2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Locomotion Strategies for an Omni-Directional Mobile Robot Using Traveling Waves Propagation

Taro Nakamura and Kuniaki Sato, *IEEE Members*
Chuo University
Faculty of Science and Engineering, Department of Precision Mechanics
1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551 Japan
nakamura@mech.chuo-u.ac.jp

***Abstract* - In this study, we present an omni-directional mobile robot based on the locomotion of a snail. The snail moves by propagating traveling waves from its tail to its head. If it were possible to propagate a traveling wave in several directions, an omni-directional mobile robot could be realized. Since the locomotion mechanism of the snail involves moving a larger area than in the case with other creatures, it is able to move not only on irregular ground such as swamps, but also on walls and ceilings. We have developed an omni-directional mobile robot that makes use of a traveling wave and have derived a kinematical model for locomotion strategy. In experiments, the robot showed good performance, as described in this paper.**

Index Terms *–Omni-directional mobile robot, Traveling wave, Snail locomotion, Biomimetic robot*

I. INTRODUCTION

At present, for a robot to realize omni-directional locomotion, a special tire is necessary such as an omni-wheel [1]. However, the wheel slides axially on a steep gradient.

On the other hand, in recent years in the field of bio-mechatronics, robots that imitate a creature's motion have been developed. We have studied the locomotion mechanism of the snail [2], [3]. The snail has an elastic motion in the direction of movement, known as pedal locomotion. In this mechanism, a traveling wave propagates from the snail's tail to its head [4]-[8]. Since the locomotion mechanism of the snail involves moving a larger area than in the case with other creatures, it is able to move not only on irregular surfaces such as swamps, but also on walls and ceilings. If it were possible to propagate a traveling wave in several directions, an omni-directional mobile robot could be realized.

Recently, researchers in the fields of robotic and biomechanical engineering investigated a mobile robot based on snail locomotion [9]–[13]. In these robot studies the authors applied various actuation methods to achieve locomotion like the pedal locomotion of the snail. However, because they developed the mechanism to elucidate the snail's locomotion mechanism, they did not examine this type of locomotion as a function of a robot. Hence, this locomotion mechanism might be able to have some functions not provided in actual snail locomotion by discussing this locomotion method as a function of the robot.

In this study, we developed an omni-directional mobile robot using the locomotion mechanism of the snail. The shape model and the locomotion kinematics of this type of robot are derived, and locomotion planning is discussed.

II. THE LOCOMOTION MECHANISM OF A SNAIL

The common belief is that the snail moves by a traveling wave locomotion mechanism in which a traveling wave is produced in the gastropod's foot that propagates in the direction of movement [4]. The state of the traveling wave seen from a section of the gastropod's foot is shown in Fig. 1, and the state of the traveling wave when moving forward is shown in Fig. 2. The snail has two kinds of muscles, the anterior oblique and the posterior oblique muscles (Fig. 1), that produce the traveling wave. When the traveling wave occurs, the part that is not forming the traveling wave in the gastropod's foot remains in contact with the ground. The ground generates a frictional force with the grounded foot of the gastropod.

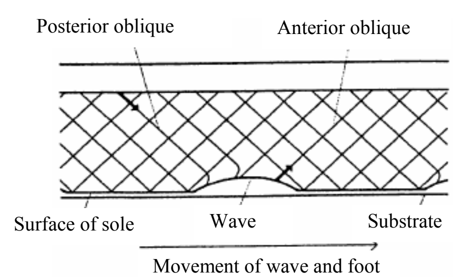


Fig. 1 Diagrammatic section of a snail's foot [4]

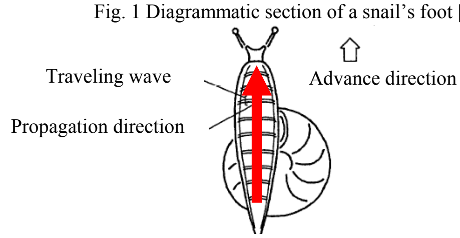


Fig. 2 Propagation of traveling wave of a snail [12]

II. THE SINGLE-DIRECTIONAL MOBILE ROBOT USING A TRAVELING WAVE

First, we developed a mobile robot that moves in a single direction to confirm the locomotion by a traveling wave based on the movement of a snail.

