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Loop Forming Snake-like Robot ACM-R7 and Its Serpenoid Oval Control

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Abstract— **This paper discusses the design of a new snake-like robot without wheels, named ACM-R7. It has 18 DOFs, is 1.6m in length and weighs 11.7kg. It features a water-tight structure, a large motion range pitch joint of ± 90 degree and a high output-power actuator arrangement, based on the coupled drive concept. Furthermore the control method "Loop Gait" is discussed. For this gait the ACM-R7 forms a loop shape and rolls like a wheel on the rim. We introduce the "Serpenoid Oval" for the loop shape. It s formed by a smooth sinusoidal angular motion of the joints. Moreover we consider the modification of the "Serpenoid Oval" for steering and obstacle avoidance. The performance is then verified by several motion experiments.**

I. Introduction

As the snake-like robots and manipulators can make new types of future field robots, we have named the snake-like robots, or "the robot forming the cord-like linear shape by the serial connection of unified units" as "Active Cord Mechanism (ACM)". Since after the world's first experiment of Hirose's snake-like robot of 1972, we have been constructing several types of ACM and studied about its control methods [1].

Most of the former ACM models that we have made so far had multiple wheels attached along the body to generate low frictional motion towards the longitudinal direction and high frictional motion towards the normal direction of the body. The difference of friction can generate a smooth and fast gliding motion. However, on sandy off-road ground for example, the wheels may sink into the sand and sand may get stuck in the rotational shaft of the wheels.

ACMs without wheels have simpler and smoother bodies and thus are suitable for the motion on sandy or uneven environments. However, frictional resistance of the wheel-less body on the ground is high, and large energy will be lost in the locomotion, if the normal serpentine motion is used. We proved that the "Sinus Lifting", observed in real snakes, is one of the effective ways to improve the locomotion efficiency of the wheel-less ACM, and we already proved that the smooth serpentine motion can be generated [2]. However, the rate of the improvement of the energy efficiency is limited, because of the sliding motion between the body and the ground.

Therefore, we focused on the "Loop Gait" for the wheel-less ACM. The loop gait is the motion of the ACM when forming a loop shape. First, the front and the rear segment of the ACM are connected to each other to form a loop shape. Then, by the synchronized swinging motion of each

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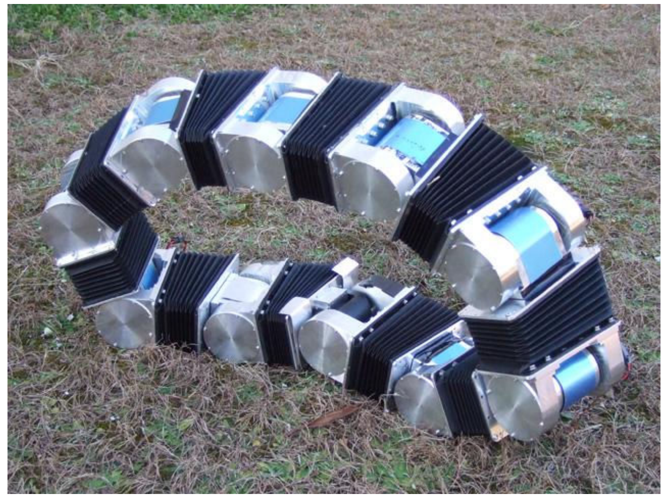
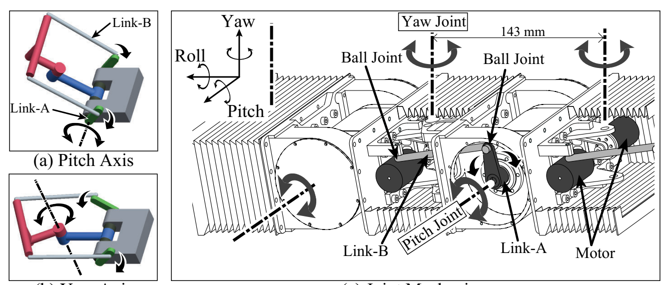


