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# Biologically Inspired Snake-like Robots

Shigeo HIROSE[1], Makoto MORI[2]

[1]*Tokyo Institute of Technology, Tokyo, JAPAN,hirose@mes.titech.ac.jp*
[2]*Tokyo Institute of Technology, Tokyo, JAPAN, mori@mes.titech.ac.jp*

## Abstract

*We have developed the snake-like robot since 1972. The body of snake has "the function of an arm" when it holds something by coiling itself, and also has "the function of legs" when it moves by creeping. The body of ACM has several functions, which are fulfilled one after another according to the situation. Especially in this paper, it introduces about the various move method realized about the move function using 3-dimensional type ACM, and its feature.*

## 1. Introduction

We have developed that snake-like robot since 1972 (**Figure 1**), and we call the functional body that is a code state and actively bends "Active Cord Mechanism (ACM)". The snake is mentioned as an example of ACM. The body of snake has "the function of an arm" when it holds something by coiling itself, and also has "the function of legs" when it moves by creeping. The body of ACM has several functions, which are fulfilled one after another according to the situation. Of the characteristics of the snake family's mobile body, we may adduce the following, which depend on the exploitation of a long and thin, active and flexible, body shape which can make bending movements:

1. The snake can propel itself over very uneven, rough ground, or along winding paths by using its slender body;
2. It is adapted to moving over places where the surface is not firm, such as marshland or sand dunes, because it can distribute its weight over its whole body;
3. Because it normally propels itself in a kinematically stable posture, it is adapted to achieve stable movement on irregular terrain, such as spanning rifts or in trees.

These are the characteristics based on the snake's body. When we regard the characteristics from the engineering viewpoint of the ACM form, we can go on to adduce the following:

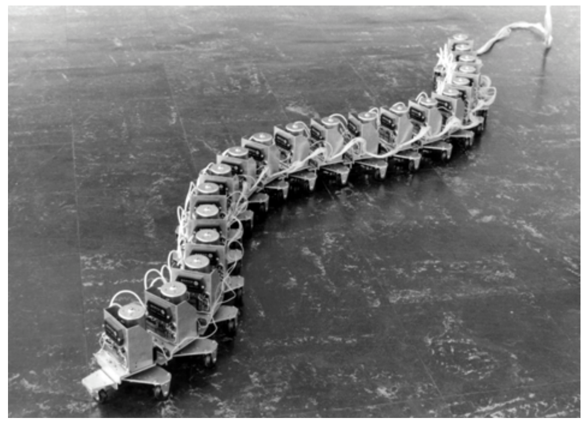

***Figure 1:*** *ACM prototype model(1972)*

4. Because its body is formed from compartmentalized sections, it has a high level of redundancy and can thus form a highly reliable system. For example, once a section is broken, all we have to do is to separate the broken section and the rest of the system will work. We can separate the body into several independent sections, and they can perform different tasks individually if necessary. It might be said to have the essence of a decentralized system.
5. Between the joints only bending movements take place, and endless rotational movements like those of a wheel are not needed. For this reason, improvements in airtightness are possible, and in addition, the fact that creeping propulsion movements are highly efficient in water offers the possibility of an amphibious mobile body.

From the above, we can think of the ACM's mode of movement as having the special characteristic of being well adapted to rough ground. From research on the ACM's movement function, we can anticipate the development of a new shape of 'off-the-road vehicle', that can propel over all types of natural and artificial environment on Earth at least where the snake lives. That is our purpose when dealing with this system: to make good use of the characteristics of ACM to the society.

Until now, the engineering applications have been examined taking these functions as manipulator and locomotor's mechanism [1]. The engineering analysis was especially carried out on creeping propulsion by the snake. It was clear that the creeping propulsion was based on the ratio of friction between the trunk direction and the direction that is orthogonal to it by the course. It can be said that this is similar to skating, and it has been proposed as "glide propulsion". Such propulsion has been realized in the mechanical models ACM-III and ACM-R1 [2]. Moreover the next mechanical model ACM-R2 was meant to add a new degree of freedom in the pitch direction at each node, and to construct an ACM that realizes three-dimensional and various functions [3]. At the moment, researchers around the world have already investigated and developed three-dimensional snake-like robots, such as Poly Bot (Mark Yim et al.) [4], Sewer Robot (K. –U. Scholl et al.) [5], GMD-SNAKE2 (Bernhard Klaassen et al.) [6], and so on[12][13]. These robots have high functions, but also have complex machineries. Another snake robot developed by Kevin J. Dowling [7], is very simple and lightweight, but it has not enough power to realize three-dimensional motions that require high energy, and is too speedy.

