

Paper:

Locomotion of 3D Snake-Like Robots – Shifting and Rolling Control of Active Cord Mechanism ACM-R3 –

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We discuss basic control strategies of a three-dimensional snake-like robot. Introduced strategies are composed of shifting and rolling, and their superimposing control. This paper clarified the generation of control commands for these movements and verified the feasibility of our proposal in experiments using the three-dimensional snake-like robot “ACM-R3”.

Keywords: snake-like robot, ACM, shifting, rolling, side-winding

1. Introduction

Snakes have very interesting applications, e.g. the function of an “arm” when coiling themselves around something to hold it, and the function of a “leg” when moving from one place to another. They propel themselves over uneven, rough terrain or along winding paths by using its slender body. They also move easily over unfirm surfaces such as marshlands and sand dunes by distributing their weight over the entire part of their surface touching the ground. Since most part of their body is on the ground and kinematically stable, they easily adapt to irregular terrain, such as spanning rifts or along tree bark.

We define the functional body that has a cord state and actively bends, like a snake, as “Active Cord Mechanism (ACM)”, and have been developing ACM robots since 1972. **Fig.1** shows one of the ACM robots for locomotion experiment. The functional long body consists of multiple links separable into unified independent segments, giving it high redundancy and concomitant reliability. They are easily waterproofed for amphibious mobility because its joints make bend only and engage in no infinite rotation. ACMs are eventually expected to propel themselves over almost any natural or artificial environment. One promising application of the ACM is in disaster relief searching among the debris of collapsed buildings for earthquake survivors.

We have studied these snake functions, mainly on locomotive mechanisms [1], and clarified that the effectiveness of basic creeping propulsion is strongly related to the ratio of friction of the trunk – small friction longitudinally and normally laterally – similar to rollerblading, ice skat-

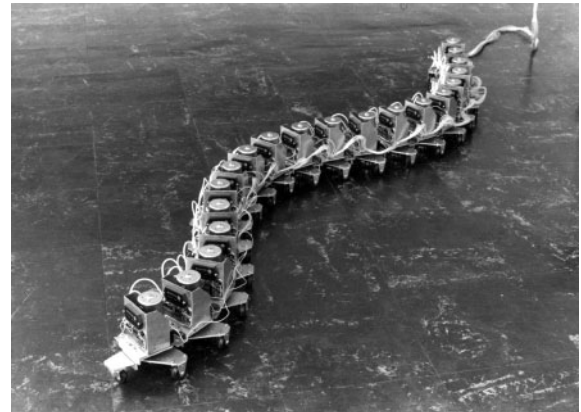


Fig. 1. ACM prototype model (1972).

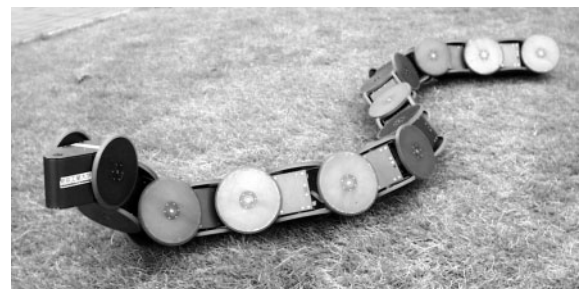


Fig. 2. ACM-R3-21 unit model.

ing, and roller skating, propulsion modes as also known as glide propulsion. We realized this motion in mechanical models ACM-III and ACM-R1 [2]. Our model ACM-R2 moves three-dimensionally (3D) at each segment [3]. Just recently, we have developed a new ACM “ACM-R3” (**Fig.2**) as a kind of standard platform provided to other researchers on snake-like robots, and we have realized several new mode of locomotion using it [8, 10].

Other work on 3D snake-like robots includes Poly Bot (Mark Yim et al.) [4], Sewer Robot (K-U Scholl et al.) [5], GMD-SNAKE2 (Bernhard Klaassen et al.) [6], and so. In this paper, we first classify various propulsion methods of the 3D snake-like robot into three kinds of control methods and then explain the characteristics of these methods by using mechanical model ACM-R3 [7, 12, 13].

