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イモムシ型探索レスキュー・ロボットの開発
Development of An Inchworm-type Searching Robot

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Abstract This paper describes an inchworm-type robot that we developed for the application of disaster relief, specially for searching victim. The robot we called AIT-ReBo1 has two types of modules, one is the head module that is equipped at the terminal of the robot's body with a small wireless camera and wireless network functions to communicate with outside, another module is the joint that has two rotational and a linear driven degrees of freedom with a decentralized controller module and energy source in a compact form. We pay attention to moving mechanism and realized the motion patterns such as moving straight, side and rotational movements like an inchworm by the progressive wave in body without using any wheels, or crawlers and legs.

This robot has already successfully debut at the AICHI EXPO 2005 and stably played for about one month.

1. Introduction

According to the differences of complexities and our pre-knowledge, working environments of robots can largely be classified into following four categories:

(1). Well-structured environment;
(2). Extreme environment;
(3). Daily life environment; and,
(4). Disaster environment.

The well-structured environment is an environment such as a production line where the overall working conditions of a robot are already known and fixed. Industrial robots can then be effectively used to perform predefined works repeatedly under this environment.

In the environment such as nuclear power facilities and space or deeper ocean, the working conditions are extremely difficult and almost impossible for human to work there. In addition, we do not have sufficient knowledge about such environment. Therefore, we have to apply the robot to realize the required tasks instead of human workers.

Recently however, researches and developments of humanoid robots and service robots, which are expected to work in our daily life environment such as the office spaces and home, have received increasing attentions. These robots are required to realize smooth communication with human and to cooperate with human safely and softly, such as to do office guard at night times and the nursing assistances.

On the other hand, due to the disasters, such as earthquake or damage by a flood, our daily life environment may suddenly be changed into a disaster environment, where the complexity is increased by the collapse of the building due to the earthquake or the landslide due to damage by a flood, etc.. In addition, the secondary danger of the disaster such as fires and further collapses may also happen. It is then risky and danger for human to work under such an environment to rescue victims. Especially, the difficulty was shown by Hanshin-Awaji (Kobe) Earthquake in Japan, where more than 5,000 people dead and the damages of the buildings were also unthinkably terrible. The rescue teams of human workers were compelled by fear of the secondary disaster. Moreover, it was clarified by a technical report [1] of the earthquake that, more victims would be extricable, if the rescue activity could be performed in time after the disaster. Therefore, since robots are more suitable than human to work under the disaster environment, researches and developments of disaster environmental robots are also very important.

In this paper, we propose an **inchworm-type rescue robot** to perform searching tasks in the Disaster environment.

With respect to task requirements, there are two basic functions that are required for the rescue robots, the searching task function and the rescue function, respectively. The searching function of the robot aims to search to discover the victim under the disaster environment, while the rescue function aims to move victims from the environment with the danger of the second disaster generation to secure surroundings.

For the searching task, the robot should have the following two specific abilities: to search for the victim and to move through complex geographical features, narrow places of the disaster environment:

- Locomotion Ability
- Searching Ability

This paper mainly considers the locomotion ability of the searching robot with a unit-type structure.

By now, there are several robots that are proposed and developed to realize locomotion under disaster environment. For example, the robots using crawlers by Hirose [2] , Osuka [3] and Borenstein[4] et al., the snake-like robot “KOHGA” by Matsuno [5] et al.. These robots have snake-like structure. The main propulsion is generated by using active wheels equipped within the robot's body, or the crawler that connects active/passive joints with two or three degrees of freedom. In the snake-like robot

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which has three degrees of freedom joint developed by Ma [5], it does not have any mechanisms like wheels and crawlers in its body, the propulsion is generated only through movement of three active degrees of freedom joint which connects between each parts of the body.

The structure of the snake-like robots has the same unit-type body connection as our **inchworm-type rescue robot**, which increases the performance for fault and low cost by mass-production. However, as will be pointed in the next section, the snake-like movement has a problem that it requires relatively large tail swing motions to obtain propulsion forces, and is not suitable to move at whose rescue places that are narrow such as to move through a pipe. Compared with the snake movement, an inchworm can realize its propulsion using the progressive wave for the body to contact with its ground with relatively small body oscillations as shown in Fig.1, which inspired us to develop such type of the robot.