A. Unit for the mobile robot using a traveling wave

A unit for a mobile robot was developed to generate a traveling wave based on the movement of a snail. A diagram of the unit [8] used in the mobile robot is shown in Fig. 3. It is composed of 4 substrate parts (side: 20 mm, depth: 5 mm): the friction part (side: 80 mm, depth: 105 mm) and a servomotor. It weighs 200 g.

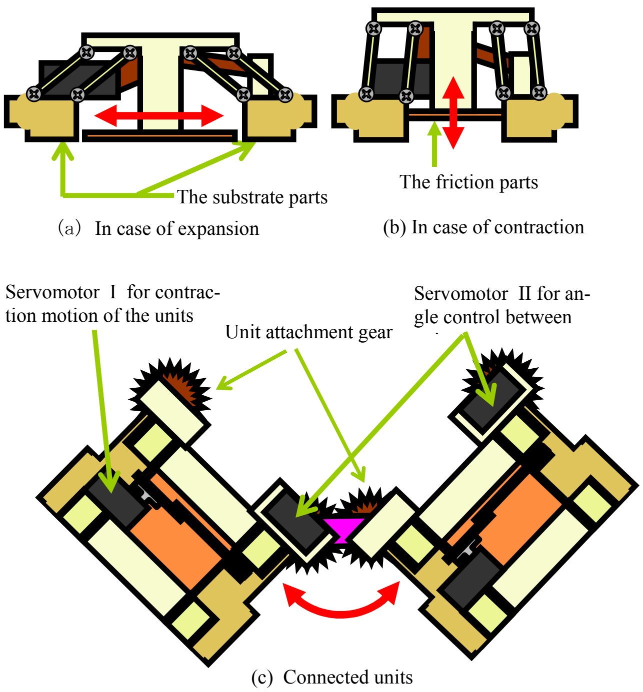


Fig. 3 The mechanism of the unit

The substrate part is always in contact with the ground. In the condition where the substrate part is grounded, the unit has elasticity in the direction of movement.

The frictional part is the part that holds the unit stationary when the unit is elongating. A frictional sheet is attached to the contact area of the frictional part, which is connected to the substrate part using parallel linkages. By using a parallel linkage, during elongation, the frictional part connects to the ground horizontally, and during contraction, the frictional part leaves the ground horizontally.

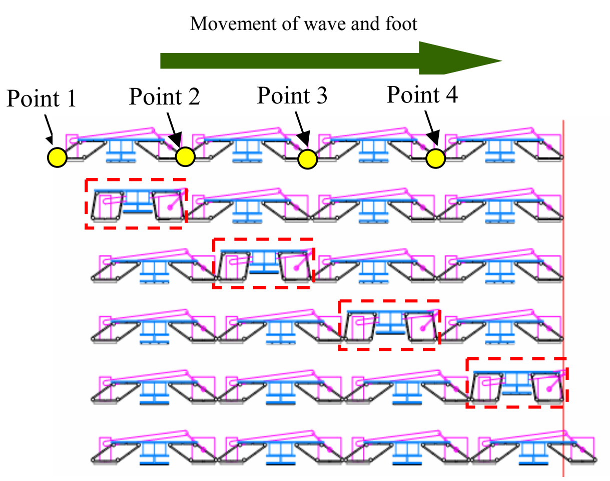


Fig. 4. Locomotion pattern of the mobile robot.

We fixed servomotor I to the substrate part, which is connected to the other substrate part using a crank mechanism. The unit can be contracted and extended by the motor-crank mechanism. Servomotor II, which is used to control the angle between units, is also fixed to the substrate part.

B. The single-directional mobile robot using a traveling wave

A number of units are connected in series. The point of each unit is marked to be able to analyze the trajectory of each unit. Figure 4 shows the locomotion pattern of the mobile robot. From this figure, we can see that this robot moves by propagating the contraction of the unit from the back to the front. This motion of the robot is similar to the traveling waves of a snail.