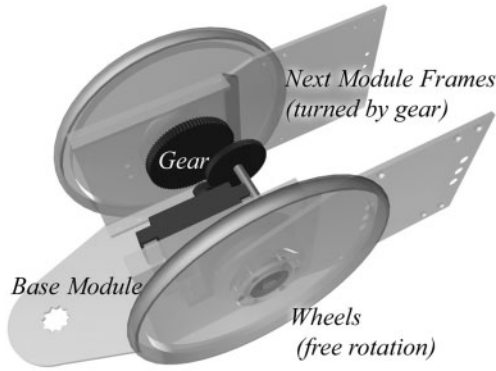


Fig. 3. Actuator output and passive wheels.

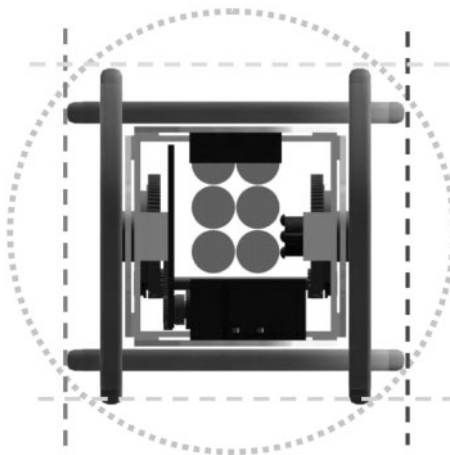


Fig. 4. Running surface (front of view).

2. Experimental 3D-ACM

Our target 3D snake-like robot model “ACM-R3” [8, 10] has the following four features:

- 1) It is designed to bend moving its backbone axis (s-axis). Its unified segments are either for yaw or pitch. The yaw and pitch segments are alternately to bend the ACM in 3D curves.
- 2) Joint torque is sufficient to support half of the body using an RC servomotor at joints reduced with additional reduction gear trains. Joint output torque is 19.1Nm.
- 3) To introduce anisotropic friction low longitudinally and high normally, regardless of the 3D posture of ACM-R3, we introduced large-bore passive wheels installed at the pivot of bending joints (Fig.3). These wheels are arranged to covering the segment, and the bending shaft of the segment is use for the wheel axis, ensuring large joint motion range of over 60° and having wheels always touching the ground regardless of posture (Fig.4).
- 4) The controller, wireless hub, its communication circuit, and battery are installed within the ACM to ensure infinite rotation. The battery drives the ACM for about two hours.

The performance of ACM-R3 is summarized in **Table 1**.

Table 1. Specifications of ACM-R3-21.

D.O.F.	20 (yaw 10/ pitch 10)
Size	1755 × 110 × 110mm ³
Weight	12.1kg (with batteries)
Movable angle	+62.5°
Output torque	19.1Nm

3. Classification of Movement

Below we introduce three elemental functions – shifting, rolling, and their superimposed ratio – and discuss the total control formula using these functions. As mentioned, the ACM consists of bending and pitch bending segments arrayed alternately in tandem. The 3D posture of the ACM having infinitesimal segments is then assumed to form continuous curve named “C”. Thus the basic curve of the ACM with infinitesimal segments is expressed as follows

$$C = \begin{bmatrix} \kappa_{yaw}(u) \\ \kappa_{pitch}(u) \end{bmatrix} \dots \dots \dots (1)$$

where C is the tracking curve, κ_{pitch} is the curvature of the infinitesimal pitch bending joints, and κ_{yaw} is the curvature of the infinitesimal yaw bending joints.

The “shifting” control is basic control method for the ACM, and most creeping methods of snakes can be classified into this control method. By shifting the control of signal to generate undulation motion of the ACM body, The ACM easily adjusts its direction and speed.

Equation (2) is the control method for the shifting control:

$$C_{Shifting} : S(s, t) = \begin{bmatrix} \kappa_{yaw}(u) \\ \kappa_{pitch}(u) \end{bmatrix}, u \equiv \frac{s}{L} - \frac{t}{T}. (2)$$

Parameter s is the position of the s-axis along the body with infinitesimal joints, parameter L is the unit length of the body, parameter t is time, and parameter T is unit time. By controlling parameter u, we drive the robot along a C(u) curve.

The “rolling” control defines rotary motion of the ACM around its body axis itself, or the s-axis. Eq.(3) shows this control method:

$$C_{Rolling} : E(s, t) = \begin{bmatrix} \kappa_{yaw}(s, t, \Psi_{(s,t)}) \\ \kappa_{pitch}(s, t, \Psi_{(s,t)}) \end{bmatrix} = E(\Psi_{(s,t)}) \cdot C. \dots \dots \dots (3)$$

$E(\Psi_{(s,t)})$ is the rotation matrix expressing the rotation of yaw and pitch joints around the s-axis. If we keep parameters s constant, we maintain the same winding of the ACM and drive the body rotate around its body axis and going sideways [14].