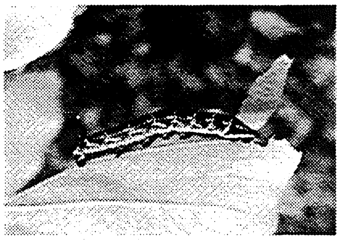


Fig.1 An inchworm propel its body motion using progressive waves

There is also another type of rescue robot system that is developed by Kawashima [7] et al. using the remote control of construction machines. The robot uses the artificial air pressure to remove tiles and pebbles.

This paper pay attention to the robot's locomotion function in rescue environment and proposes a novel unit-type of searching robot AIT_ReBo.1 that can move by the progressive wave in a body without using any wheels, crawlers or legs. The AIT-ReBo.1 has three degrees of freedom joints together with a small controller and battery in a unit. Five units are connected in a series structure to realize inchworm-like movements, such as back/forth movement, side winding and rotating movement. In addition, a wireless camera is installed at the head of the AIT-ReBo.1, the image from it can be presented to the operator so as to control the robot with wireless communication module installed at the tail. The robot has successfully been exhibited at the last international exposition "Love and earth Expo" in 2005. Various operations were performed stably during one month of the exhibition.

The following of this paper is composed as follows. Section 2 studies basic features of unit-type searching robots, and section 3 describes detailed structure design of our unit developed in AIT-ReBo.1 and a small decentralized controller that is developed to control the robot. 3D dynamic simulations and real locomotion experiments of the robot are shown in section 4 and the conclusion is given in section 5.

2.UNIT-TYPE SEARCHING ROBOT

In this section, we first analyze the basic features and problems of unit-type robots for rescue searching tasks so as to clarify our robot design.

The main objective of searching task under disaster environment is to search victims at the first time of disaster. Since snake-like robots can move under narrow spaces, for the rescue searching tasks, they seem to be one of the most effective selections.

By now, there are many snake-like robots that are developed to imitate the natural snake's motion mechanisms. These robots basically generate propulsion by using the friction difference between the vertical direction and the direction of progress, and along the direction of progress, wheels are installed in the robot. An example can be found in the snake-like robot ACM-3[8] developed by Hirose, the wheels on the body can reduce the friction along the direction of body motion.

However, in order for a snake-like robot to reduce friction along the direction of progressing efficiently and to get larger promotion power, it must swing its body widely. This will be a main difficulty for the robot to move in the limited narrow disaster spaces.

In addition, although motion driving mechanisms, such a active wheel or clawer, can realize propulsion easily, because there is a danger for the robot to be buried in obstacles or fall down in the disaster environment, it is necessary to set them on all sides of the robot body so as to move according to any posture. However, if wheels and crawlers were set at everywhere on all side of robot to generate propulsion, not only the length of the robot body but also its weight will be largely increased. On the other hand, if we reduce the length of each body unit, the unit will come to contact with each other within the body and the range of joint operation will become narrow. Moreover, a lot of energy should be necessary for driving the heavy body, and accordingly arrangement of energy source, such as a battery, in such a snake-like robot with multi-degrees of freedom will become difficult or even impossible.

Therefore, we come to the conclusion that, it is unsuitable for the searching task robot to use the driving mechanisms of wheels and crawlers, they may be buried in tiles and pebbles and require larger energy source for driving.

In order to overcome these problems, Kamekawa et al.[9] proposed a movement method by twisting the joints of robot body without using any active wheels or clawer mechanisms. Ma et al.[10][11] proposed the straight line type inchworm-like movement of a robot with three degrees of freedom joint. As shown in Fig.2, this is a movement method that gets propulsion by shortening and making a mountain shape on the body, the shape is moved in the direction of progress to the tail of the body. This locomotion approach can obtain larger propulsion force and requires smaller joint rotations. However, since the late part of the robot body should always making slid on the ground while moving, it is still far away from satisfaction as seen from the point of view of robot's energy efficiency. Fig.3 shows the difference a inchi-worm locomotion and movement of inchworms that get propulusion by shortening and making a mountain shape on the body.

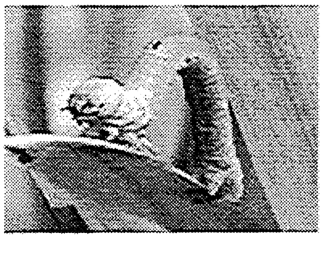
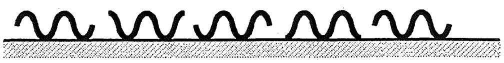


Fig.2 Movement of an inchworm that get propulsion by shortening and making a mountain shape on the body.

(a) propulsion by shortening and making a moutain shape on the body



(b) inchi-worm locomotion

Fig.3 A difference between two locomotion mechanisms.

