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# Locomotion Strategy for a Peristaltic Crawling Robot in a 2-Dimensional Space

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***Abstract*— An earthworm moves by peristaltic crawling, which propagates a longitudinal wave from the front of the body to the back by varying the thickness and length of its segments. This locomotion mechanism can move while keeping a large area in contact with the ground. Further, the amount of space required by this locomotion mechanism is less than that by other locomotion mechanisms. Therefore, it is desirable to apply this mechanism not only to robots for rescue and limited environment exploration operations but also to locomotive endoscopic robots for medical engineering.**

**In this study, we developed a peristaltic crawling robot that can move not only in a tube but also on a plane surface Furthermore; we propose a peristaltic crawling robot and its locomotion strategy. As a result, the simulation and experimental results showed good performance.**

***Index Terms – peristaltic crawling motion, earthworm, robot, locomotion pattern***

## I. Introduction

An earthworm moves by peristaltic crawling, which propagates a longitudinal wave along the anteroposterior direction, by varying the thickness and length of its segments. This locomotion mechanism has redundancy, and can move while keeping a large area in contact with the ground. Thus, it has the following benefits:

*1)* The amount of space required by this locomotion mechanism is less than that by other mechanisms, such as bipedal, wheel-based, and meandering locomotion.

*2)* The locomotion mechanism is likely to provide stability on irregular ground and inside a narrow pipe.

Therefore, it is desirable to apply this mechanism not only to rescue robots, and robots exploring limited environments, but also to locomotive endoscopic robots for medical engineering.

Recently, some robotic and biomedical engineering research has investigated a peristaltic crawling robot based on earthworm locomotion [1]–[4]. These robot studies apply various actuation methods to achieve locomotion with peristaltic crawling. Further, the authors also developed a peristaltic clawing robot using actuators [5]–[8], and discuss the influences of various conditions on peristaltic crawling locomotion patterns—they must be systematically examined to provide for stable adjustment to environmental variations.

However, though these robots can move through a single pipe, these cannot select the correct pipe at a turning point. Moreover, these robots cannot move in free spaces, such as on a plane. It would be useful if the robots could move in free space, and the attitude of the robot be controlled actively, in particular for applications including robots for rescue and limited-environment-exploration operation. In addition, because this robot is good at moving in a narrow space, a locomotion strategy that supports direction changes is needed to allow the robot to move in as narrow a space as possible, while staying on a given route.

In this paper, we developed a peristaltic crawling robot that can actively control its attitude on a plane. First, we explain the peristaltic crawling motion of an actual earthworm. Next, we propose a peristaltic crawling robot and its locomotion strategy. Then, we discuss the robot's locomotion on given routes through simulation and experimental results.

## II. PERISTALTIC CRAWLING MOTION OF AN EARTHWORM

### *A. The structure of an earthworm and its peristaltic motion mechanism*

The inner structure of an earthworm's body is shown in Fig. 1 [9]. The earthworm consists of numerous segments which are combined serially. Each segment is divided by a septum and has a coelom containing an alimentary canal and nerve circuits. The inner wall of the body is composed of two muscle layers: the outside is called the circular muscle and the

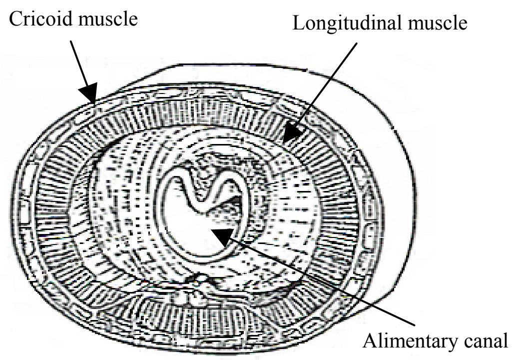


Fig.1 An inner structure of an earthworm body [9]

inside the longitudinal muscle. When the circular muscle is actuated in a radial direction, the segment becomes thinner and extends in the axial direction. When the longitudinal muscle is contracted in the axial direction, the segment becomes thicker and shorter [10].

Fig. 2 shows the locomotion pattern of an earthworm with peristaltic crawling. The earthworm propagates a longitudinal wave along the anteroposterior direction by contracting the muscles in each consecutive segment. The locomotion pattern can be illustrated as follows:

*1)* The anterior segments of the earthworm are contracted by the longitudinal muscle. In this case, because the thicker segments contact the surface for locomotion, the friction between the segments and the ground is increased. Hence, the segments remain in contact with the surface.