We apply shifting and rolling control simultaneously, generating combined movement. In superimposing these controls, we consider the introduction of one more function, function A(s,t), to adjust the ratio of superimposition. Total control method to generate ACM curve is ex-

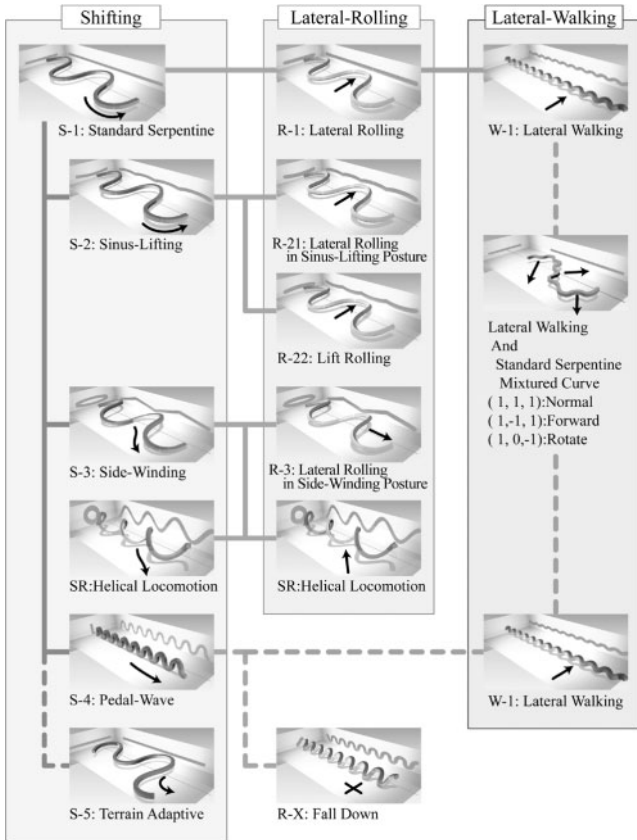


Fig. 5. Locomotion categorized.

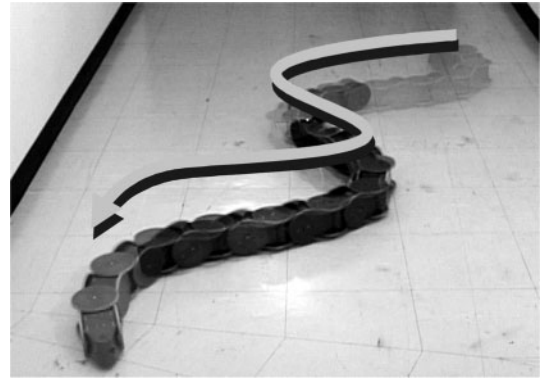


Fig. 6. Serpentine movement.

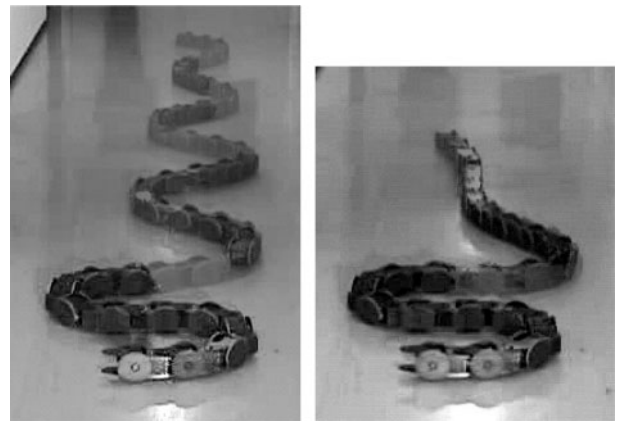


Fig. 7. Change winding angle.

pressed as follows:

$$C_{Sum} : \sum_{i=1}^n C_i = \sum_{i=1}^n (A_i(s, t) \cdot E_i(s, t) \cdot S_i(s, t)) \dots (4)$$

Based on these considerations, we classify various movement of the ACM as shown in Fig.5. From now on, we can characterize many realized locomotion of the ACM by these classifications.