Fig. 1. ACM-R7



(a) Pitch Axis (b) Yaw Axis (c) Joint Mechanism

Fig. 2. Joint Mechanism of ACM-R7

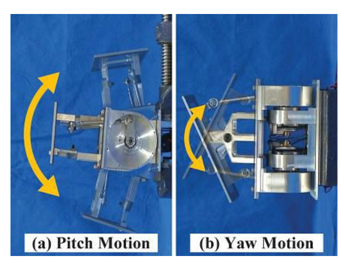


Fig. 3. Joint Motion

joint, the looped body of the ACM generates a whole-body rolling motion, just like a spinning wheel rim on the ground. The loop gait is much suitable for moving on flat terrain, because there exists several drawbacks, such as the instability problem, due to comparatively high center of mass. However, the loop gait has the amazing advantage of high efficiency. Because, although joints of the ACM body make swinging

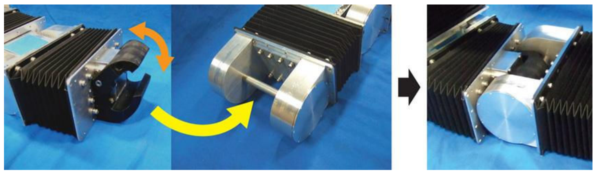


Fig. 4. Gripper and Rod

TABLE I
SPECIFICATION OF ACM-R7

Dimension	1589 × 140 × 74 mm
Mass	11.7 kg
Number of Joint	18
Motor	6W DC Motor × 18
Joint Torque	16 Nm
Joint Angle Range	± 90 deg
CPU	SH2 7047 (Renesas)
Battery	NiMH 7.2V 900mAh × 9

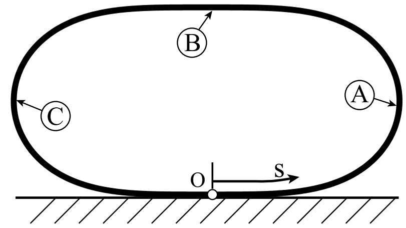


Fig. 5. Standard Shape of Serpenoid Oval

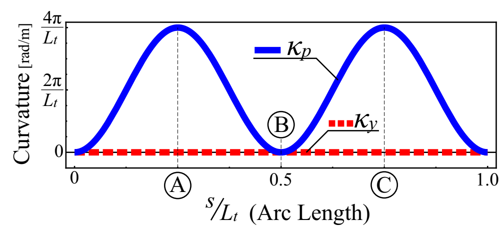


Fig. 6. Curvature of the Serpenoid-oval ($C_f = 1$, $C_t = 0$, $C_1 = 0$)

motion, just as in the case of serpentine motion, the looped ACM can create infinite spinning motion of the whole body and there is no sliding motion between the body and the ground, the motion is fast and energy efficient.

Until now, several robots which make the loop gait have already been proposed, such as Polybot [3] [4] and MTRAN [6]. They are moduler robots, which transform into a snake, a loop and other various shapes. They can move straight, and make accelerated motion by changing their ellipse shape [5]. MTRAN accomplished it with the neural oscillators "CPG" [7]. In addition, the terrain adaptive motion by using touch sensors has also been studied and Polybot has already achieved the step climbing motion with the loop gait [8]. However, most of them are in the experimental stage and the performances of the mechanisms were limited. Of course they were not made as a watertight structure. The control methods were also in the preliminary stage and simple ellipses were introduced for their basic shapes.

In this paper, we discuss about the development of a new type of snake-like robot, ACM-R7, having the mechanism to form a loop shape and having a rugged watertight structure. We also propose the new fundamental shape of the loop gait named "Serpenoid Oval" and discuss the modified serpenoid ovals for steering and obstacle avoidance. The performance of the developed ACM-R7 and its control methods based on serpenoid oval is successfully verified by the several motion experiments.

II. Design of ACM-R7 Capable of Loop Gait

We have developed the snake like robot "ACM-R7" which has the above-mentioned properties (Fig. 1). It has 18 joints and the total length is 1.6 m. The orthogonal rotation 1 DOF joints are connected alternately. The specification of ACM-R7 is shown in Table I.