The trajectory of each unit of the single-directional robot is shown in Fig. 5, when the robot moved by using a traveling wave. The propagation of the contraction of the units from the back (Unit4) to the head (Unit1) can be confirmed.

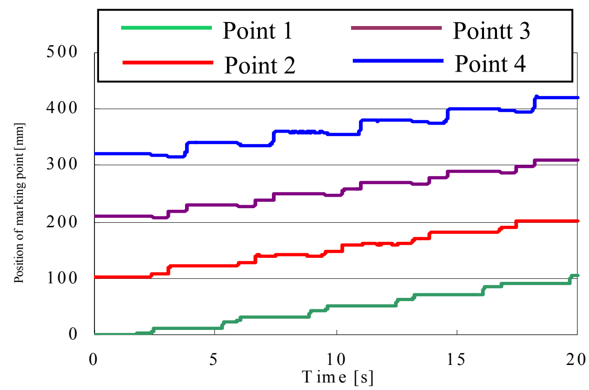


Fig. 5 Locomotion progress of the single-directional mobile robot using a traveling wave.

IV. THE OMNI-DIRECTIONAL MOBILE ROBOT USING A TRAVELING WAVE

A. Overview of the omni-directional mobile robot

We have developed an omni-directional mobile robot that uses the locomotion mechanism of the snail (Fig. 6). The diameter of the robot is 500 mm, and it weighs 1600 g. The omni-directional mobile robot is composed of eight units arranged in a circle, and each abutting unit is connected by unit attachment gears, as shown in Fig. 3.

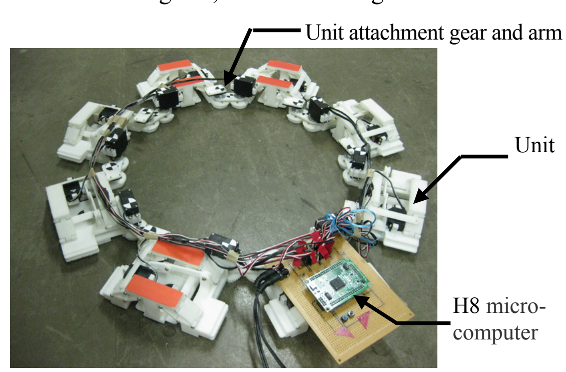
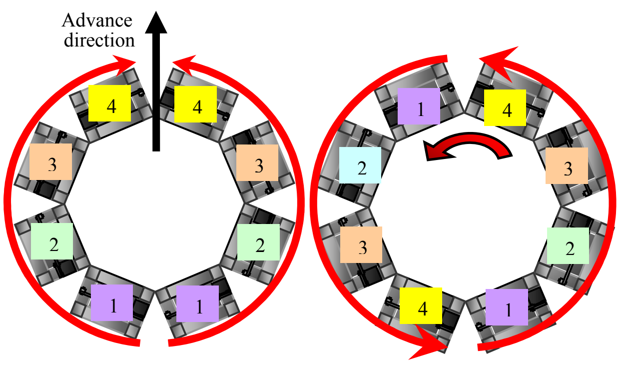


Fig. 6 Omni-directional mobile robot using a traveling wave

B. Method of locomotion

When the unit is stationary, it adopts the elongation condition from the servomotor, the frictional part is in contact with the ground, and the unit is fixed on the ground. On the other hand, when the unit is moving, it adopts the contraction condition from the servomotor, and the frictional part does not come in contact with the ground. As a result, because the friction of the unit is small, it is able to move freely. As described above, the robot generates a traveling wave by elongation and contraction of the units and realizes omni-directional locomotion.

Figure 7 shows the locomotion of the robot. The default position is the condition in which all the units are extended. First, the robot contracts the pair of units shown as unit1 at the same time. Then, the robot contracts the unit2 pair at the same time of extending the unit1 pair. Later, the robot contracts the unit3 pair at the same time of extending the unit2 pair and then contracts the unit4 pair at the same time of extending the unit3 pair. Finally, the robot extends the unit4 pair and we call this complete cycle one period. Because of this movement, the robot generates the traveling waves shown in Fig. 7 (a) and moves forward in the advance direction. To change the advance direction, the robot changes to a different unit1 pair appropriate for the new direction of travel. These units contract first and this changes the direction of propagation of the traveling wave. In the case of turning propagation, these units propagate shown in Fig. 7 (b).