4. Shifting Motion

4.1. Serpentine

Serpentine shifting is used most of the formerly made snake-like robots (Fig.6). It requires anisotropic friction of the body. Fig.7 shows the motion of ACM R3 when the signal to produce winding motion of the ACM-R3. This planar movement is expressed as follows by changing the yaw angle curvature sinusoidally while keeping the pitch angle null:

$$C_{S1} = \begin{bmatrix} \kappa_{yaw}^0 \sin(2\pi u) \\ 0 \end{bmatrix} \dots \dots \dots (5)$$

4.2. Sinus-Lifting

When an animal snake creeps, it is observed that some part of the body is lifted from the ground. This specific

habit of the serpentine motion had been observed by one of the authors, Hirose, and regarded as one means the snake uses to reduce the friction loss in gliding and increase friction to prevent slippage. This habit is called "sinus-lifting" [1].

The sinus-lifting lifts the sinus part of the body and supports the body centrally in undulating motion that contacts the ground [9]. This sinus-lifting is realized by the composition of the horizontal serpenoid curve and half-cycle sagittal serpenoid curve. Control method to generate this motion is thus described by the following equation:

$$C_{S2} = \begin{bmatrix} \kappa_{yaw}^0 \sin(2\pi u) + \kappa_{yaw}^1(s) \\ \kappa_{pitch}^0 \sin(4\pi u) + \kappa_{pitch}^1(s) \end{bmatrix} \dots \dots \dots (6)$$

Each function of κ^1 is introduced to correct error generated by superimposing of two waves as discussed in the paper [14]. The realized sinus-lifting motion of ACM-R3 is shown in Fig.8.

Through experiments with ACM-R3 in sinus-lifting under several different ground conditions, we found following features.

When the ACM moves serpentine in sinus-lifting on solid but somewhat slippery ground, the ACM is supported by few units. It concentrates weight on these supporting units and increases frictional resistance to the ground to

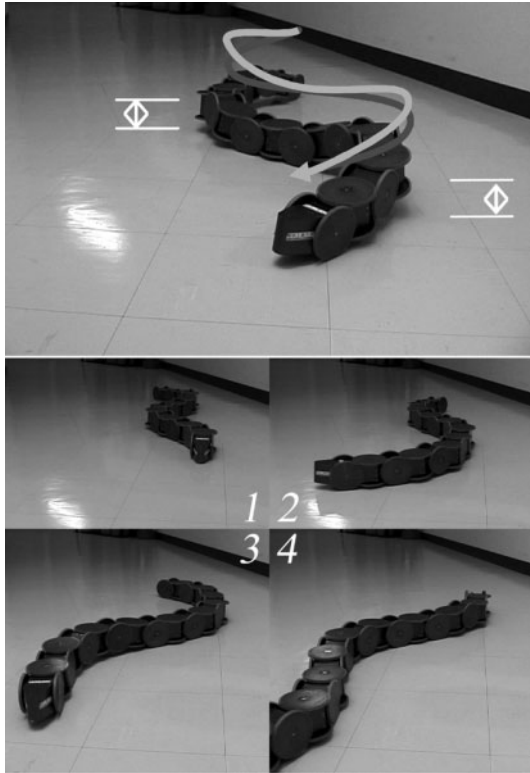


Fig. 8. Sinus-lifting.

prevent slippage in the normal direction. As a consequence, the ACM could move more effectively. This is the same result which has been discussed in the motion of the real snake [1].

When the ACM moves on a soft carpet by the normal serpentine motion, the body of the ACM tends to sink and generates large frictional resistance. But if the sinus-lifting motion is used on the carpet, only units generating propulsion sink as other units are lifted and freed of friction, enabling the ACM to move more smoothly on the carpet using the sinus-lifting motion.

4.3. Side-Winding

The animal snake which lives in desert is observed to perform the side-winding motion. ACM could realize side-winding motion by introducing both of yaw serpentine waveform control and pitch serpentine waveform control having low amplitude signals and a phase difference of one-quarter of the yaw waveform.

When we try to utilize this motion, we must design the number of grounding points properly to maintain stability, just as in the case of sinus-lifting motion. Introduction of the body with straight posture in every cycle of undulation helps increase stability more.

The side-winding motion is especially effective on ground with high friction because it does not rely on gliding between the body and the ground. Basically, the lifted part of the body moves sideways continuously over the

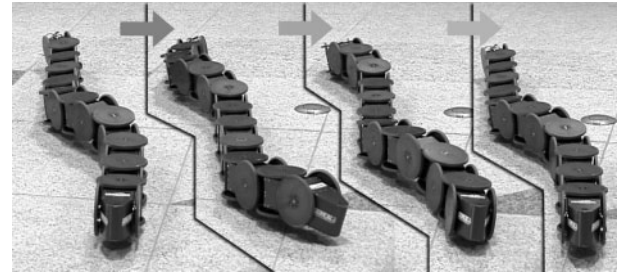


Fig. 9. Side-winding.