Many snake-like robots have unit-type mechanical structure that constructs the bodies by many units and joints. The unit-type structure has the possibility to adapt to complex environment because the shape of the robot is changeable by reform the unit connections. Moreover, it is suitable for moving while avoiding obstacles and complain to complex geographical features because the robot of multi degrees of freedom can be composed, and can be rearrange to a snake-like, a ring type, and a multiped type according to the task requirements. The unit-type robot can also easily be recovered from some damages only by exchanging of breakdown unit but not need to exchange the entire robot when some parts are broken down. This is because that two or more units are connected and it composes one robot. Moreover, it is also possible to make the best use of multi degrees of freedom to supplement the broken unit or to simply remove it out. A robot with one complete structure however is inconvenient when some parts are broken down. In summary, compared with the complete robot structure design, the cost of the unit-type robot can be reduced by mass-producing of the units.

Furthermore, for the robotic applications in a disaster environment, considering the wide range of the disaster, it is expected to have huge amount of robots with low cost and even low functions to work in a distributed way than just to use one or two high cost and high functional robots. Moreover, since generally the snake-like robot has large length of body, it is unsuitable for transporting it directly, but rather to set the robot in a unit structure, which makes us possible to decompose and reconstruct it at disaster places.

Based on above discussions, we develop a novel inchworm-type robot with the unit-type structure for searching tasks in disaster environment. The movements of the robot are generated through directly interaction between the robot body and its ground without utilizing any other driving mechanisms such as wheels, crawlers, and legs. In detail, unlike Ma's approach, we realize the robot's body propulsion by generating progressive waves on the body that is inspired by the basic driving principle of an ultrasonic motor. By adjust the phase differences between each unit, the robot can easily change its motion from back to forth.

3.Design of AIT-ReBo.1

Here we come to show system designs of our robot --- AIT-ReBo.1 in this section.

AIT-ReBo.1 is composed of five units as shown in Fig.1. For each body unit as shown in Fig.4, there are two rotational joints, a linear joint and a controller which is used to calculate the control input and to communicate with neighbouring units. The head unit has wireless LAN module and a wireless camera that can communicate with outside PC and human operators. The units can be connected in a straight way and move like an inchworm. In the following, we will introduce the detailed mechanical and electric system designs.

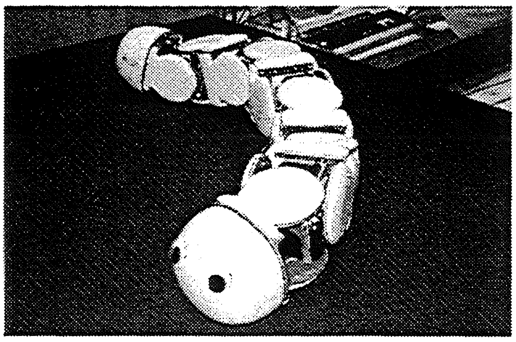


Fig. 4 AIT-ReBo.1 connected by five units.

3.1 Mechanical Design of the Unit

Considering the fact that a complicated mechanical design may result in the increment of the robot weight as well as electrical power capacity, in designing of AIT-ReBo.1 we aim to develop the unit mechanism as simpler as possible.

However, if a unit joint has only one degree of freedom of activation, then we must add another offset angle among the unit that may lead to the increase of connection mechanism between each unit. Therefore, in the unit of AIT-ReBo.1 we have two degrees of freedom that located orthogonally. Moreover, a linear joint is added for the unit to get propulsion by longitudinal wave like an earthworm. The actuators placed in a unit are chosen among RC-Servo motors obtained from the market that can put high torque. Fig.5 shows the shape and structure of one unit. The unit shape forms a hexahedron with its length and breadth 64cm, height 100cm, respectively. The connection plates are placed at each end of the unit to connect with other units. The unit's total weight is 400g include battery and controller. Each side of unit can install contact materials as shell (for example, the green shell in Fig.4) to make soft mechanical interaction with its environment.

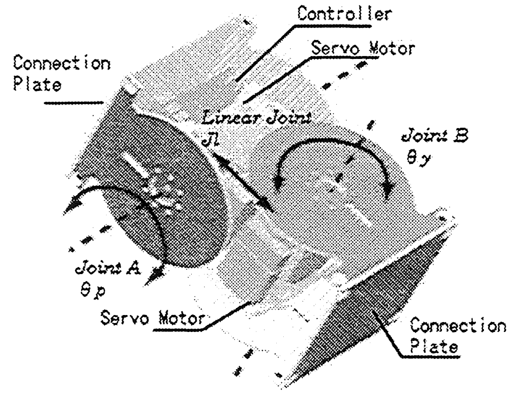


Fig. 5 Mechanical design of a unit that has 3-DOF joints, a distributed general controller and a battery.