A. Joint Mechanism

The joint torque should be large to lift the body in the loop gait. The wide motion range of the joint is required to form a loop shape. Therefore, the coupled drive mechanism is installed to each joint to increase the output torque and the motion range. In this mechanism, the outputs of two motors are combined and drive two joints as shown in Fig. 2 (a) (b). The detail of the joint mechanism is shown in Fig. 2(c). First, the two Link-As are rotated by two motors independently. Link-A is connected to the fore unit with Link-B and ball joints. Then, the pitch joint is driven when the Link-As are rotated in the same direction. If the Link-As are rotated in the different direction, the yaw joint is driven. The output torque of the pitch axis joint is twice as large as a mechanism in which one joint is moved by one motor. Furthermore the joint angle range is 90 degree (pitch axis). The pitch axis joints are mainly used in the loop gait. The wide angle range makes it easy to archive a loop shape. The joint mechanism is covered with bellows and oil seals, so that ACM-R7 can move in wet and dusty environments.

It is believed that the importance of the loop gait was increased, because a waterproof and dustproof robot capable of the loop gait in outdoor environments has been developed.

B. Connecting Mechanism with the Gripper

A gripper is attached to the end of ACM-R7 (Fig. 4). ACM-R7 becomes a loop shape by grasping the rod at the opposite end with the gripper. The gripper is driven by a worm gear to prevent its accidental opening. Therefore, the gripper is able to keep the grasping, even if the motor output is turned off.

III. Serpenoid Oval for the Kinematics of the Loop Gait

A. Proposal of Serpenoid Oval

There are various loop shapes like circles, ellipses and combinations of circular arcs and lines. However, a combination of circular arcs and lines is not smooth. An ellipse has parts of which curvature varies widely. Further, it is difficult to apply an ellipse to a robot as we discuss later. Therefore, we propose the serpenoid oval which is an applied shape of

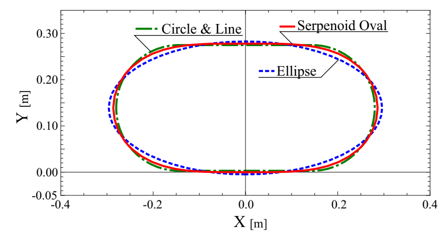


Fig. 7. Comparison of the Loop Shapes

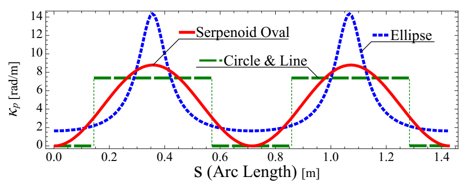


Fig. 8. Comparison of Curvature of Loop Shapes

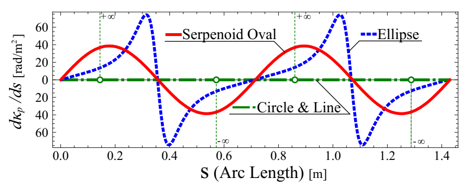


Fig. 9. Comparison of Derivative of Curvature of Loop Shapes

a serpenoid curve. The shape of a serpenoid oval is smooth, because the curvature of it changes sinusoidally.

Serpenoid oval is defined by a shape control method, which has been developed for snake-like robots [9]. In this method, the shape of a snake-like robot is expressed in 3D curve by defining two curvatures. The curvatures are functions of body trunk length. The curvatures of a serpenoid oval are defined by the following equations.

κ_p, κ_y:	Curvature
s:	Body Trunk Arc Length
t:	Time
L_t:	Total Length of the Loop
T_t:	Cycle Time
C_f:	Coefficient of Flatness
C_t:	Coefficient for Turning
C_1:	Coefficient for Posture Offset

$$\kappa_p(s,t) = \frac{2\pi}{L_t}\left\{1 - C_f \cdot \cos 2\pi\left(\frac{2s}{L_t} - \frac{t}{T_t}\right)\right\} \tag{1}$$

$$\kappa_y(s,t) = \frac{2\pi}{L_t}\left[\left(C_t + \frac{C_1}{2}\right)\left\{1 + \cos 2\pi\left(\frac{2s}{L_t} - \frac{t}{T_t}\right)\right\} - C_1\right] \tag{2}$$

The cycle time T_t changes locomotion velocity, not affecting the shape of a serpenoid oval. Therefore, we discuss the equations with $t = 0$ to ignore the influence of T_t. The meanings of the coefficients (C_f, C_t, C_1) are described in the following parts. First of all, the standard shape of a