Fig. 10. Helical motion (HELIX).

ground (Fig.9). Using the following equation:

$$C_{S3} = A(s, t) \cdot E(\psi_{roll}^1(s)) \cdot \begin{bmatrix} \kappa_{yaw}^0 \sin(2\pi u) \\ \kappa_{pitch}^0 \cos(2\pi u) \end{bmatrix} \cdot (7)$$

Function $A(s, t)$ is introduced to generate intermittent up and down movement peculiar to side-winding. Function E is introduced to correct minute rolling caused by special bending .

4.4. Helical Locomotion

Shifting control drives the ACM longitudinally if the ACM has a curved form and anisotropic friction, i.e., low friction longitudinally and high friction normally. This is valid underwater in swimming, as verified by swimming ACM HELIX (Fig.10). In experiments, the control formula to generate a spiral was used in swimming, demonstrating one of the special solutions of side-winding equations [11].

4.5. Pedal Wave

A pedal wave is generated by waveform shifting of perpendicularly, and shifting the direction of the wave forward. Locomotion is slow compared to serpentine, but does not rely on gliding on the ground, so it can move more effectively over surfaces having high resistance (Fig.11).

This motion is expressed by the following equation:

$$C_{S4} = \begin{bmatrix} 0 \\ \kappa_{pitch}^0 \sin(2\pi(\frac{s}{L} + \frac{t}{T})) \end{bmatrix} \cdot \dots \cdot (8)$$

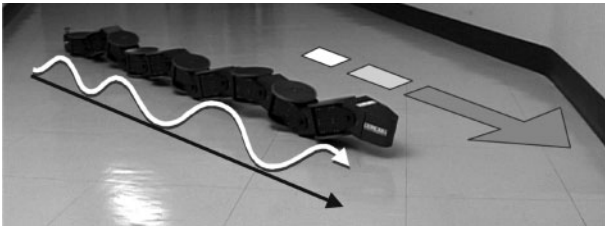


Fig. 11. Pedal wave.

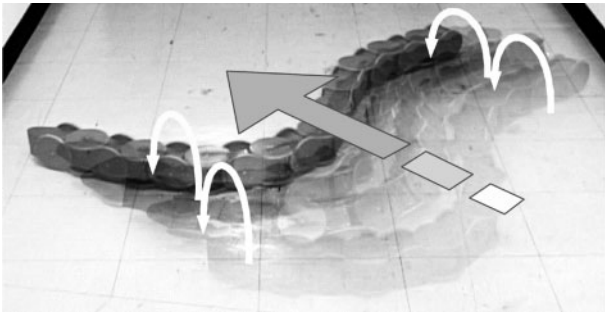


Fig. 12. S-character like lateral rolling.

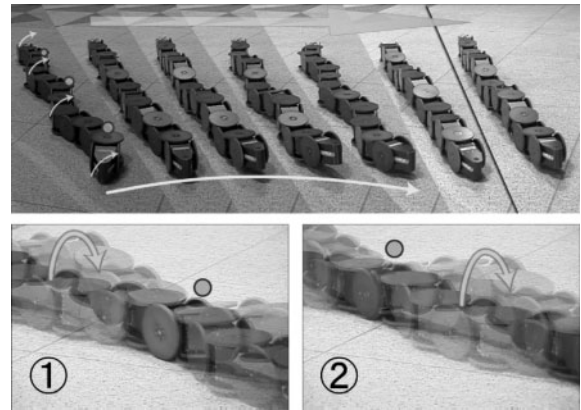


Fig. 13. Lateral walking.

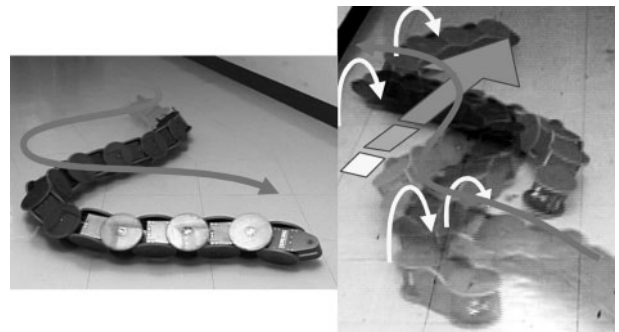


Fig. 14. Serpentine motion in leaned posture.