3.2 Control System Design

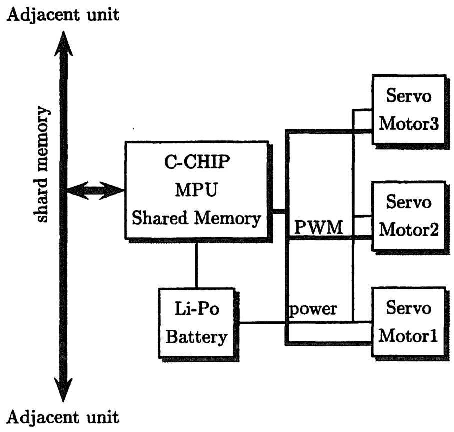


Fig. 6 Controller structure inside the unit.

The control system designed within each unit is shown in Fig.6. In detail, there are three RC-Servo motors, two for rotational joints and one for linear joint that are controlled by a small controller C-CHIP [12](Fig.7, Fig.8) we developed. The controller generate PWM signals to drive each joint angle motions. As a power source for the RC-Servo motor and C-CHIP, we placed Li-po battery.

The small controller C-CHIP has its size of 3cm by 4cm, and is composed from some function modules. There are six kinds of functional modules: AD, DA, serial communication, distributed shared memory, digital I/O and two phase counter function, respectively. AD and DA module has eight channels with twenty bit resolution for each channel.

The distributed shared memory module contains 512 bytes memory area that can share with other controllers to maximum 64 controllers with 2msec of data update cycle. The serial communication module has four channels par board and contains 64 bytes FIFO transmits and receiving buffers to assist in programming.

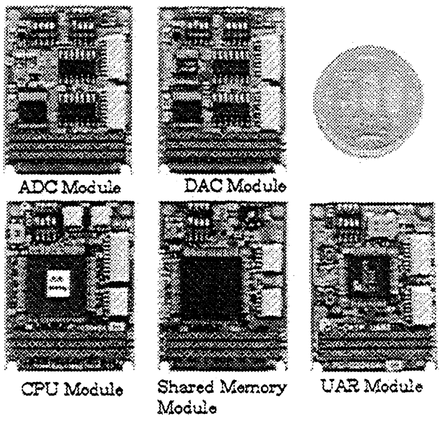


Fig. 7 Functional modules of the general controller.

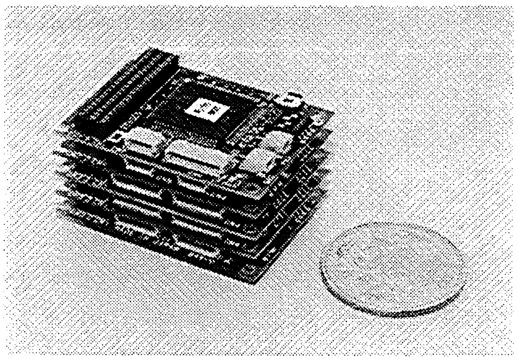


Fig. 8 Distributed controller: stacked from five modules.

One of the main features of the C-CHIP small controller is that it is possible to construct any types of function modules by selecting the necessary functions as shown in Fig. 8, where 5 different functional modules are selected and assembled.

3.3 Control Approaches

By utilizing the distributive controller network, two control approaches for the unit are studied, they are centralized control mode and distributed control mode.

In the centralized control mode, we transmit by shared memory all units' reference joint angles of the robot calculated on each control cycle at outside PC via wireless LAN. The unit controller then controls its RC-Servo angles by PWM signals following the reference joint angles. This control mode is useful for designing a specific motion of the robot because it can intensively control angles of all units of the robot from an external PC.

On the other hand, in distributed control mode, the motion pattern is calculated by the controllers within every unit. Specifically, each local controller calculates internal oscillator phase that is influenced by the oscillator of neighbouring units. Ito [13] et al. gave the method of deciding the interaction between each oscillator from the potential function of the phase difference space. This technique was used to control the AIT-ReBo.1. Each oscillator connects with each other as shown in Fig.9.