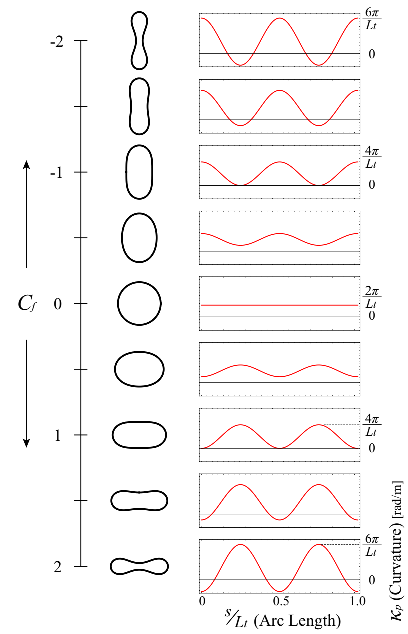


Fig. 10. Change of the Flatness of Serpenoid Oval

serpenoid oval is shown in Fig. 5 ($C_f = 1$, $C_t = 0$, $C_1 = 0$). The relationship between the arc length and the curvatures is shown in Fig. 6.

Compared to the other loop shapes, the smoothness of the change of the curvatures is the most characteristic point of a serpenoid oval. The change of the joint angle is smooth if the change of the curvature is smooth. Thus the loop gait based on a serpenoid oval is able to move fast.

The comparison of the loop shapes (a serpenoid oval, an ellipse and a combination of circle arc and line) is shown in Fig. 7. The relationship between the arc length and the curvatures are shown in Fig. 8. The derivatives of Fig. 8 are shown in Fig. 9. This serpenoid oval is the standard shape which is shown in Fig. 5. The total length and the aspect ratio of all shapes are equal.

The curvatures and the derivatives of curvatures of the serpenoid oval change smoothly. However, the derivative of curvature of the combination of the circle arc and the line reaches an infinite value. It means that the joint speed becomes very fast when the shape is applied to the robot. The change of the curvature of the ellipse is also larger than serpenoid oval. In addition, it is difficult to express the curvature of an ellipse by the arc length s, because an ellipse is generally defined by other parameters. Therefore a serpenoid oval is suitable as a basic shape for the loop gait.

B. Change of Flatness

It is possible to change the flatness of the serpenoid oval by changing the definition of the curvatures with the coefficient of the flatness C_f. The relationship between C_f and the flatness of serpenoid oval is shown in Fig10. The flatness can be changed by the control of the value of C_f. The standard value is $C_f = 1$. A serpenoid oval becomes a flat shape when C_f becomes large. In contrast, the shape changes to a

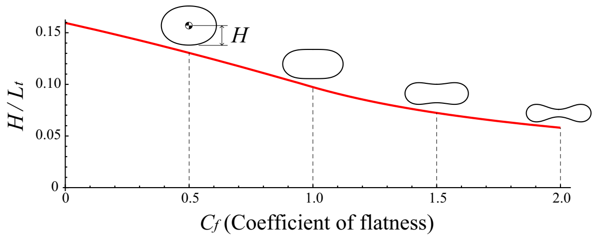


Fig. 11. Height of the Center of Serpenoid Oval

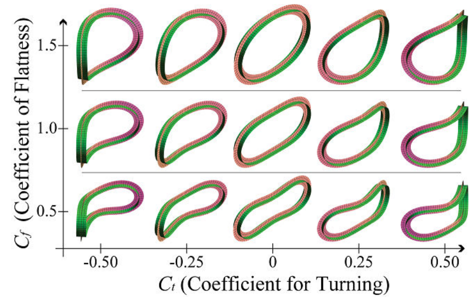


Fig. 12. Relationship between Serpenoid Oval and C_t

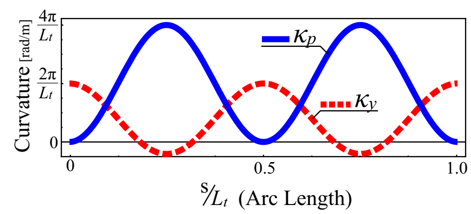


Fig. 13. Curvature of the Serpenoid Oval ($C_f = 1$, $C_t = 0.5$, $C_1 = 0.2$)

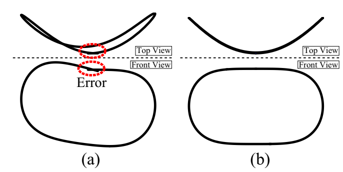


Fig. 14. Difference of the Shape by C_1

circle, if C_f is close to zero. If C_f has a negative value, the shape is rounded 90 degrees from the shape in which C_f is positive.