*2)* The contracted segments continuously propagate to the rear end. This movement pulls the rear segments in the direction of movement.

*3)* The anterior segments of the earthworm are extended in the axial direction by the circular muscle. In this case, since the friction between the segments and the moving surface is decreased, thinner segments can move smoothly. Furthermore, because the rear segments remain in contact with the surface, the thinner segments can move forward.

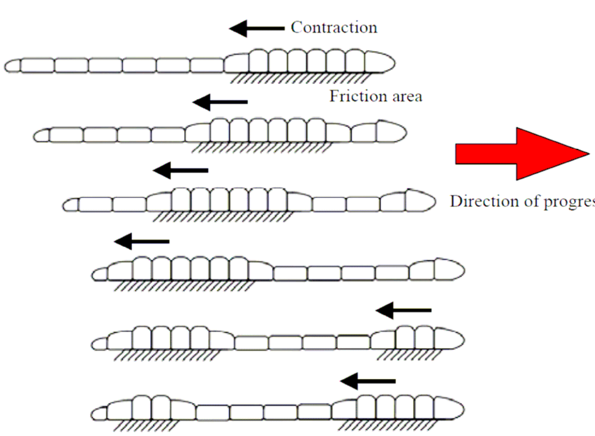


Fig.2 locomotion pattern of an earthworm with peristaltic cowling

*4)* The extended segments propagate to the rear direction continuously. The forward segments are pushed in the direction of movement.

### *B. Measurement of an earthworm's peristaltic crawling*

The motion of an actual earthworm was analyzed to apply its peristaltic crawling motion to the robot locomotion. An earthworm about 140 mm long and 4 mm thick was used. Markers were placed on the earthworm's segments at intervals of 19 mm, as shown in Fig. 3. The locomotion was video-taped with a digital video camera, then, the file was analyzed using motion-analysis software (MOVIAS Pro: Nac Image Technology Inc. )

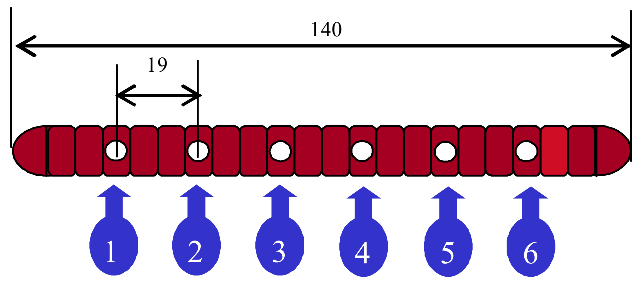


Fig. 3 The earthworm segments and the markers

The measurement result for peristaltic crawling of the earthworm is shown in Fig. 4. This figure shows that the contraction of the segments begins from the anterior part of the earthworm and continuously propagates towards the posterior part. The anterior segments contract again, after propagation to the posterior part is complete. The average velocity of the earthworm was 16.1 mm/sec. The peristaltic crawling robot was designed taking these results into consideration.

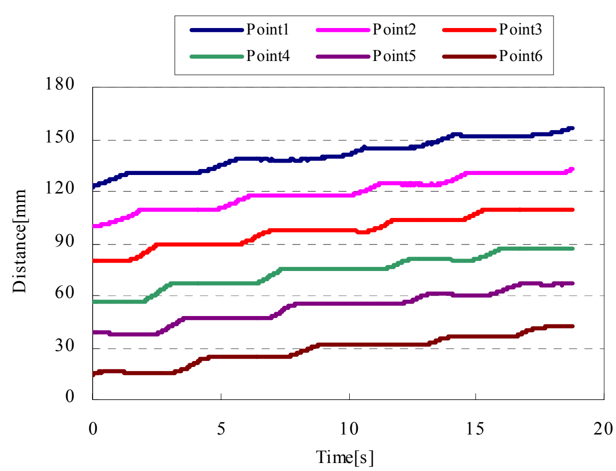


Fig.4 Peristaltic crawling motion for the actual earthworm

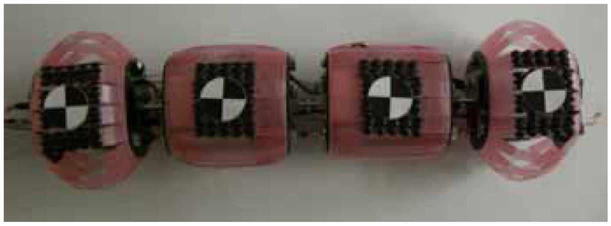

Fig.5 The Peristaltic Crawling Robot(PEW-RO)