Active Cord Mechanisms are useful for disaster relief such as searching for survivors of earthquakes through the debris of collapsed houses. With possibilities to approach these issues in mind, we developed the new Active Cord Mechanism "ACM-R3" (**Figure 2**) to be used easily by snake-like robotics researchers in several applications [8][10].

In this paper, the various move methods realized by 3-dimensional ACM are divided into three kinds, and are introduced. One is movement by which a Shift control system and one are generated by the Rolling control system, and another is generated by those compositions.

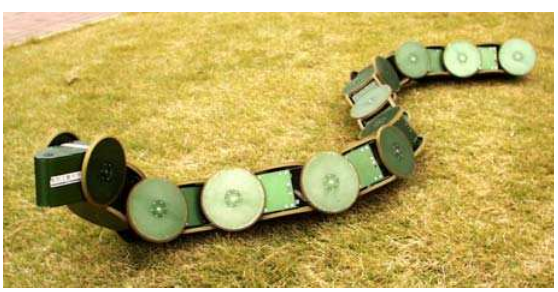

***Figure 2:*** *ACM-R3-21 unit model*

## 2. Shift-control Category

### 2.1. Serpentine

Two-dimensional Serpentine Locomotion has already been realized (**Figure 3**). ACM-R3 can go ahead and backward according to the shape in the continuous curve of body (s-axis) by transiting an angle using only the yaw angle joints. It also can control its speed, and steer itself by adding a bias to the angle order.

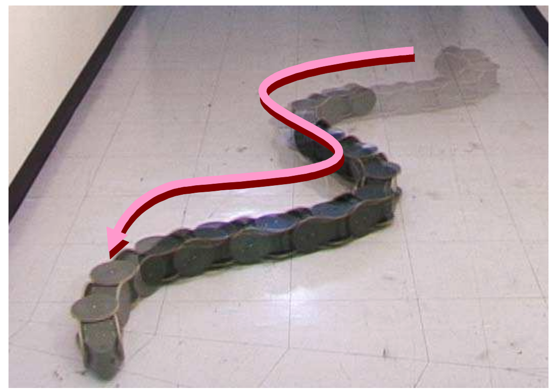

***Figure 3:*** *Serpentine movement*

In this mode the winding angle alpha can be changed to the maximum of 97.4 degrees continuously. It can also be steered if the sum of bias angle and alpha angle is within the limit of 61.2 degrees for every joint. **Figure 4** shows ACM-R3 moving with the alpha angle changing continuously.

***Figure 4:*** *change winding angle*

### 2.2. Sinus-Lifting

When a snake winds and progresses, it floats and oscillates both ends in the air, because they work as frictional resistance. We call this three-dimensional motion as Sinus-lifting [1]. This motion can be realized by the composition of the horizontal serpenoid curve around the yaw axis and the sagittal serpenoid curve from the bending angle around the pitch axis. The ratio of the wave length of serpenoid curves in the horizontal and the sagittal plane is 1:2.This body-shaped curve raises the body at the extremities and supports itself at the center of the horizontal serpenoid curve [9]. ACM-R3 realizes this motion as shown in **Figure 5**.

The main advantages when performing this motion with a snake-like robot such as ACM-R3 are the following.

Firstly, in this method there are fewer units generating impelling force and touching the ground. This is especially effective when creeping on a slippery floor, so that wheels with a higher concentrated will not slip so easily.

In addition, when moving on a surface with high friction, dispersion of the model as a difference from a theoretical value causes binding force from the ground, and generates large resistance forces. If two-dimensional serpentine locomotion is carried out on such rough surfaces, large resistance occurs, and there are cases when the mechanism cannot move. By reducing the grounding portion sharply, these resistances can be minimized.

