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From Dream to Reality: Snake-like, Spider-like Robots

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Abstract

In this paper, we introduce two types of robots started to develop from the inspiration of the motion of wild life and at the same time aiming at practical applications. One is a snake-like robot. Variable motion of the snake-like robots is introduced and demonstrated their motion by the constructed mechanical model ACM-R3. Another is spider-like walking robot. Design of the construction walking machine which can move around on the steep slope is discussed and demonstrated the feasibility of the concept by the constructing TITAN XI, seven ton quadruped waking machine.

1. Introduction

The acquisition of useful knowledge in engineering from studying living things is not necessarily easy. Movements and shapes, etc., of living things are determined by a large number of factors. To extract the contributions of desired factors from their large-scale system requires not only careful observations but also carefully planned experiments. Even should the contributions be clarified, direct engineering application is often difficult because the constitutive elements of living things such as the muscular and neural systems differ greatly from engineering elements which can be utilized by man. However, the biological inspiration is very variable and they sometimes visualize us brand new type of the machines.
In this paper, we introduce two types of robots started to develop from the inspiration of the motion of wild life and at the same time aiming at practical applications. One is a snake-like robot and another is spider-like walking robot.

2. Snake-like robot

2.1. Research on biomechanisms of snakes

We have been developing snake-like robot since 1972 as **Figure 1** and try to make the machine practical for many applications. We called the snake-like machine, having a slender code-like body with active bending function as "Active Cord Mechanism (ACM)". The feature of the ACM or snake-like machine is versatility. The body of snake can be an "arm" when it holding something by coiling the body around the object, it can be a "leg" when it makes creeping motion and it can be a "trunk" when it moves from brunch to brunch. It is surprising that the very simple slender body of the snake can be transferred to perform such versatile motions. The feature of the snake-like robots will be said as follows:

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,

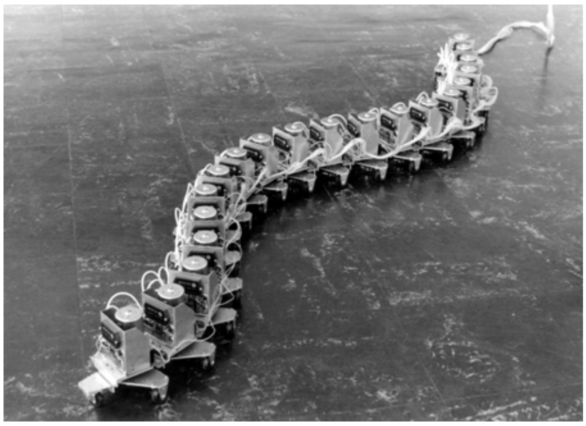

Figure 1: *ACM prototype model(1972)*

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 derived from the specific feature of the snake's slender and active body. When we regard the characteristics of the ACM from the engineering viewpoint, we can add following features:

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. In short it has the feature of the essence of a decentralized system.

5. Between the joints make bending movements only, and endless rotational movements is not used. 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.

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]. Snake-like robots are also studied around the world, such as Poly Bot (Mark Yim et al.) [4], Sewer Robot (K. –U. Scholl et al.) [5], GMD-SNAKE2 (Bernhard Klaassen et al.) [6], snake robot by Kevin J. Dowling [7] and so on[12][13].

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.

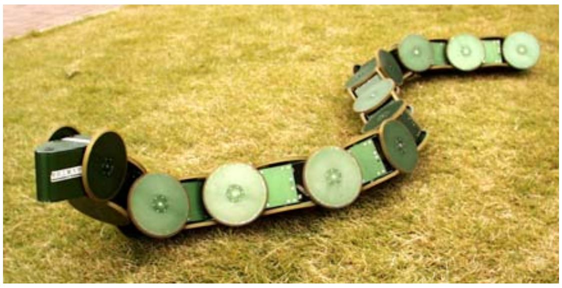

Figure 2: *ACM-R3-21 unit model*

2.2. Shift-control Category

2.2.1. 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.