Fig. 11 shows the relationship between C_f and the height of the center of the serpenoid oval. When a serpenoid oval becomes flat, the position of the center of mass is lowered and it is difficult to fall. Therefore, the flat loop shape is effective, when ACM moves over obstacles or climbs a slope with the loop gait.

On the other hand, a serpenoid oval which is close to a circle is suitable for high speed locomotion, because the bending speed of the joint is slow when the shape is close to a circle. The bending speed is determined by the derivative of κ_p. The maximum value of the derivative of κ_p is calculated from the following equation.

$$\left.\frac{d\kappa_p}{ds}\right._{max} = \frac{8\pi^2}{L_t^2} C_f \tag{3}$$

Therefore, the maximum locomotion speed becomes fast by increasing C_f instead of by rising of the position of the center of mass.

C. Turning

We introduce the coefficient for turning and the coefficient for posture offset to make the turning motion. The lower part, which touches the ground, has to be bent horizontally to make turning motion in the loop gait. However, it is difficult to bend only the lower part because of the loop shape. In our method of turning, the whole loop shape is bent horizontally.

The degree of bending is determined by C_t. The relationship between C_t and the shape of a serpenoid oval is shown in Fig. 12. Serpenoid oval is not bent when $C_t = 0$. The whole shape becomes bent when C_t is increased. Even if the flatness of a serpenoid oval is changed, it is bent. Fig. 12 shows the shape of the serpenoid ovals with different values of C_f and C_t. It is bent to the opposite direction when the value of C_t becomes negative.

The relationship between the arc length and the curvatures ($C_f = 1.0$, $C_t = 0.5$, $C_1 = 0.2$) is shown in Fig. 13. κ_p is the same as in straight motion, and κ_y is also changed sinusoidally.

The meaning and calculation method of C_1 is defined as follows; The position gap between the head and the tail will be observed (Fig. 14), when the loop shape is bent with $C_1 = 0$. C_1 is the coefficient to offset the gap. The calculation method of C_1 was developed as follows.

First, it is assumed that C_f is constant, and the loop shape is calculated. C_t is changed in increments of 0.01. The value of C_1 which makes the gap minimum is calculated in each C_t. Next, the relationship between C_t and C_1 is calculated in each C_f ($C_f = 0$ to 1.5, with increments of 0.1). The relationship between C_t and C_1 in each C_f is approximated by a linear function. Fig. 15 shows them. For example, the function of C_1 is approximated by the following equation.

$$C_1 = 0.410 \cdot C_t \tag{4}$$

Then the relationship between C_f and the gradient of the Fig. 15 is approximated by a quadratic function. Therefore C_1 is expressed in the following equation with C_t and C_f.

$$C_1 = \left(-0.136C_f^2 - 0.298C_f + 0.841\right) C_t \tag{5}$$

The serpenoid oval is bent horizontally without the gap by defining C_1 from Eq. 5.

An approximation error is observed when the continuous model is approximated to the discrete model. There may be a gap in the discrete model, even if there is no gap in the continuous model. A large gap should be reduced by recalculation and adjustment of the joints. However we did not make adjustments, because the gap is thought to be small enough to be absorbed with mechanical elasticity.