(a) Straight propagation (b) Turning propagation

Fig. 7 Movement of the robot in the advance direction and turning

IV. MODELING OF THE OMNI-DERECTIONAL ROBOT

A. The shape modeling for the robot

The developed robot is modeled to allow evaluation of its position, attitude, and shape. The robot and its setup coordinates are shown in Fig. 8. The robot can be divided into a contraction part and a rotational part modeled as a slide joint and a rotational joint, respectively. The shape of this robot is modeled by a homogeneous transformation matrix.

The shape of the robot is derived with regard to the position and the orientation of the model coordinate system in each joint by using the following equations, respectively:

$$x_1 = E \tag{1}$$

$$x_{i+1} = x_i Rot(\theta_i) Trans(L_i) \tag{2}$$

The shape of the robot can be understood by connecting the position of the requested coordinates. Here, θi is the angle between units and Li is the unit length as shown in Fig. 8.

Restraint conditions are shown in the following equations. First, because the unit moves symmetrically along the Y axis during straight propagation, it is restrained as shown in the following expressions:

$$L(i) = L(N+1-i) \quad (i=1\sim N/2) \tag{3}$$

$$\theta(1+i) = \theta(N+1-i) \quad (i=1\sim(N/2-1)) \tag{4}$$

In addition, since the round shape of the robot must be maintained, the following equations are also needed as restraint conditions:

$$d_{N/2+1}(x) = 0 \tag{5}$$

$$d_{N+1}(x) = 0 \tag{6}$$

Here, X component of ith joint is expressed with $di(x)$ and N is number of units of the robot. Moreover, the point was set in each joint of this robot, and it was defined as a center point when the robot moved the point such that all the point coordinates were averaged.

When the units are extended, their friction parts come in contact with the ground and gain friction. Therefore, the extension unit maintains the position and orientation of the previous motion. When the units are contracted, their friction is quite small. Hence, the angle between units can be controlled to a desired value by using servomotor II, as shown in Fig. 3.

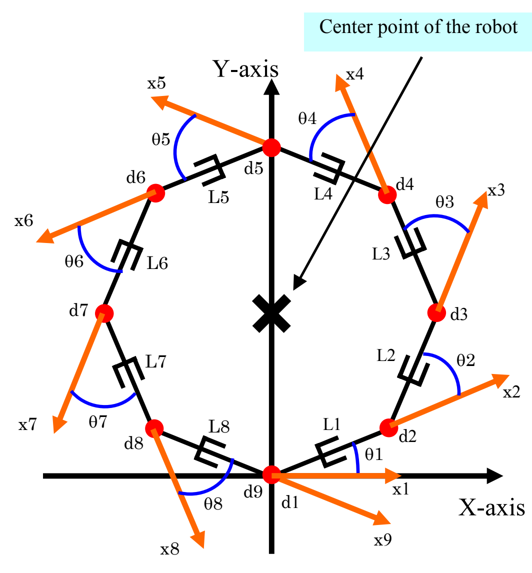


Fig.8. The setting of parameters (N=8)

We next discuss experimental results for the shape of the robot. Figure 9 shows a comparison of the ideal and actual robot shape. Although these figures show that the actual robot's shape deviates a little from the ideal, the robot does follow the given ideal shapes without large deviations.