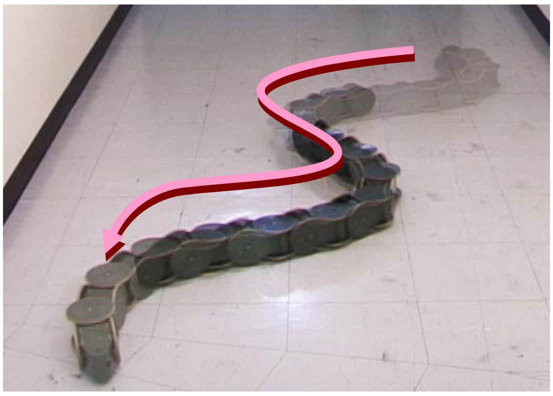

Figure 3: *Serpentine movement*

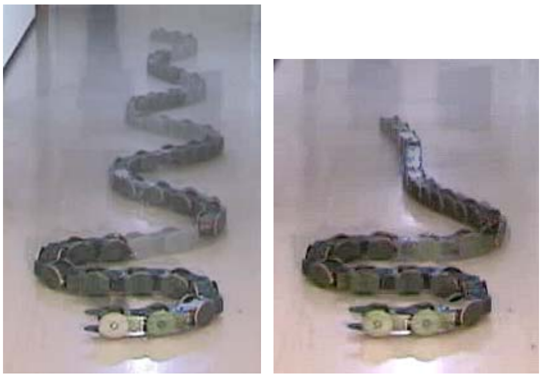

Figure 4: *change winding angle*

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.

2.2.2. 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**.

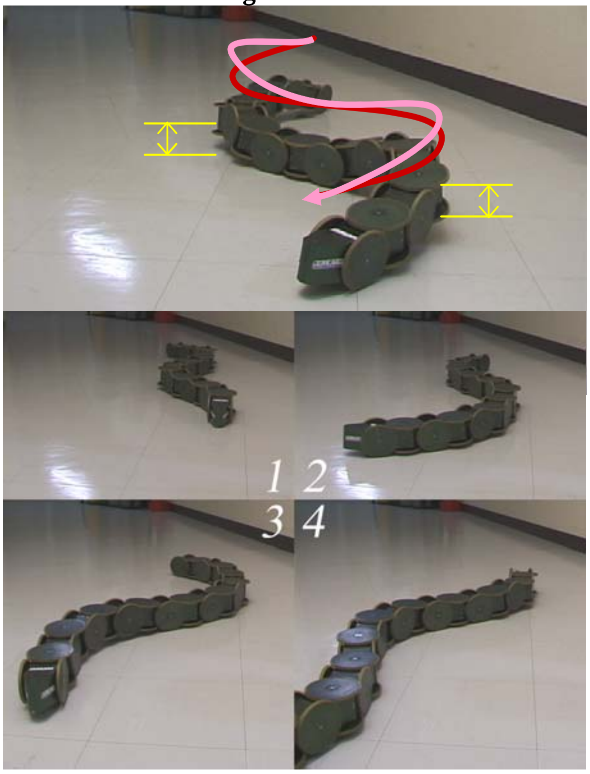

Figure 5: *Sinus-lifting*

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.

2.2.3. 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.

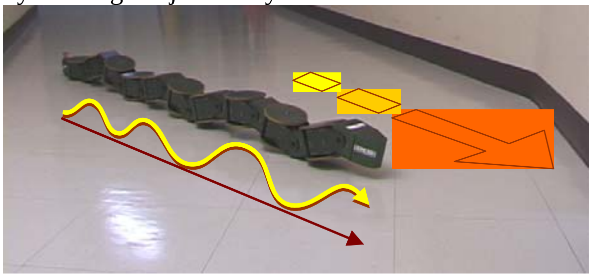

Figure 6: *Pedal Wave*

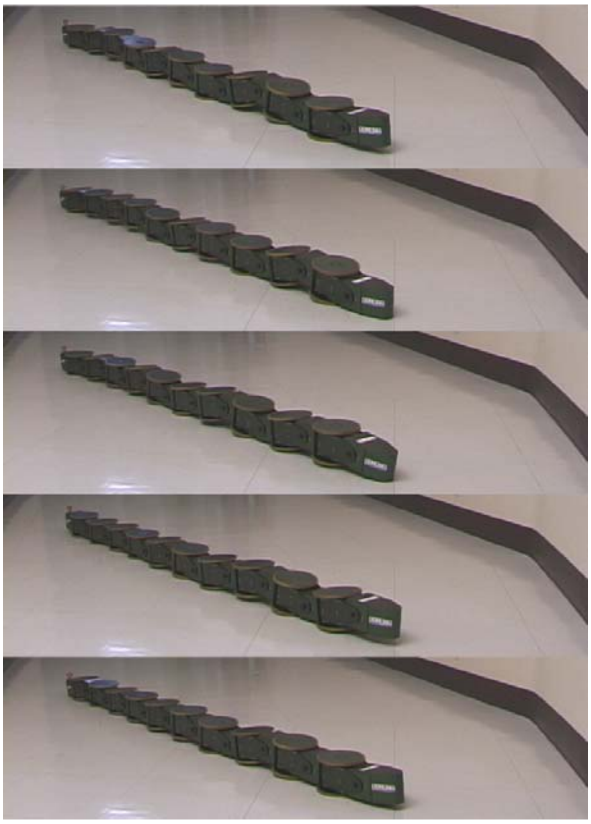

Figure 7: *Pedal Wave sequence*

2.2.4. 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.