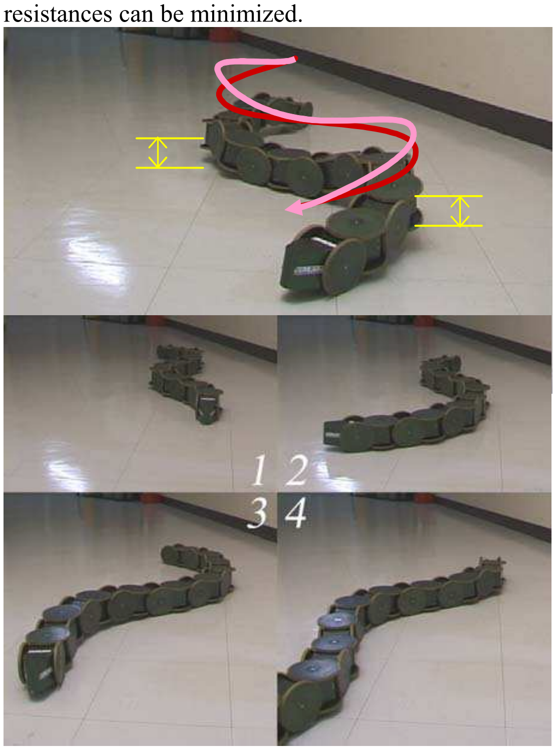


***Figure 5:*** *Sinus-lifting*

### 2.3. Pedal Wave

The locomotion of "pedal wave" without stretching also can be realized. A serpenoid curve is generated in the perpendicular direction of the s-axis, and it makes slow progress in the main direction by sending a wave, as shown in **Figure 6**, and **Figure 7**. However, only the grounding passive wheels are removed in order not to slip. It was also verified that it could steer by bending the joints of yaw axis.

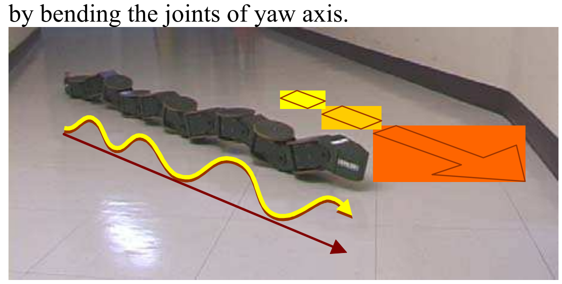

***Figure 6:*** *Pedal Wave*

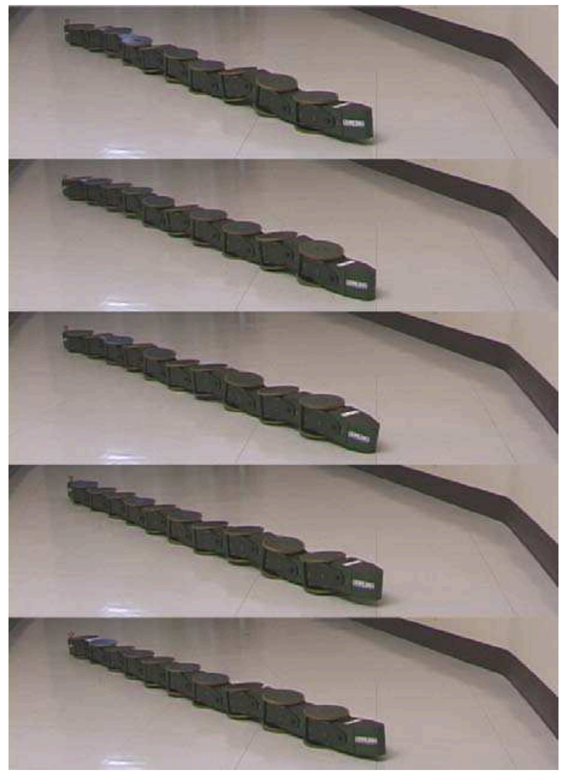

***Figure 7:*** *Pedal Wave sequence*

### 2.4. Side-Winding

The snake which lives in a desert performs the Side-Winding locomotion as a method of moving. This locomotion carries the body to move for side direction by shift control. The projection form to a run plane is mostly in agreement with the usual serpentine promotion, so it can apply the control formula of serpentine locomotion about yaw axes control. On the other hand, it is necessary to adjust perpendicular direction so that it may ground for every cycle. To apply basic angle control of pitch axes to same cycle sine-curve makes this form.

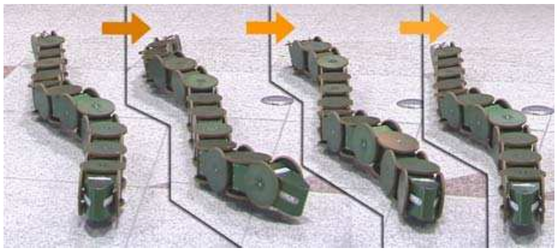

***Figure 8:*** *Sinus-lifting*

In this locomotion with continuous sine-curve angle control, the body-line may ground with curve. Unless it generates the waveform of two or more cycles to whole length, it puts grounding mark only to one point and cannot carry out stable movement. Furthermore, it has the feature which is easy to cause rocking along with a grounding curved surface like the state of the Lateral-Rolling promotion under below-mentioned Sinus-Lifting locomotion.