B. Derivation of a Kinematics model for omni-directional traveling waves locomotion

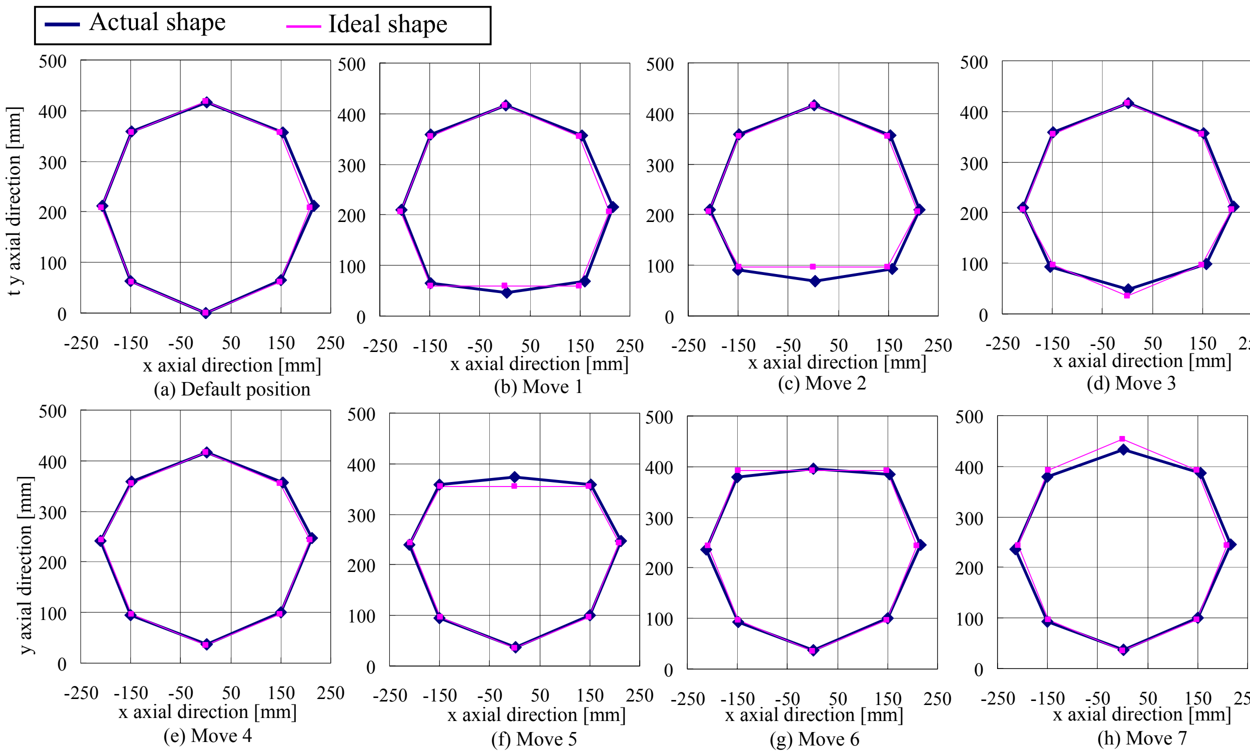


Fig. 9 Experimental comparison of the ideal and actual robot shape

When the robot moves, the relationship between the contraction length of the unit and the velocity of the robot was requested by using locomotion kinematics. The obtained equation is shown in (7).

Here, v_x, v_y, and v_θ are the velocity in the X and Y axis directions and the rotational speed, respectively. The contraction length of each unit is m_i. The average radius of the robot is d. Further, as parameters of wave propagate motion for the robot locomotion, the contraction speed of the unit is $\tau_0(t)$. The wave length, number of waves of the robot, and wave speed are l, s, and n, respectively. These parameters can be expressed by the number of units. a is the adjustment coefficient for the robot motion, Move 1 and Move 6. (Because these motions are different from other motion a little , this coefficient is needed.)

$$\begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{bmatrix} = \frac{\{(N-4l)+2an\}\tau_0(t)}{2ns} \begin{bmatrix} \cos\left(\frac{\pi}{N}\right) & \sin\left(\frac{\pi}{N}\right) & d \\ \cos\left(\frac{3\pi}{N}\right) & \sin\left(\frac{3\pi}{N}\right) & d \\ \vdots & \vdots & \vdots \\ \cos\left\{\frac{(2n-1)\pi}{N}\right\} & \sin\left\{\frac{(2n-1)\pi}{N}\right\} & d \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_\theta \end{bmatrix} \quad (7)$$

The amount of contraction of each unit to move at the desired velocity can be calculated by using this equation.