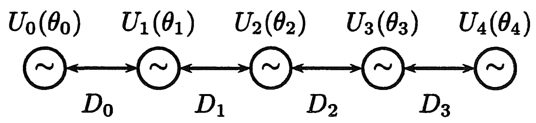


Fig. 9 Connection of five internal oscillators.

The phase of the internal oscillator of the adjacent unit is acquired every control cycle, and the phase of the oscillator is updated based on target phase difference *Di* (i=0,1,2,3) between units given from external PC. Dynamics of the oscillator is shown by eq.(1).

$$\dot{\theta} = \omega_i + f_i \tag{1}$$

where ω_i is the angler velocity and $fi(i=0,1,2,3,4)$ is interaction between oscillators that are given as follows:

$$\begin{aligned}
f_0 &= \tau_0(\theta_0 - \theta_1 + D_0)\\
f_1 &= \tau_1(\theta_0 + \theta_2 - 2\theta_1 + D_0 - D_1)\\
f_2 &= \tau_2(\theta_1 + \theta_3 - 2\theta_2 + D_1 - D_2)\\
f_3 &= \tau_3(\theta_2 + \theta_4 - 2\theta_3 + D_2 - D_3)\\
f_4 &= \tau_4(\theta_3 - \theta_5 + D_3)
\end{aligned} \tag{2}$$

τ_i is a constant value which adjusts the value of the interaction between oscillators.

The controller in the unit calculates angles θ_{pi} and θ_{yi} of the joint by using eq.(3) from the phase of the oscillator, in which, Vm is the maximum joint angle and ϕ_i are the phase differences of angle θ_{pi} and θ_{yi} of the joint.

$$\begin{aligned}
\theta_{pi} &= Vm\sin(\omega t + \theta_i)\\
\theta_{yi} &= Vm\sin(\omega t + \theta_i + \phi_i)
\end{aligned} \tag{3}$$

In the centralized control mode, the robot's motion patterns are generated by an external PC. Therefore, it is simple to design the robot's motion behaviours. However, calculation and communication cost will increase with respect to the increase of unit numbers. Conversely, the calculation and communication cost will never change even if the number of units increases in the distributed control mode.

Based on above system designs, AIT-ReBo.1 can realize not only the snake-like motion by swing along the horizontal direction of the ground, but also inchworm-like motion by oscillate along the vertical direction of the ground, which makes it possible to move in the narrow rescue places.

4. SIMULATION And EXPERIMENT

Since it is difficult to formulate the model of interaction between our robot and its ground, in order to select the optimal control parameters of phase difference *Di* and maximum joint angle *Vm* for the fast motion, we performed 3D dynamic simulation as shown in Fig.10.

4.1 Simulation Studies

ODE (Open Dynamic Engine) was used for the computer simulation of AIT-ReBo.1. The robot developed in the simulator is the same as the real AIT-ReBo.1.

For each case of the control parameter of the maximum joint angle *Vm*, we increased the parameter of phase difference *Di* between oscillators of each unit and measured the robot's motion speed during straight locomotion, where we set

$$\begin{aligned} \omega_0 = \omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega \\ D_0 = D_1 = D_2 = D_3 = D \end{aligned} \qquad (4)$$

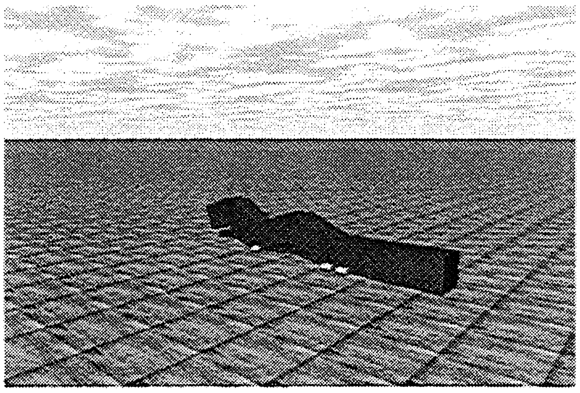


Fig. 10 3D dynamic simulation of the robot.

The result is shown in Fig.11. At the phase difference of 0.75π, the robot's speed becomes maximum, and if the phase difference approaches π, the robot stops its motion. Moreover, the robot's speed can be increased by increasing the maximum joint angle *Vm*.