5. Rolling Motion

When the ACM maintains a certain posture on the ground while keeping the command for the posture is fixed and apply the rolling control by applying a rotation matrix of Eq.(2), the ACM rolls around the s-axis and moves sideways. The classification of the “rolling motion” and its control are as follows:

5.1. Lateral Rolling

The “lateral rolling” is the motion of the ACM to roll around s-axis. This motion does not require anisotropic friction, that is, low friction longitudinally and high friction normally.

Lateral rolling is shown in Fig.12.

The equation to generate this motion is shown by Eq.(2):

$$C_R = E(\psi_{(s,t)}) \cdot C \dots \dots \dots (9)$$

5.2. Lateral Walking

The above lateral-rolling is produced when undulation is larger than the width of the ACM . If undulation of the body is larger and it tries to rotate around its s-axis, it rotates while keeping the undulation posture of the ACM body relative to the ground.

However, if the undulation of the body is small compared to the thickness of the ACM, the command to rotate around the s-axis does not generates rotating motion of the body, and instead, generates sideways walking-like motion of the ACM body while avoiding rotation. We involuntarily found this interesting motion while operating ACM-R3 under many conditions, and designated this

movement “lateral-walking”. We have not yet observed it in an actual snake, however.

The width of ACM-R3 segments is 43mm, so if the amplitude of undulation is less than this width, rotation is suppressed and lateral-walking is generated (Fig.13).

Control signals for lateral-walking is expressed by Eq.(10):

$$C_{W1} = E(\psi_{(s,t)}) \cdot C_{ripple} \dots \dots \dots (10)$$

The formation of this Eq.(10) is the same as for Eq.(9).

6. Superimposed Movement

6.1. Lean Serpentine

By superimposing serpentine shifting and lateral-rolling, the ACM starts to creep in new directions (Fig.14) that we call lean serpentine – serpentine Locomotion while leaned posture.

This differs from usual serpentine because both pitch and yaw bending units are driven coupled. This is considered omni directional serpentine movement. Using Eq.(4), the control equation is simply described as follows:

$$C_{R1} = E(\psi_{(s,t)}) \cdot C_{S1} \cdot \dots \dots \dots (11)$$

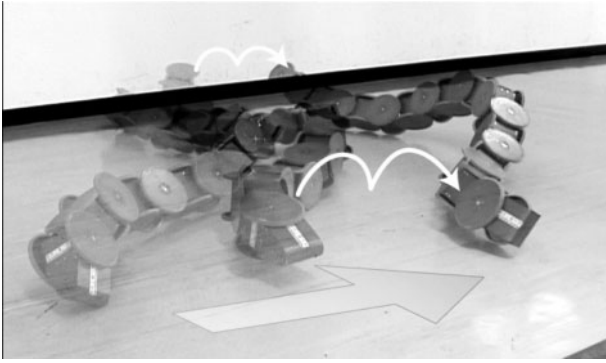


Fig. 15. Sinus-lift rolling.

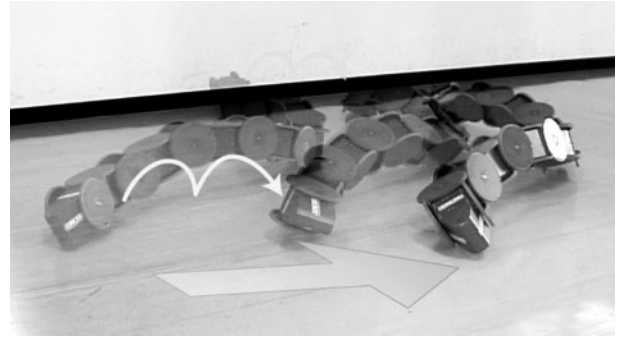


Fig. 17. Lift rolling.

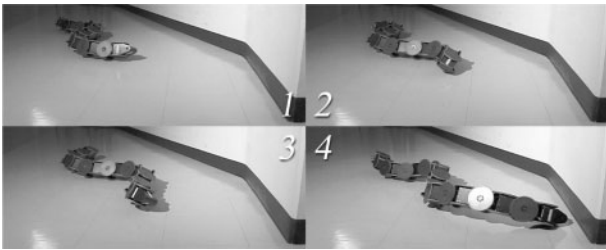


Fig. 16. Sinus-lifting in leaning.