We produced experimental results for the velocity of the robot. The amount of contraction of the robot is controlled, and the robot is moved going straight along the Y axis. We also measured the locomotion speed of the center point of the robot experimentally. Figure 10 shows the experimental results of the relationship between contraction length of the unit and velocity of the robot, when experimental parameters are set as shown in Table 1. From this figure, we can see that the velocity of the robot in experimental results showed the tendency similar to the desirable values. How ever, the experimental velocity is smaller than the desirable velocity. This may have been caused by slipping between the friction sheets and the ground

Table 1 Experimental parameters
(s, n are number of units)

N	8	s	1
d mm	209	n	1
$\tau_0(t)$ s	0.6	a	5

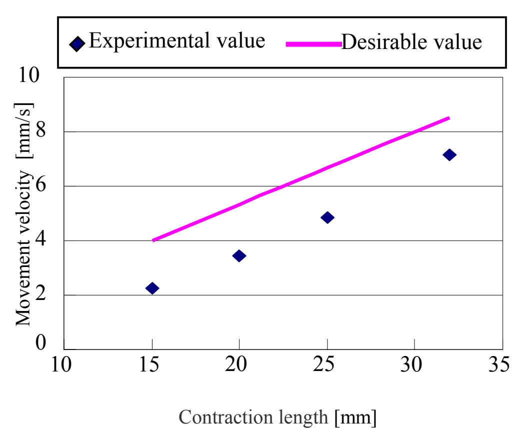


Fig. 10 Comparison of the contraction length and movement velocity

IV. LOCOMOTION PLANNING

In this paper, the locomotion strategy of the robot is assumed for execution on an ideal track to be composed of straight and circle tracks [14]. Here, we examine two methods of locomotion planning for this robot to travel on a circle track.

A. Straight locomotion method for circle tracks

This method is a strategy for moving according to an ideal circle track with the orientation maintained.

Since the developed omni-directional robot can move only in a straight line, it is difficult to get it to move on the ideal circle track precisely. Here, if the number of units of the robot is N, the robot can move in N directions. Thus the planning track along an ideal circle track is accomplished by combining straight-line movements in eight directions. Figure 11 shows the ideal circle track and desirable planning track of the robot in the case of applying the straight motion method, when r=130 mm.

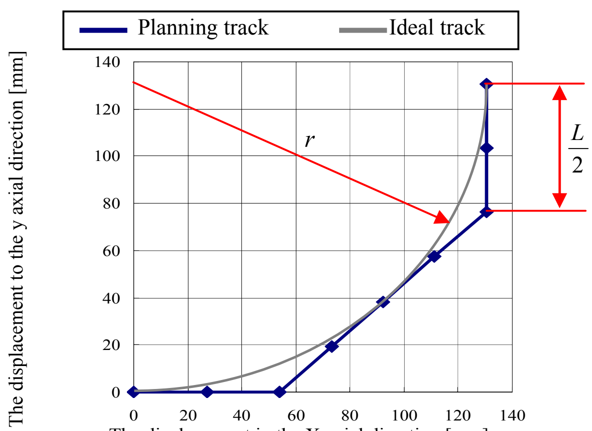


Fig. 11 The planning tracks in straight motion

Length L in this figure is determined as follows, using ideal track radial r:

$$L = r/1/2 + \sum_{i=1}^{N/4-1}\{\cos(2i\pi/N)\} \tag{8}$$

In this case, L is larger than the locomotion distance the robot can move in one cycle. The points are attainment points of the robot every one cycle in the direction of the planning track.

B. Straight and turning locomotion method for circle tracks

In this method, the omni-directional robot can move on the ideal circle track by executing alternately straight movement and turning motion. By using this method, the attitude of the robot can be changed along a tangent direction of an ideal circle track. Since the planning track is a polygon that is inscribed in the ideal circle track, the number of polygonal corners c and the turning angle of the robot θ are derived by the following equations that used ideal orbit circle radius r and straight motion distance L as parameters:

$$c = \frac{\pi}{\tan^{-1}(L/2r)} \tag{9}$$

$$\theta = \frac{2\pi}{c} \tag{10}$$

Further, the ideal circle track and the desirable planning track of the robot in the case of applying the method are shown in Fig. 12. Here, r=130 mm, L=27 mm, and θ=12 deg.

