so that the module on top is lifted up to the height of the step. Finally the module on the top uses the basic locomotion to climb down from the top of the lifting module and move on to the elevated surface.

A real sequence of operation is shown in Fig.9 in the order of ①≤ ⑧ activity sequence. The climbing module gets on on the another module from ① to ⑤, then the lifting module stands up and it is made to come alongside the step on the difference in ⑥ and ⑦.

However, there is a necessity for verifying the optimality of the operation of each module about each operation of the action sequence. It succeeded in climbing the difference of about two times higher than the level difference scalable by one module. The height of the level difference was found to be 22cm for successful climbing. It took about one minute to achieve this operation.

By this experiment, the possibility of the modules' mutual cooperation and complementing the low degree of individual ability of moving in uneven surface of small robot modules was shown.

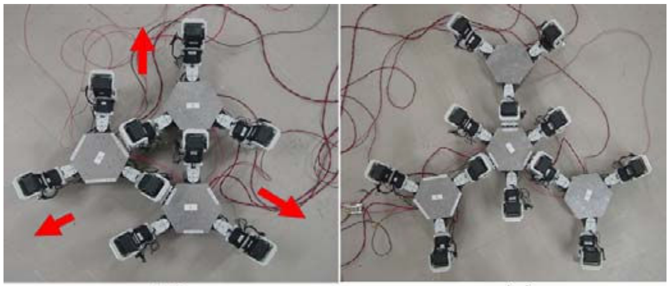
(a) (b)

Fig. 10. (a) Toroidal conection of three robot modules, (b) Radial conection of four robot modules

D. Traveling direction switching in a Toroidal Connection of three modules

Each of these robot modules can connect using any of the three limbs and in turn they may get connected at three inter-limb segments of the body. Thus the modules can be connected in a toroidal structure. As shown in Fig.10, three modules are connected in a toroidal structure, which is symmetric in three directions. Thus in this connection, the robot can change the traveling direction at any point of time without requiring turning around. The walking experiment while switching the traveling direction by the walking pattern that the phase of the adjoined legs is different by 180 degrees was performed. In this case the way the leg joints move is different for each foot. Thus it is necessary not only to adjust the phase of each foot but also to adjust the movement of each foot so that the leg trajectory to the traveling direction is made to become equal. The triangular structure formed in this interconnection, is found to have better structural stability than series type connectivity. Thus this offers a suitable connectivity option for activities where steadiness of operation is essential.

E. Transportation task by Radially Connected four robot modules

Three modules are connected surroundings a centrally located module like Fig.10(b). By this connection, three modules of surroundings perform the locomotion task, and the limbs of the module at the center is free to be used for manipulation tasks.

The images of the experiment to transport a ball is shown in Fig.11. The operation is in the order of ①≤ ⑦. It advances toward the ball in ①≤ ③, and in ④, the ball

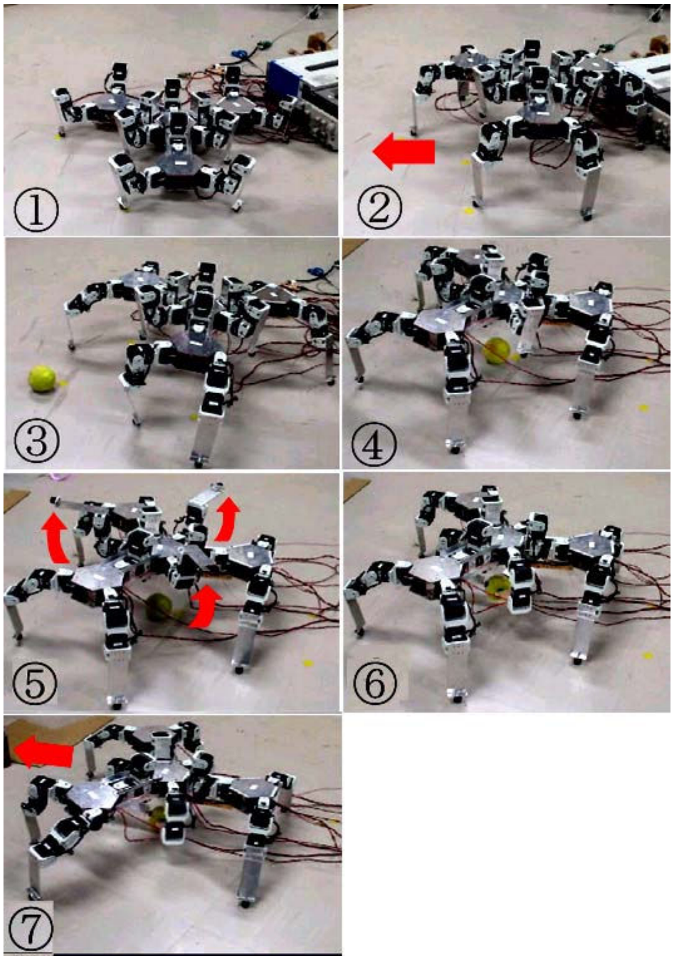

Fig. 11. Transportation task by a radially connected assembly of four robot modules

becomes right under the module at the center. Then the central module spreads out the arms (which are the legs in case of locomotion role) in ⑤ and grips the ball in ⑥, and surrounding modules begin the walking again in ⑦.

This experiment also demonstrates that even if the ability of each module is not very high, when two or more modules unite and cooperate, various abilities arise out of the structural interconnection and functional role distribution among the collaborating modules.

By these experiments, it was confirmed that the leg type modular robots has different advantages in different interconnected structures. Currently the above-mentioned experiments were conducted to demonstrate this concept. Thus all operations were programmed beforehand. Autonomous connectivity-planning and task distribution among the collaborating modules remain the focus of subsequent research.

VI. CONCLUSION

In this paper, we described about hardware and the system configuration of the modular robot we have developed. We also report the experiments involving activity by a single module robot, walking by connected multiple modules, task of climbing a step by cooperation of two single-module robots, traveling direction switch by toroidally connected three modules and object transportation task by a radically connected four robot module assembly.

During the experiments, we realized that the strength and stability of the interconnecting mechanisms are important design criteria for the robot modules. In some configurations a high value of loading - often of the order of a whole robot-module body weight - may be expected to be imposed on the coupling parts of the modules. Thus, during design stage we need to consider which interconnected configurations are to be supported by that robot module.

In the context of locomotion, it is necessary to walk while keeping static stability when walking. However, in the case of robots composed out of smaller components, the center of gravity position changes by the structural interconnections. Therefore, we need to constructs the mechanics model, and the system that recognizes the interconnected structural shape and walks while adjusting the center of gravity position accordingly.

The main issues requiring detailed study in the future are summarized as follows.

- Development of uniting part that can do the separation re-composition and offer sufficient rigidity
- Construction of system that automatically recognizes interconnection and adapts the locomotion accordingly
- Computation of task specific optimal structural interconnection by sensory information integration

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