Fig. 18. Steering of pedal-wave.

6.2. Lean Sinus-Lifting

The same idea of “lean serpentine” is applied to the “sinus-lifting”. We call this motion as “lean sinus-lifting”, the sinus-lifting locomotion in leaning posture. The omni directional mobility of the lean serpentine is also produced. The motion of the “lean sinus-lifting” is shown in **Figs.15** and **16**. The equation of the control signal for this motion is as following:

$$C_{R21} = E(\psi_{(s,t)}) \cdot C_{S2} \cdot \dots \dots \dots (12)$$

6.3. Lift Rolling

Lift rolling corresponds to inverted sinus-lifting, with rolling used instead of shifting with body segments arrayed in almost the same direction. This feature will enhance the effectiveness of the rolling propulsion (**Fig.17**).

The control command for lift-rolling is to invert pitch bending angle in the direction opposite sinus-lifting and rotating the s-axis, so it is expressed by the following equation:

$$C_{R22} = E(\psi_{(s,t)}) \cdot \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \cdot C_{S2} \cdot \dots \dots \dots (13)$$

6.4. Steering of Pedal-Wave

In pedal wave movement, the wave travels from back to front, but if the pedal wave motion is for steering, the wave travels from front to back, and these directions of wave propagation are opposite. Superimposing steering control is done by assigning a pitch axis for pedal-wave shifting and assigning the yaw axis for steering wave

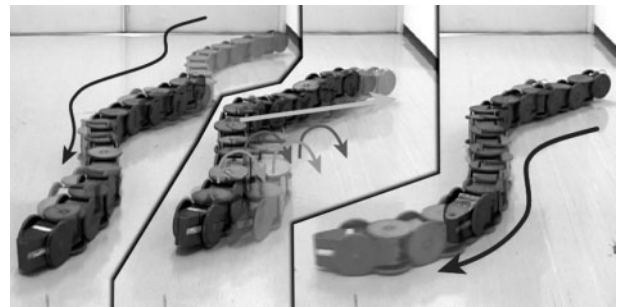


Fig. 19. Lateral-walking with serpentine motion.

shifting (**Fig.18**). Using the following equation:

$$C_{S4S1} = C_{S4} + \begin{bmatrix} \kappa_{yaw}^1(v) \\ 0 \end{bmatrix} \cdot \dots \dots \dots (14)$$

$$v \equiv \left(1 - \frac{L_p}{L} \right) \left(\frac{s}{L} - \frac{t}{T} \right)$$

where parameter L_p is the average projection length of unit length L . This is useful to pass through narrow and winding passages.

6.5. Lateral-Walking with Serpentine Motion

While the ACM is moving serpentine and must go sideways without rotating around its axis by rolling control, we superimpose lateral-walking on shift control of serpentine movement. This might be useful if a camera is on top and maintain its posture for monitoring. It is done by generating lateral-walk whose control is operated independently (**Figs.19** and **20**).

When the ACM is winding as shown in **Fig.21**, both

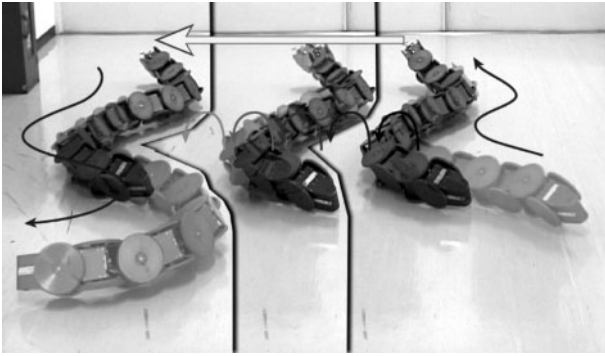


Fig. 20. Lateral-walking with lean serpentine.

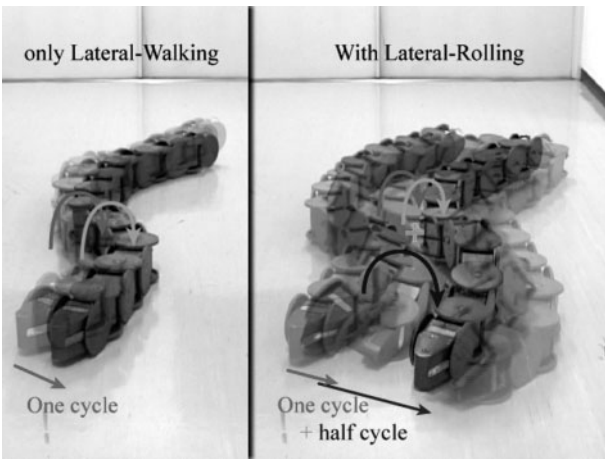


Fig. 21. Lateral-walking with lateral-rolling in serpentine posture.