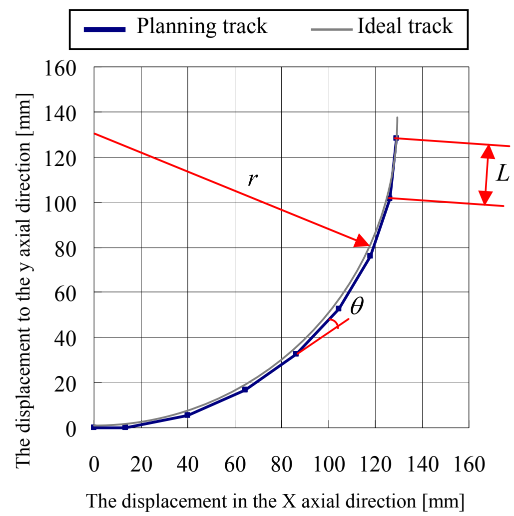


Fig. 12 The planning tracks by straight motion and turning motion

V. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments with the omni-directional mobile robot using traveling waves were performed based on the planning tracks derived from Eq. (8) to (10). 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, a center point is defined as the point to have averaged the point of all units. A board (ground) made from chloridization vinyl so that the frictional force should not be changed by the environment was used as a plane that was in contact with the robot. The coefficient of friction between this board and the robot was 0.5.

A. Experimental results of the straight locomotion method

Figure 13 shows the experimental results for movement

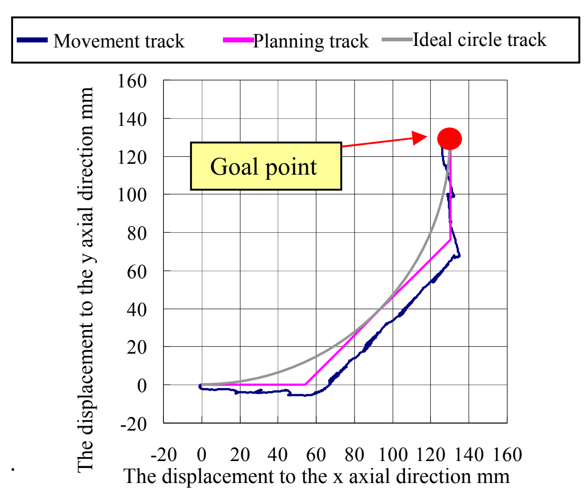


Fig. 13 The movement tracks by straight locomotion

tracks of the robot when applying the straight locomotion method shown in Fig. 11. Although this figure shows that the robot's tracks deviates a little from the desirable planning track, the robot does follow the given routes without large deviations. The error margin of the end the goal point was 5 mm, and accurate movement to the target value point was confirmed.

B. Experimental results of the straight and turning locomotion method

Figure 14 shows the movement tracks by the straight and turning locomotion method shown in Fig. 12. From this figure, we can see that, while the robot's tracks are not quite as close to the path as in the desirable planning track, the robot moves around the planning track. In particular, we confirmed that the movement track of the robot deviates gradually from the planning track, though it almost traces the planning track. By analyzing the movement of this robot in detail, we confirmed that the orientation could rotate up to 90 degrees when the straight and the turn motion was repeated for 9 cycles. Thus, the robot was turning the orientation only 10 degrees with each turn motion (the desirable angle is 12 degrees). Because a rotation angle θ necessary to reach the goal is insufficient, the robot veered from the planning track.