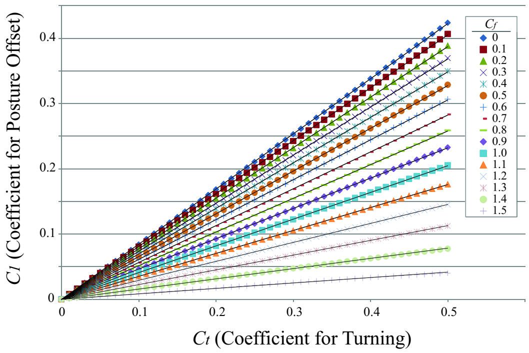


Fig. 15. Relationship between C_t and C_1

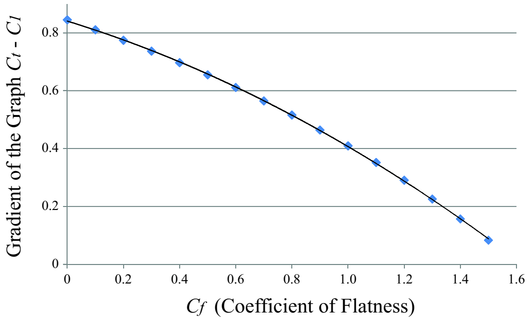


Fig. 16. Relationship between C_f and the Gradient of the Fig. 15

IV. Experiment

A. Control Method

The loop gait with a serpenoid oval was tested using ACM-R7.

In order to control a snake-like robot with a serpenoid oval, a continuous model has to be approximated to a discrete model. The joint angle of the discrete model is calculated by integration of the curvatures of the continuous model in the following equation [9].

i: Joint Axis (p or y)
j: Joint Order in Each Axis
θ: Joint Angle
L_u: Length between Joint Axes
s_0: Length from the Edge to the First Joint

$$\theta_{i,j} = \int_{s_{0,i}+\frac{j-1}{2}L_u}^{s_{0,i}+\frac{j+1}{2}L_u} \kappa_i(s)ds \tag{6}$$

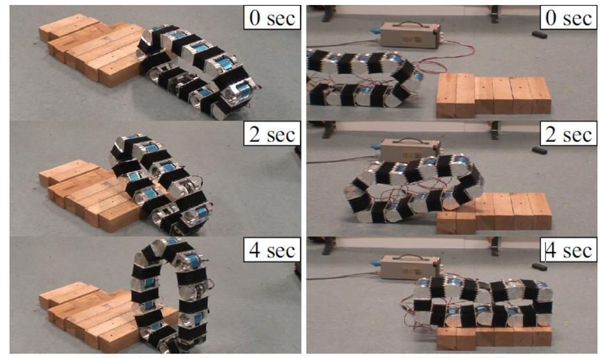
ACM-R7 calculates the joint angle using Eq.6 with the main CPU mounted on the tail unit. The joint angle value is transmitted to the local CPU in each unit with CAN BUS. The joints are proportionally-controlled.

B. Flatness

1) Change of Flatness: The change of flatness of the serpenoid oval was tested. It was confirmed that the flatness of a serpenoid oval is changed by C_f. The limitation of the value of C_f was 1.5 because of the maximum joint angle of the pitch axis joints.

(a) $C_{flat} = 0.5$ (b) $C_{flat} = 1.0$ (c) $C_{flat} = 1.5$

Fig. 17. Experiment of the Change of the Flatness of Serpenoid Oval with ACM-R7



(a) C_f = 1.0 (b) C_f = 1.5

Fig. 18. Step Climbing (Step Height: 9cm)

2) Locomotion Velocity: When C_f was 1.0 (standard shape), the fastest locomotion velocity was 1.0 m/s. In the experiment, the locomotion acceleration was not controled. Therefore, the loop shape rolled backward by its acceleration, when ACM-R7 was moved faster than it.

3) Step Climbing: Step climbing experiment was conducted. ACM-R7 was made to climb the 9cm step with $C_f = 0.5$, 1.0, 1.5. It was not able to climb the step when $C_f = 0.5$, 1.0, because it rolled backward before the center of mass got over the edge of the step. When the serpenoid oval is flat (C_f=1.5), it was able to climb the same step. The flatness and the dent of the center of a serpenoid oval were effective to climb the step. The dent fit to the shape of the edge of the step (Fig. 18(b)).

4) Slope Climbing: The slope climbing performance was tested on an outdoor slope. The inclination angle was about 33 degree. The locomotion direction was parallel to the slope. When the loop shape was a standard serpenoid oval ($C_f = 1.0$), ACM-R7 rolled down the slope. However, the flat shaped ACM-R7 ($C_f = 1.5$) was able to go up the slope (Fig. 19).