## III. THE PERISTALTIC CRAWLING ROBOT

### A. *The constitution of the peristaltic crawling robot*

The peristaltic crawling robot (PEW-RO) was developed by referring an actual earthworm's motion. Fig. 5 shows the configuration of PEW-RO. It consists of several units that can extend and contract in the axial direction. The units are connected with a rotational degree of freedom. Hence, it is possible to bend between units. Since peristaltic crawling requires at least three contraction segments, the robot also must consist of at least three units [10]. However, in practice, the robot requires at least four units to change its attitude, since a free unit is needed to change the direction of the unit.

### B. *On the units using servo motors*

Functions similar to those of the earthworm segments are achieved by the units as shown in Fig. 6. The units use two servomotors. Servomotor A provides contraction and extension of the unit. The swing motion of the servomotor is converted into a slide motion by a crank mechanism. The unit expands in the radial direction during contraction due to the curvature of belts made from flexible plates. Servomotor B provides bending between the units. A rubber sheet is

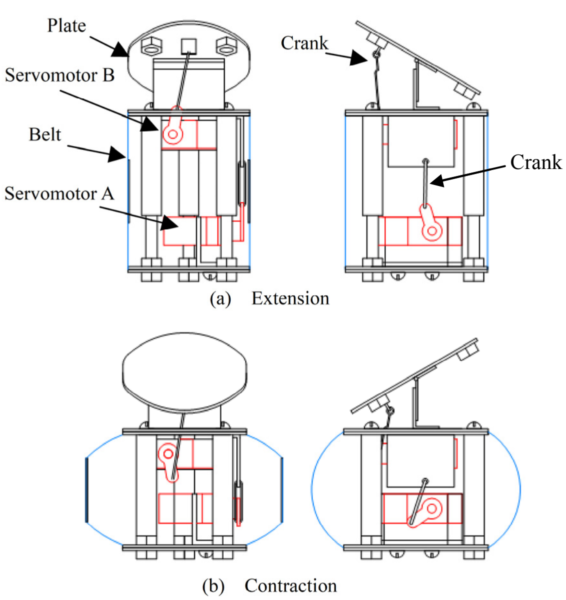


Fig.6 A unit of motion for extension contraction and bending.

attached at each belt to increase the friction between the units and the ground when the belts contact the moving surface.

Each unit is 65 mm long and of 40 mm in diameter, when fully extended, and 50 mm long and 75 mm in diameter, when fully contracted. It has a mass of 70 g. The bending angle ranges from −30 to 30 degrees.

## IV. MODELING OF THE ROBOT AND SIMULATION

The developed robot is modeled to evaluate its position and attitude, and a simulation analyses its movement over given routes in 2-dimensional space.

### A. *Setup coordinates*

The robot and its setup coordinates are shown in Fig. 7. The robot can be divided into a contraction part and a bending part modeled as a slide joint and a rotational joint, respectively. The rotational angle, anterior segment, and posterior segment are paid particular attention the coordinates of each unit are set from the posterior to the anterior segment,

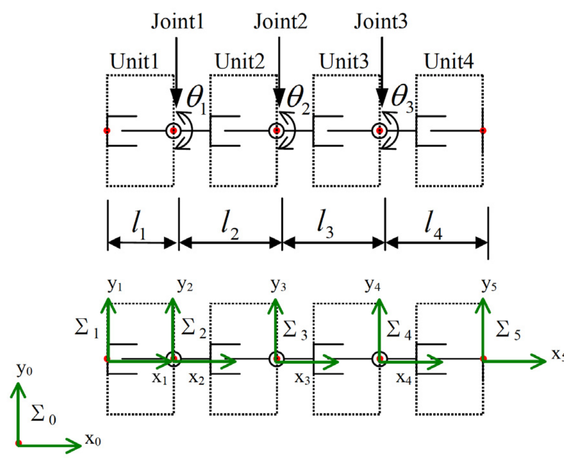


Fig.7 A set-up of the coordinates of the robot.

as Σ1–Σ5. $l_i$ is a distance between the origins of Σ*i* and Σ*i*+1, and $\theta i$ is the rotational angle at Σ*i*+1. Further, $\Sigma_0$ is the world coordinate system.