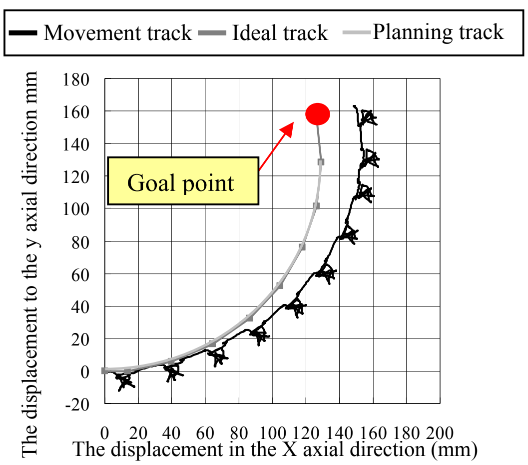


Fig. 14 The movement tracks by straight and turning locomotion

VI. CONCLUSIONS

In this study, we developed a traveling waves type omni-directional mobile robot and proposed a locomotion strategy for it. The conclusions are as follows:

1) An omni-directional mobile robot using traveling waves propagation based on snail locomotion was developed.
2) We derived a shape model of the robot and the locomotion kinematics models of the robot. The derived models were compared with experimental results, and the validity of the model was proven.
3) We proposed two methods to trace an ideal circle track. Locomotion kinematics was modeled to determine the robot's positions and orientation.
4) Experiments with the mobile robot, using traveling waves, were carried out, based on the locomotion strategies. Although the robot did not track the path as closely as the planning track, the robot moved around the tracks.

In the future, the odometery of this type of robot will be measured from the derived shape model. In addition, a feedback controller will be applied to the robot, attached to sensors, allowing the robot to move more accurately on the given routes.

REFERENCES

[1] For example, Masayoshi Wada and Shun-ji Mori, "Development of homonymic omni-directional robot," *J. of RSJ*, Vol. 15, No. 8, pp.1139-1146, 1997.

[2] Taro Nakamura and Kuniaki Satoh, "Development of an omni-directional mobile robot using traveling waves based on snail locomotion," *Journal of Industrial Robot,* Vol. 35, No. 3, pp. 206-210, 2008.

[3] Yuki Mitamura, Syohei Imai, and Taro Nakamura, "Development of a travelling wave robot based on snail locomotion,", *JSME Robotics and Mechatronics Conference 2006*, 2P-A19, 2006.

[4] H.D. Jones, "Circulatory pressures in Helix pomatia," *L. Comp, Biochem. Physiol*, Vol. 59A, pp. 291-303, 1973.

[5] H. W. Lissmann, "The mechanism of locomotion in gastropod molluscs, I. Kinematics," *J. Exp. Biol*. Vol. 21, pp. 58-69, 1945.

[6] H. W. Lissmann, "The mechanism of locomotion of gastropod molluscs, II. Kinetics," *J. Exp. Biol*. Vol. 22, pp. 37-50, 1946.

[7] M. W. Denny, "A quantitative model for the adhesive locomotion of the terrestrial slug *Ariolimax columbianus*," *J. Exp. Biol*. Vol. 91, pp. 195-127, 1981.

[8] S. Moffett, "Locomotion in the primitive pulmonate snail *Melampus Bidentatus*: Foot structure and function," *Biol. Bull.* Vol. 157, pp. 306-319, 1979.

[9] A. Ito and H. Yasukawa, "Film structured soft actuator for biomimetics of snail's gastropod locomotion," in *The 6th International Conference Control, Automation, Robotics and Vision*, 2000.

[10] Brian Chan, N.J. Balmforth, and A.E. Hosoi, "Building a better snail: Lubrication and adhesive locomotion," *Physics of Fluids*, pp. 113101:1-10, 2005.

[11] Bai Chen, Yinsheng Zhou, Daqiang Gu, and Jie Zhong, "A novel snail-like micro robot", *ICIMA, China*, 2004.

[12] Ryousen Fujihara, Hirohisa Morikawa, and Shun-ichi Kobayashi, "The mechanism of pedal locomotion of gastropod," *The Japan Society of Mechanical Engineers, JAPAN*, Vol. 67, No. 658, pp. 1934-1940, 2001.

[13] Ryousen Fujihara, Hirohisa Morikawa, Yuya Hukuya, Hiroshi Sakai, and Shunichi Kobayashi, "Pedal-like locomotion mechanism modeled on pedal crawling of terrestrial gastropod," *The Japan Society of Mechanical Engineers*, JAPAN, Vol. 70, No. 695, pp. 2103-2109, 2004.

[14] Eiji Nakano *et al.*, "Intelligence mobile robotics," Kodan-sya, pp. 171-223, 2004.