C. Turning

The turning motion was experimented, which is shown in Fig. 20. ACM-R7 was able to turn, even if the serpenoid oval is transformed to flat or rounded shape by changing C_f. The turning radius was controlled by the coefficient of turning C_t. The relationship between C_t and the turning radius is shown in Fig. 21. The curve shown in Fig. 21 is the minimum radius of the curvature of the continuous model, which is theoretically calculated from κ_y. When C_t is increased, the radius of the curvature of the continuous model becomes small. Then, the experimental turning radius becomes small,

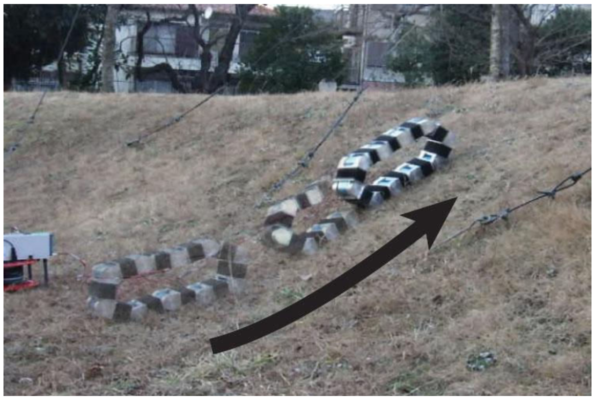
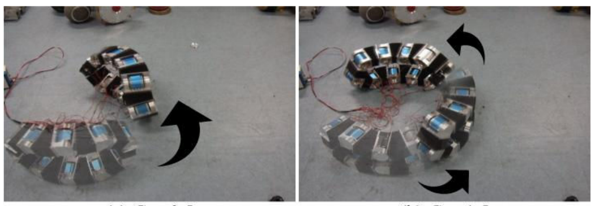


Fig. 19. Slope Climbing on Grass (The Angle of the Slope: 33 deg)



(a) $C_f = 0.5$ (b) $C_f = 1.5$

Fig. 20. Steering Motion

too. Therefore, it became possible, that the ACM in the loop gait makes turning motion in arbitrary radius.

Outdoor experiments were made on grass, because ACM-R7 is waterproof and dustproof. The straight and turning motion is shown in Fig. 22.

V. Conclusions and Future Works

A. Conclusions

The new snake-like robot ACM-R7, which is suitable for loop gait, was developed, with waterproof structure. The new smooth shape "Serpenoid Oval" was proposed for the loop gait. The shape control method of a serpenoid oval was formulated to make turning and step climbing. The experiments confirmed the usefulness of those methods using ACM-R7.

B. Futureworks

There will be more shape control methods of a serpenoid oval. Future work will include the formulation of those methods. In addition, another loop shape that considers the effect of its own weight should be examined, because only the kinematics of the loop gait were discussed. The joint torque is able to be adjusted by the new shape because a loop shape has redundant joints to fix the posture.

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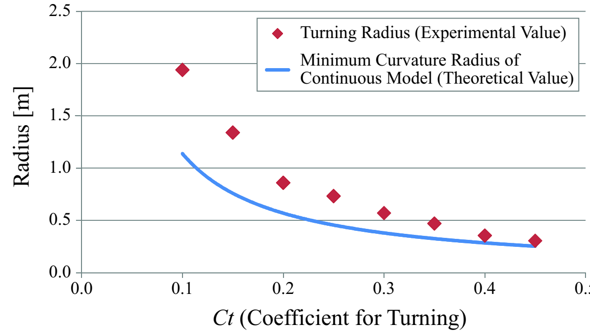

Fig. 21. Relationship between C_t and Turning Radius

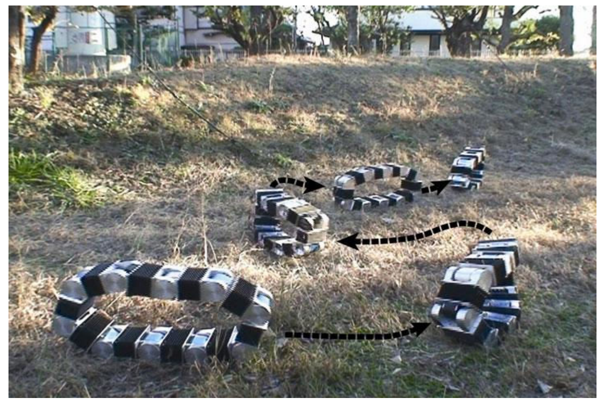

Fig. 22. Locomotion on Grass with Serpenoid Oval

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