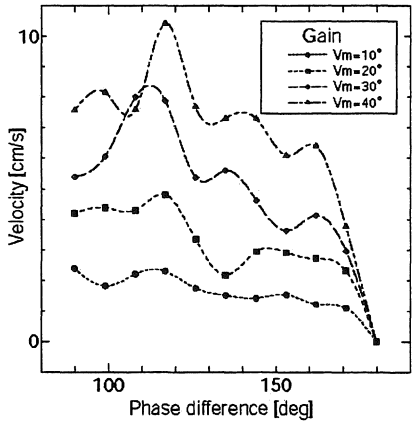


Fig. 11 Simulation result on the optimal control parameters for the fast straight locomotion.

4.2 Experiments on Various of Locomotion Patterns

In the experimental studies, we realized various locomotion patterns by the robot. Here, the wireless module to communicate with external PC and wireless camera in the head modules are installed at the both end of robot. The image from a wireless camera can be presented to robot operator who operates it with the joystick installed in external PC. In the operation experiment, phase difference is set as *Di=0.75π* which was the optimal parameter obtained from above simulation study.

The target angle of a horizontal servomotor was assumed to be constant 0 degrees for *Vm=0*. Therefore, it moves forward, and can climb slope of about 20 degrees as shown in Fig.12. In Fig.13, we set $\phi_{pi} = 0.5\pi$, this time, the robot did not move forward, and began to move slide. In Fig.14, the robot realized the rotational movement by set $\theta_{yi} = \theta$ a constant angle.

The robot was also succeeded in moving through a narrow pipe, that is expected to be realized during rescue activities.

The battery of 720mAh was built into all units, respectively without any power supply from outside, and makes it possible for the robot to move autonomously for about 30 minutes.

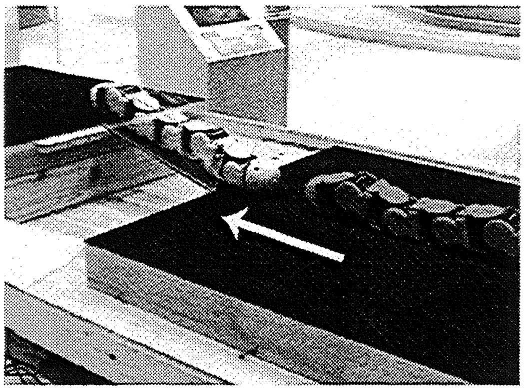


Fig. 12 Straight locomotion.

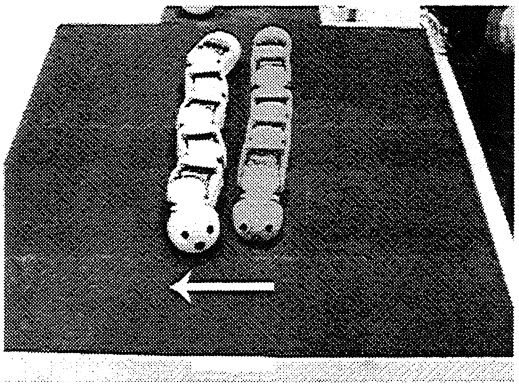


Fig. 13 Slide locomotion.

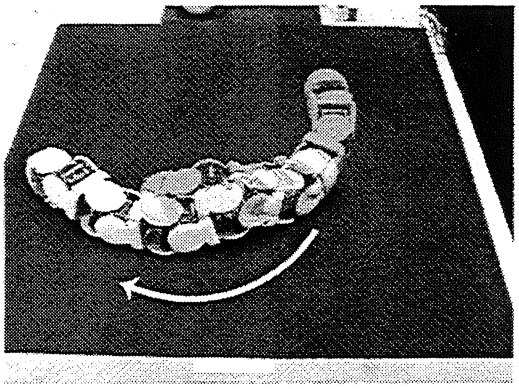


Fig. 14 Rotational locomotion.

5. SUMMARY AND CONCLUSIONS

In this paper, a novel robot system with unit-type structure is developed for rescue searching tasks in the disaster environment. This robot does not use any driving mechanisms such as wheels, crawler or leg. The progressive wave on the robot body generates its motion propulsion.

The effectiveness of the robot motion was shown by dynamic simulations and experiments. The real robot has successfully debut at the last international exposition "Love and earth Expo" in 2005.

It stably demonstrated its beautiful locomotion for 31 days with eight times of 30 minutes everyday.

In our next researches, we will consider the problem on how to design the mechanical links between each unit so that the robot can easily exchange the connection and reform its body structure with respect to the environmental conditions and task requirements. In addition, the actuator should also be improved, and the robot is expected to generate its adaptive locomotion pattern with respect to the complex rescue situations autonomously.

6. Acknowledgment

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