The above problem affects a dispersion problem greatly in the system to which the number of paragraphs is restricted. Applying the waveform of about four cycles to the system can also realize Side-Winding. However, as a cycle is increased, promotion distance also becomes small and the influence of dispersion also becomes quite larger. If the intermittent state of straight line form is wedged whenever it generates Side-Winding by one cycle, it will become unnecessary to suppress rocking, and to become possible to stabilize and ground, and for the number of cycles to full length to be also two or more cycles. It checked that it could stabilize and move also with the system by this method.

Although the friction coefficient to sidewall was theoretically movable satisfactory even if it was uniformly high, also in the experiment which attached the passive wheel for glide promotion (also setting in the state with few friction coefficients of the direction of a trunk axis), it checked that the direction movement of the side was possible as **figure 8**.

### 2.5. Spiral Swimming Locomotion

Fundamentally, in shift control, since it promotes by crookedness, application can be done also to underwater movement. The ACM for underwater type "HELIX" is already developed, and it proved experimentally that underwater movement can be performed using the generation formula of the spiral form which is the special solution of a Side-Winding formula [11].

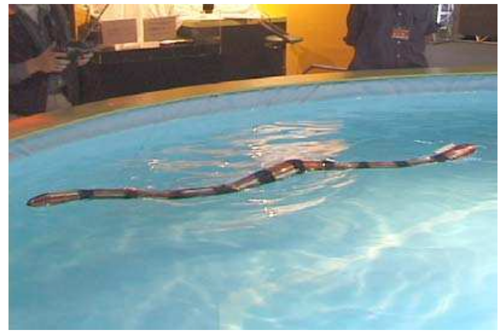

***Figure 9:*** *Spiral locomotion(HELIX)*

## 3. Rolling-control Category

The snake-like robot makes its s-axis to be curved on the ground plane, rotates in a bending direction around the s-axis, and then rolls at the lateral direction.

### 3.1. Basically Lateral Rolling (arch type)

In conventional research, experiments are mainly conducted with simple circle forms in which the point of inflection does not exist. For an Active Cord Mechanisms that is able to bend along its s-axis, it is also possible to make a part of the body bended and to move in this way. This is an effective motion method for when some joints break down. There is little load in each joint, since the whole bended body is used. Both shapes have been realized by ACM-R3, as shown in **Figure 10**. Since the units rotate at right angles to the rotating direction of the passive wheels, they actually do not depend on attached wheels to perform this motion.

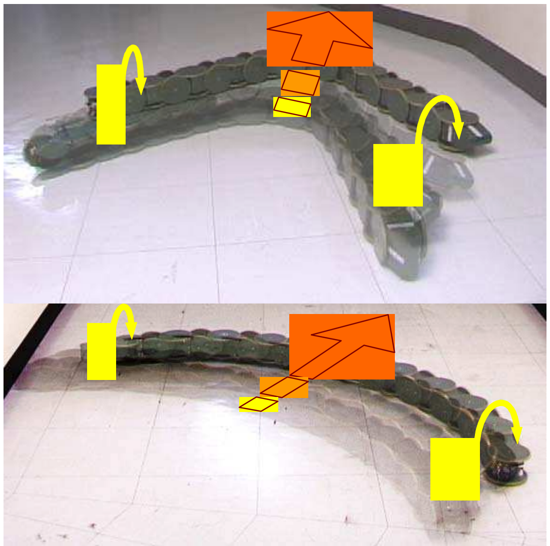

***Figure 10:*** *Lateral Rolling*

### 3.2. Lateral Rolling (winding type)

In the previous method, motion toward the inner side of the s-axis bended body is more stable than toward outside. For this reason, in movement on a slope, if an inner side is turned to the bottom of the slope, it can always perform stable movements. If bending angle is enlarged, its stability increases. However, rotating a straight body or a body bended in a single curvature are not the only options. It is possible to perform Lateral Rolling in the posture (in the shape "S" character) to which the point of inflection exists in the bended s-axis. When the general serpentine movement, which has one cycle assigned to the total length, is considered, the center of gravity is always located in the center position of the wave axis. Besides, in the waveform posture in any arbitrary phase generated in such state, experiments confirmed that Lateral Rolling movement to the direction of the side is possible, as shown in **Figure 11**. If it has only bending portion touched to a run plane steadily, it can advance with Lateral Rolling movement.