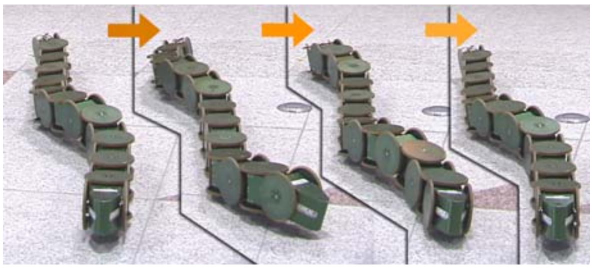

Figure 8: *Sinus-lifting*

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**.

2.2.5. 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)*

2.3. 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.

2.3.1. 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

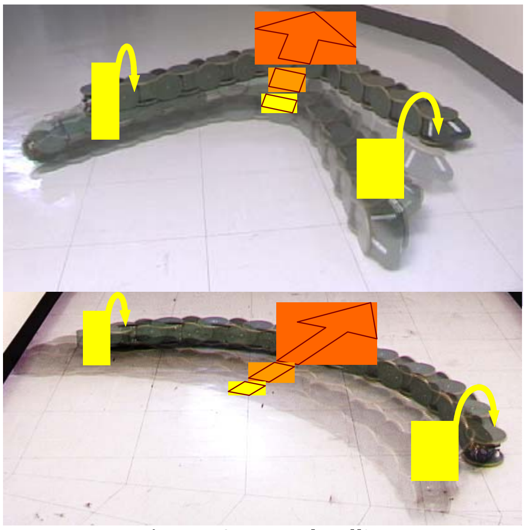

Figure 10: *Lateral Rolling*

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.

2.3.2. 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.

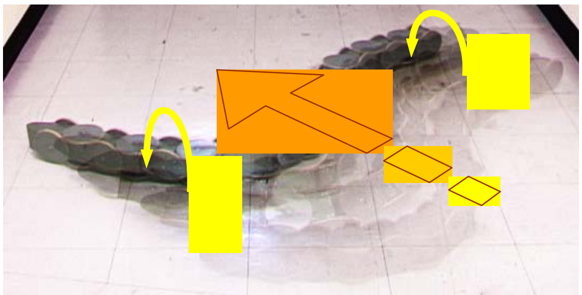

Figure 11: *S-character like Lateral Rolling*

2.3.3. 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.

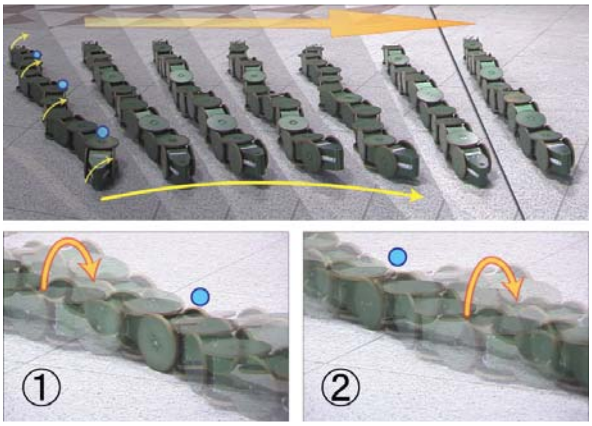

Figure 12: *Lateral Walking*

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.

2.4. Mixture Category

2.4.1. 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.

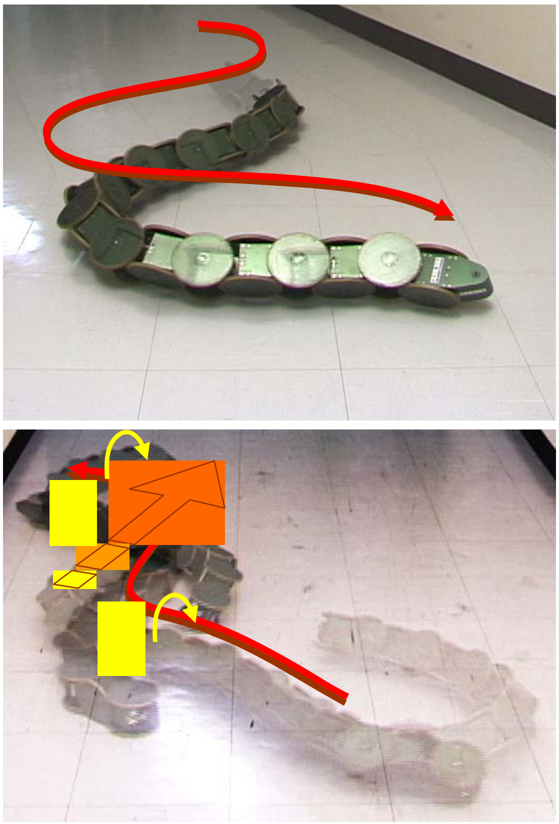

Figure 13: *Serpentine Locomotion in leaned*

2.4.2. 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**).