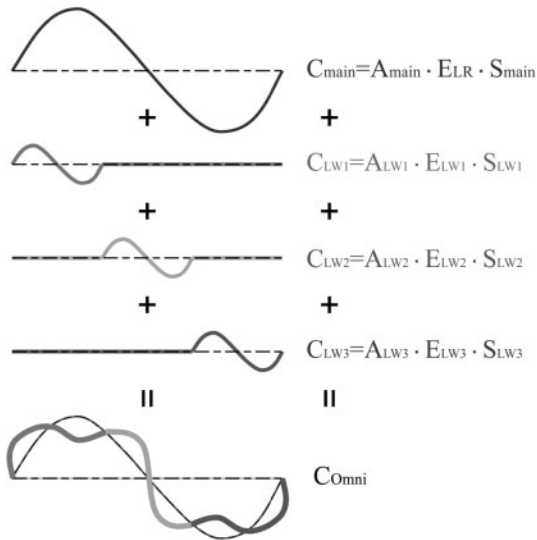


Fig. 22. The three lateral-walking waves mixture.

lateral-rolling and lateral-walking are generated simultaneously, described by identical equations:

$$C_{RIW1} = C_{R1} + C_{W1} \dots \dots \dots (15)$$



Fig. 23. Forward motion with four waves mixture.

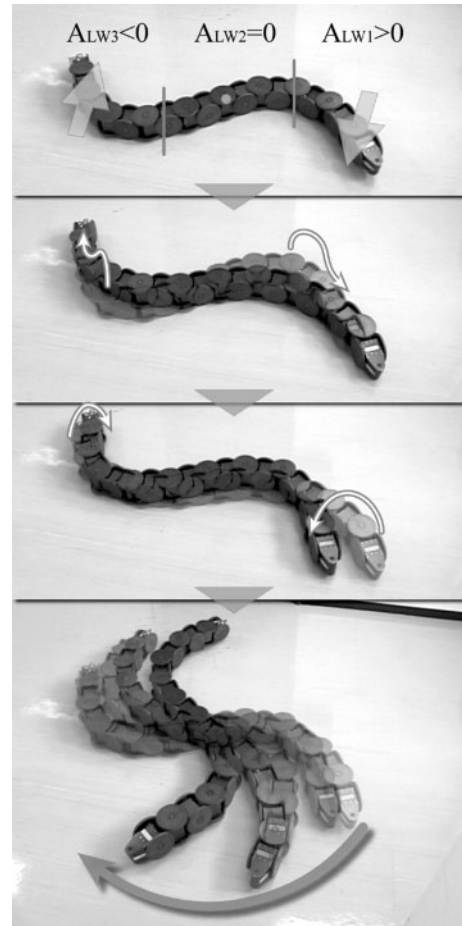


Fig. 24. Pivot motion with four waves mixture.

6.6. Omni Directional Movement with Lateral-Walking

Lateral-walking is regarded as an operation that generates power to progress sideways, so if we apply this partially to the ACM, it moves omni-directionally. We made the ACM-R3 fit the mixed waveform – a main serpentine waveform, and sub-wave-form of three waves of Lateral-walking (Fig.22), expressed by the following equation:

$$C_{Omni} = C_{main} + C_{LW1} + C_{LW2} + C_{LW3} \dots \dots \dots (16)$$

By changing parameters of Eq.(16), we generate parallel transference (Fig.23) or pivotal turning (Fig.24).

7. Summary and Conclusions

We have discussed the importance of snake-like robots and introduced mechanical model ACM-R3 with its small, highly efficient, lightweight drive newly developed in order to examine the various functionalities of ACM. We describe three control strategies, each required to achieve these, classified into Shifting, Rolling, and Superimposition.

In shifting control, serpentine movement which an animal snake creeping method, Sinus-Lifting, Side-Winding, Spiral-Swimming, and Pedal-Wave were realized. Lateral-Rolling was realized as motion of rolling control, and Lateral-Walking was shown as special conditions. Lateral-Rolling of each inclination state, Pedal-Wave Steering, and Omni Directional movement were realized by superimposing these methods.

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