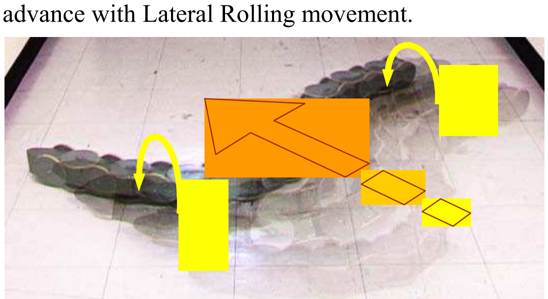

***Figure 11:*** *S-character like Lateral Rolling*

### 3.3. Lateral-Walking

The above-mentioned Lateral-Rolling is movement produced with the posture relation of the curve and run side which a trunk axis should imitate by performing rotation centering on a space curve held. However, since it has limited width unlike a space curve, though the system is in not a curve but a straight line state, it has static stability. The grounding paragraph has the 43mm stable domain also for ACM-R3 used for the experiment in the main subject at the maximum in the trunk axis radius direction. If the center of gravity has been settled in a static stable margin domain to every angle of the circumference of a trunk axis, a trunk paragraph will begin static walking in the direction contrary to the advance direction of original Lateral-Rolling locomotion, without rotating to a run plane (**figure.12**). Suppose that this movement is called Lateral-Walking.

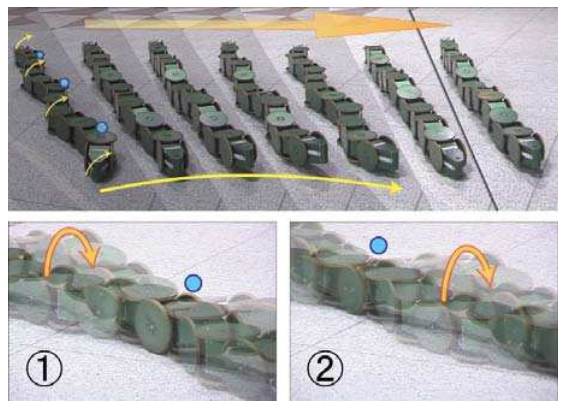


***Figure 12:*** *Lateral Walking*

Unlike the usual Lateral-Rolling, the feature of this moving method is in what "grounding point keeps still" like Side-Winding promotion. In order that the above-mentioned Lateral-Rolling movement may progress with rotational movement to the ground like a wheel, it is needed to all the directions of the circumference of a trunk axis for grounding to be possible. Therefore, in a brittle run side like the sands, the trouble of the promotion accompanying decline in movement efficiency or run side collapse may happen. Lateral-Walking does not almost have the posture change under movement, and a grounding portion is not accompanied by rotational movement, either. If it is the system which has grounding capability in the one direction of the circumference of a trunk axis, it is realizable promotion movement.
However, promotion speed becomes remarkably slow compared with the usual Lateral-Rolling. If both sides compare by movement of one cycle, although perimeter distance part promotion is possible at the maximum in Lateral-Rolling, it can promote only to

stable domain width at the maximum in Lateral-Walking.

## 4. Mixture Category

### 4.1. Lean Serpentine

The posture of ACM-R3 in the above-mentioned “S” character-like Lateral Rolling is exactly the same as the posture in two-dimensional Serpentine locomotion. Therefore, it is possible to start Lateral Rolling operation from any position while in Serpentine form.
In addition, since ACM-R3 has all the body covered by passive wheels, the friction ratio required for glide propulsion can be obtained in the direction of s-axis to every side. So, if ACM-R3 started performing Lateral Rolling from Serpentine movement, it means that Serpentine movement can be resumed by the mechanism at any time (even after rotating a certain angle), as shown in **Figure 13**.
Therefore, if "Serpentine Locomotion", which moves in the direction of s-axis, and "Lateral Rolling", which is propelled in the perpendicular direction of s-axis, are compounded, the new proposed method "Lean Serpentine (Serpentine Locomotion in Leaned Posture)" is realizable, as shown in **Figure 13**.

This locomotion differs from the usual Serpentine method in the fact that both pitch and yaw axes are coupled at an arbitrary rate. Although there is a difference in the effectiveness of this propulsion method, the great advantage is that omni-directional motion is possible. With this feature, ACM-R3 can also perform in narrow spaces.