### B. *Locomotion patterns for peristaltic crawling*

Fig. 8 shows the pattern of each unit movement required for straight line peristaltic crawling. As shown in this figure, peristaltic clawing is a locomotion pattern whereby contractions of two units propagate along the anteroposterior direction. When the units contract, they come in contact with ground and gain friction. Therefore, the shadowed contraction unit in each motion (Fig. 8) maintains the position and attitude of the previous motion. This is defined as a basic unit. Hence, when Unit *i* is the basic unit, Σ*i* should be set as the position and attitude of the previous motion.

A contraction unit that has not been shadowed in Fig. 8 is defined as semi-basic unit. When the attitude of the units is changed to alter the robot's direction, the position and the

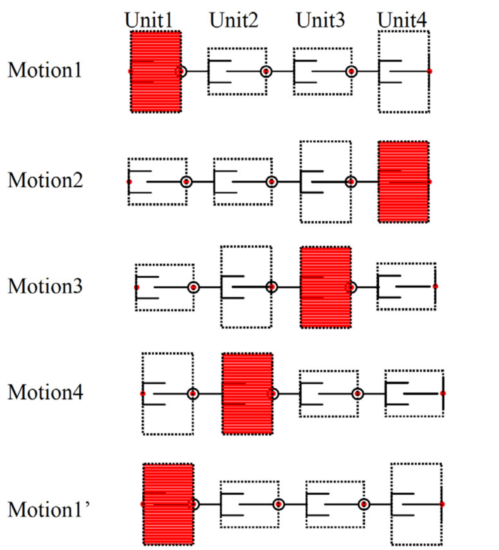

Fig.8 Locomotion pattern of the peristaltic crawling robot

attitude of the basic and semi-basic units must be fixed. When extension units are between contraction units, such as in Motion 1, the units cannot change their attitude.

### C. Homogeneous transformation matrix of the robot

The attitude of the robot observed from the basic unit in each Motion is derived. It is transformed to world coordinate systems to derive a homogeneous transformation matrix of the robot. For instance, a homogeneous transformation matrix for Motion 1 is shown in (1) to (4). The transformation matrix that gives the relationship between the world coordinates $\Sigma_0$ and $\Sigma i$ is shown in (5).

$$^{1}T_2 = \begin{pmatrix} c\theta_1 & -s\theta_1 & \ell_1 \\ s\theta_1 & c\theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

$$^{2}T_3 = \begin{pmatrix} c\theta_2 & -s\theta_2 & \ell_2 \\ s\theta_2 & c\theta_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$$^{3}T_4 = \begin{pmatrix} c\theta_3 & -s\theta_3 & \ell_3 \\ s\theta_3 & c\theta_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$^{4}T_5 = \begin{pmatrix} 1 & 0 & \ell_4 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4}$$

$$^{0}T_i = \begin{pmatrix} c\phi & -s\phi & x_i \\ s\phi & c\phi & y_i \\ 0 & 0 & 1 \end{pmatrix} \tag{5}$$

### D. Setting routes and evaluation functions

A simulation is performed using the robot's derived position and attitude. The contraction pattern of units for robot locomotion is used for the pattern in Fig. 8. The robot can move along the given routes by changing the angle of the joint between units.

First, locomotion routes are decided. The given routes that the robot moves along are expressed by the following functions from (6) to (8), representing Route 1, Route 2, and Route 3. The robot's tail is set at the origin. Route 1 shows advancement along a straight line, Route 2 shows a 45-degree turn, and Route 3 shows a continuous curve.

$$y = 0 \tag{6}$$

$$\begin{cases} y = 0 & (x < 300) \\ y = x & (x \geq 300) \end{cases} \tag{7}$$

$$\begin{cases} y = 0 & (x < 300) \\ y = 0.001x^2 & (x \geq 300) \end{cases} \tag{8}$$

Next, the evaluation function for motions is discussed. The difference between the robot attitudes and the route in each Motion is examined. Then, the evaluation functions shown in (9)–(11) for Route 1–3 are set. Each evaluation function shows the distance from the origin of Σ1–Σ5 (in world coordinate systems) to the route. The attitude of the robot in each Motion, when these calculation results are the smallest, is defined as the optimal Motion.

$$E_0 = \sum_{i=1}^{5} |0 - y_i| \tag{9}$$

$$\begin{cases} E_0 = \sum_{i=1}^{5} |0 - y_i| & (x < 300) \\ E_1 = \sum_{i=1}^{5} |x_i - y_i| & (x \geq 300) \end{cases} \tag{10}$$

$$\begin{cases} E_0 = \sum_{i=1}^{5} |0 - y_i| & (x < 300) \\ E_2 = \sum_{i=1}^{5} |0.001x_i^2 - y_i| & (x \geq 300) \end{cases} \tag{11}$$

Here, the range of the angle of each joint is from −30 to 30 degrees (counterclockwise rotation is assumed to be positive), with a resolution of 5 degrees.