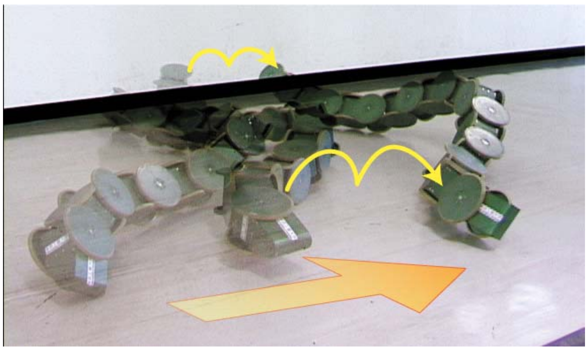

Figure 14: *Sinus-Lift Rolling*

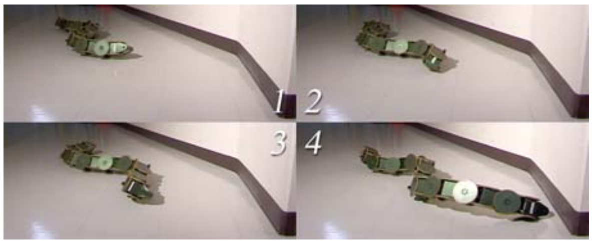

Figure 15: *Sinus-lifting in leaning*

2.4.3. 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.)

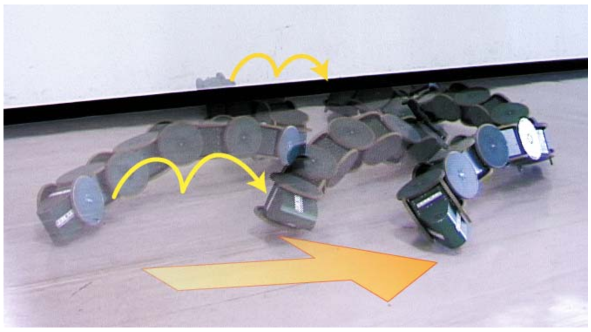

Figure 16: *Lift Rolling*

3. Spider-like robot

3.1. Research on walking machines

We have been working on walking machine research since 1976. In general, walking machines are not practical. Its mechanism usually weights too much because more numbers of actuators are required to drive system of the multi DOF legs than the wheeled or crawler vehicle and commercially available

actuators are bulky and heavy. However, the foot of walking machines contacts the ground with discrete points and the contact points can be arbitrary selected according to the terrain condition, walking machines have such special characteristics:
1) Walking machines can move stably over a rugged terrain, and can pass over fragile objects on the ground without touching them.
2) Walking machines can change the direction of motion without slipping even if the sole contacts the ground with a large area.
3) The legs can be utilized not only for motion, but also rest. At standstill posture, the legs become outriggers to hold the upper body stable even on an uneven ground. The upper body can be actively driven while the feet are fixed to the ground.
In addition, the legs that are insect-type like a spider has the following characteristics:
4) It provides high stability during both walking and working, as the legs are sprawled.
5) It can provide a wide movable range for the legs on the ground, which facilitates terrain-adaptive walking.
So, by carefully selecting the applications, walking machines will be used in practical situations.

We believe that optimum numbers of the leg are four which is the minimum number for walking machines to walk statically stably. The number of the leg should be as small as possible because this reduces the number of the actuators, and total body weight decreases. So we have been mainly studying on mechanisms, gait control, sensor system of quadruped walking machines.