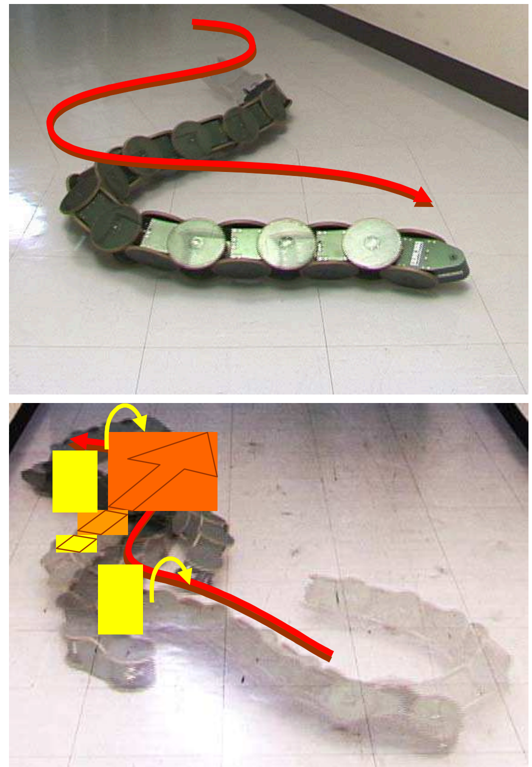

***Figure 13:*** *Serpentine Locomotion in leaned*

### 4.2. Lean Sinus-Lifting

The same idea of Lean Serpentine is applied to Sinus-lifting. By combining Sinus-lifting and Lateral rolling, a new motion mode is obtained, called Lean Sinus-lifting (Sinus-lifting locomotion in leaning). In this method, the same effects of Lean Serpentine are obtained, such as omni-directional movement.(**Figure 14,15**).

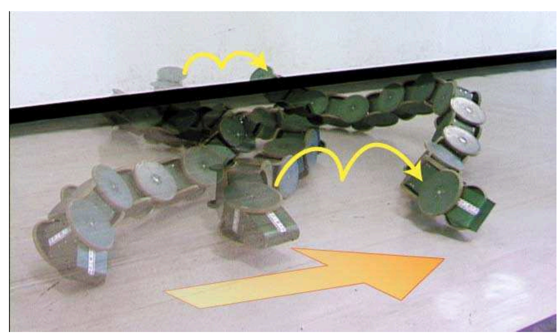

***Figure 14:*** *Sinus-Lift Rolling*

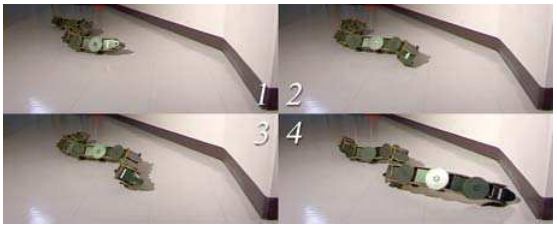


***Figure 15:*** *Sinus-lifting in leaning*

### 4.3. Lift Rolling

If Sinus-Lifting posture is inverted, only the points of maximum amplitude touch the ground (**Figure 16**). This propulsion method can reduce useless friction, so that wheels are grounded in the state perpendicular to the advance direction and grounding points decrease on the whole. In other words, it gives an effect of moving on the ground similar to vehicles. (It can be realized without wheels around the body, though.)

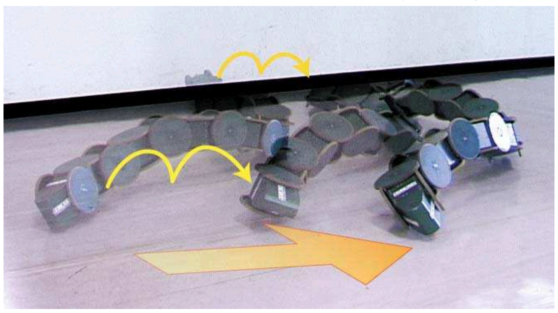

***Figure 16:*** *Lift Rolling*

## 5. Summary and Conclusions

This paper describes the propulsion experiments using the snake-like robot "ACM" series with the small highly efficient, lightweight drive system newly developed in order to examine the various functionalities of Active Cord Mechanism. As a Shift control system, the serpentine locomotion which a living body snake performs, Sinus-Lifting, Side-Winding, Spiral-Swimming Motion, and Pedal-Wave were realized. Lateral-Rolling was realized as a Rolling control system, and Lateral-Walking was shown as special conditions. And promotion and Lateral-Rolling of each inclination state generable by combining each were shown.

### Acknowledgment

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