### E. Simulation results and discussion

The simulation results for each route are shown in Fig. 9 to Fig. 11. Points 1–4 in these figures show motions of center of

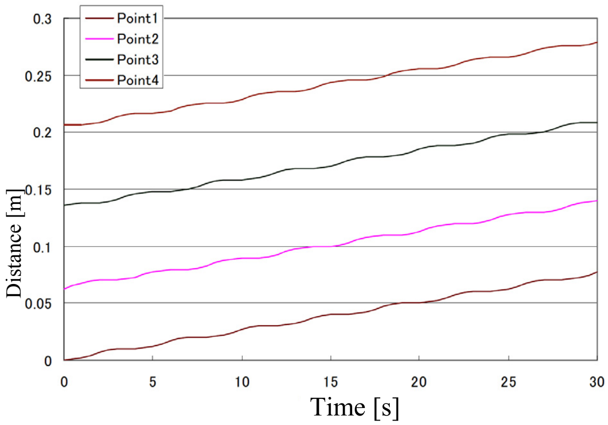

Fig.9 Simulation results of movement tracks of the robot (Route1)

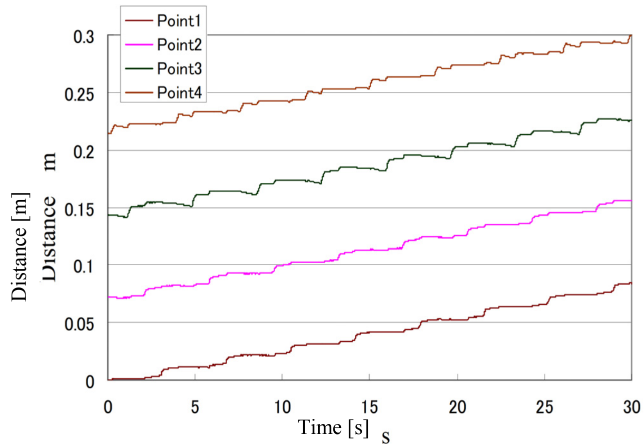

Fig.12 Experimental results of movement tracks of the robot (Route1)

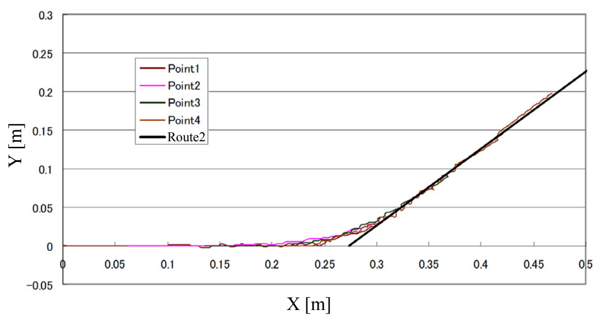

Fig.10 Simulation results of movement tracks of the robot (Route2)

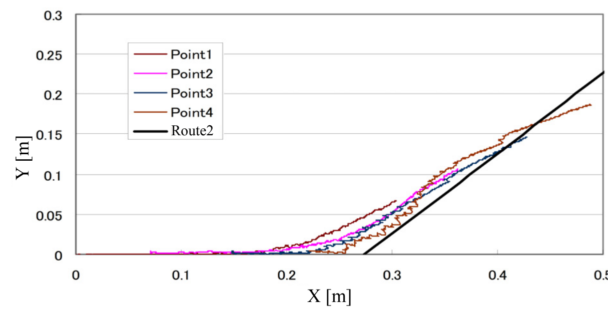

Fig.13 Experimental results of movement tracks of the robot (Route2)

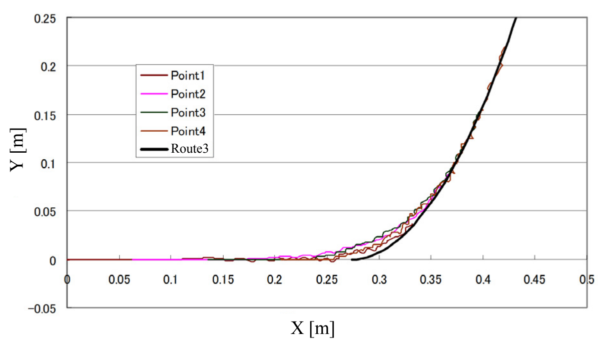

Fig.11 Simulation results of movement tracks of the robot (Route3)

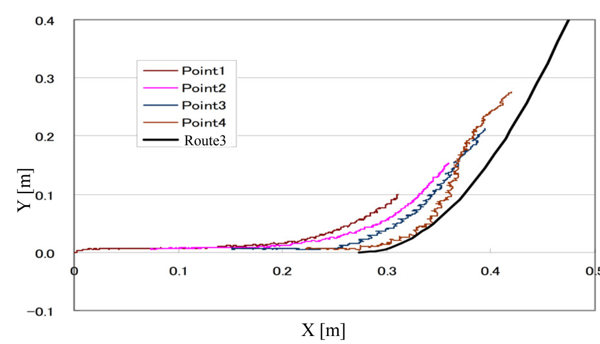

Fig.14 Experimental results of movement tracks of the robot (Route3)

each unit.

First, consider the simulation results for Route 1. If we look at Fig. 9 (the relationship between the advancement distance and time), it confirms that the robot advances by repeated propagation of contractions from the anterior to posterior part. Thus, the simulation results accurately expressed peristaltic crawling motion.

We next discuss the simulation results for Route 2 and Route 3. Fig. 10 and Fig. 11 show movement tracks of the robot in 2-dimensional spaces. Although these figures show that the robot's tracks deviate a little from the route, the robot does follow the given routes without large deviations. This robot is good at moving in narrow spaces, for straight advancement movement, such as Route 1. Thus, it is desirable that the robot passes closer to bending and curve paths, such as Route 2 and Route 3. We think that the robot can be made to follow these tracks more faithfully by increasing the joint size.

## V. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments of the mobile robot using peristaltic crawling motion were performed based on the simulation results. A video of the robot moving on the plane was taken from directly overhead and the tracks of the points marked on each unit were analyzed. Here, The board made from the chloridization vinyl so that the frictional force should not change by the environment is used as a plane that comes in contact with the robot. The coefficient of friction between this board and the robot is 0.5. Further, contraction and the rotational speed of the units are controlled slow enough to reduce the influence of the inertia force and moment of the unit. (Settling times for contraction are 2.5 second). The experimental results are shown in Fig. 12 to 14.

### A. The movement track for Route 1

From Fig. 12, we can see that the motions of the robot are qualitatively similar to those of the actual earthworm shown in Fig. 4, because the longitudinal wave from the front to the back of is propagated by contracting the units, There is, however, a little slipping caused by the relationship between inertia of the units and its friction force.

### B. The tracks for Route 2 and Route 3

The tracks are shown for Route 2 and Route 3. Here, the angle of the servomotors is controlled using only the values obtained by simulation results, and no feedback control is applied.

Fig. 13 and 14 show that, while the robot's tracks are not quite as close to the path as in the simulation, the robot moves around the routes. In particular, the robot starts changing its attitude before reaching the point that the curve function actually changes.

The peristalsis crawling robot is moved by using the difference of the friction of the contraction units and the extension units. Therefore, if the basic and semi-basic units that constitute the contraction units slip, there is a possibility of influencing the distance moved and the bending angle. Also, the robot's weight prevented the belts from achieving full expansion in the radial direction (Fig. 6). Hence, there is a possibility that enough frictional force difference cannot be achieved. It is necessary to discuss the use of the belts with higher rigidity to maintain an enough expansion of the unit in the radial direction.

## VI. CONCLUSIONS

In this paper, we developed a peristaltic crawling robot based on earthworms, and proposed a locomotion strategy for motion in 2-dimensional space. The conclusions are follows:

A peristaltic crawling robot (PEW-RO) was developed, based on an actual earthworm's motion. Because the robot can bend between units, it can move in 2-dimensional space, such as on a plane.

We proposed a locomotion strategy in 2-dimensional space, based on peristaltic crawling. The robot was modeled to determine its positions and attitude. We performed a simulation of its movements on given routes. The simulation results showed good performance.

Experiments with the mobile robot, using peristaltic crawling, were carried out, based on the simulation results. Although the robot did not track the path as closely as the simulation, the robot moved around the routes.

In the future, the robot will be improved to move in 3-dimensional space. In addition, a feedback controller will be applied to the robot, attached to some sensors to be able to move the robot more accurately on the given routes.

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