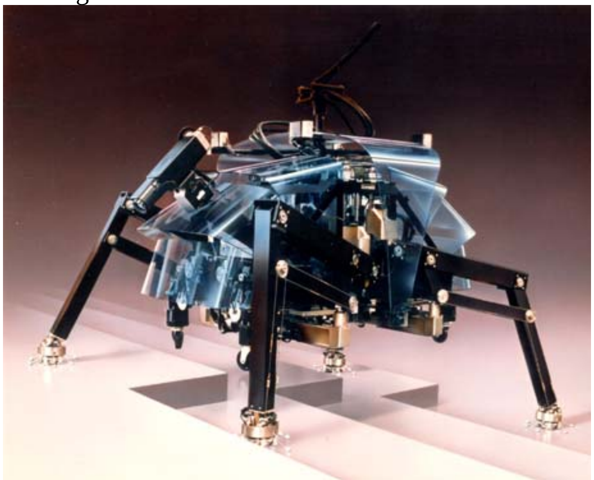

Figure 17: TITAN IV on staircase

A typical example of a quadruped walking machines, TITAN IV [14] is shown **Figure.17**. TITAN IV was exhibited at the science exhibition of Tsukuba in 1985.
It has made straight and turning walking on a stage with three steps for half a year (**Figure.17**). It has walked, in total, about 40 km. On sole of the feet are installed whisker sensors which identify the ground contact conditions and detects the obstacles such as the step of staircase. The body of the machine is maintained horizontal by using inclination sensors.

3.2. Walking machine for steep slope operation

We have been developing a quadruped walking robot for steep slope operation [15].
In Japan, many slopes are being reinforced in order to construct road or railway in sites surrounded by mountains. These slopes need to have concrete frames installed and anchor/rock bolts inserted, and these works are performed by man. However they are large-scale works and the conventional methods are inefficient and consume too much money and time. In addition, they are very dangerous because the workers may fall down. From this background, the automation of some steps is required.

Figure.18: Conventional mechanized construction method on slopes

Construction machines with wheels or crawlers that drill holes for inserting rock bolts have already been developed and this construction method is called "Non-scaffold construction method", as shown in the left picture of **Figure.18**. This construction method should be better than the conventional method, but these machines have difficulties in working on such an environment. The workspace of the wheeled machines is limited because of rugged terrain and crawler machines have possibilities of destroying concrete frames.
Taking a different approach, we have already pointed out the advantages of a quadruped walking robot supported by tethers for this kind of works, such as stable motion on rugged terrain and motion on the slope without damaging the obstacles [16].
So, we decided to develop a practical quadruped walking robot for steep slope operation, TITAN XI, which is intended for practical use, in order to improve existing construction methods.
TITAN XI shall perform the following three operations:

1. Transfer from the ground to the slope.
2. Walk on the slope with concrete frames and transport the drilling machine to the work site.

3. Control the posture of the drilling machine using the legs and perform drilling to install rock bolts.

The operation on slopes using TITAN XI shall be performed according to the following procedure, as shown in **Figure.19**.

1. Transported by the truck to the vicinity of the site.
2. Use auxiliary crawlers to descend from the truck and travel on the level terrain to get close to the slope.
3. Switch to walking when the robot is near the slope and transfer from the ground to the slope.
4. Walk on the slope to transport the drilling machine to the work site (mainly crossings of concrete frames).
5. Control the posture of the drilling machine using the legs and perform drilling.
6. Repeat 4 and 5.

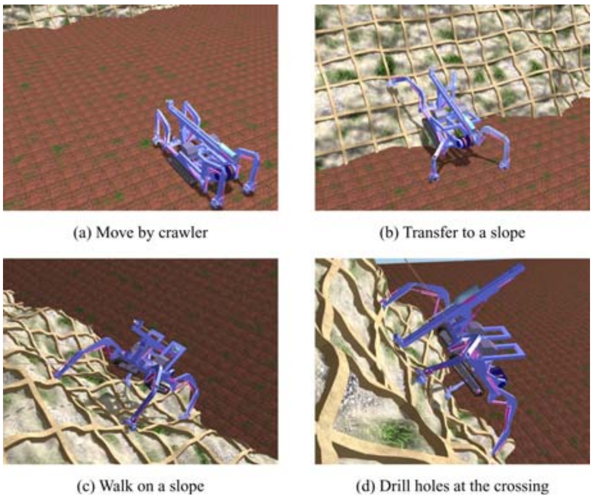

Figure.19: Construction steps

To perform such works, TITAN XI is composed mainly of the following mechanism elements (**Figure.20**):

1. A box-shaped body of 2.2×3.4×0.2 [m]
2. 4 legs of the same characteristics
3. Auxiliary traveling crawlers to travel on the level terrain
4. Two winches to rewind auxiliary tow wire
5. A drilling machine
6. An engine-lift to keep the engine in a horizontal position.
7.

Based on the discussion above, we manufactured a prototype of TITAN XI, as shown in **Figure.21**. The specifications are shown in **Table.1**.

Figure.21: TITAN XI

To confirm the performance of TITAN XI, we have conducted the basic experiment of walking (**Figure.22**), tether system (**Figure.23**).

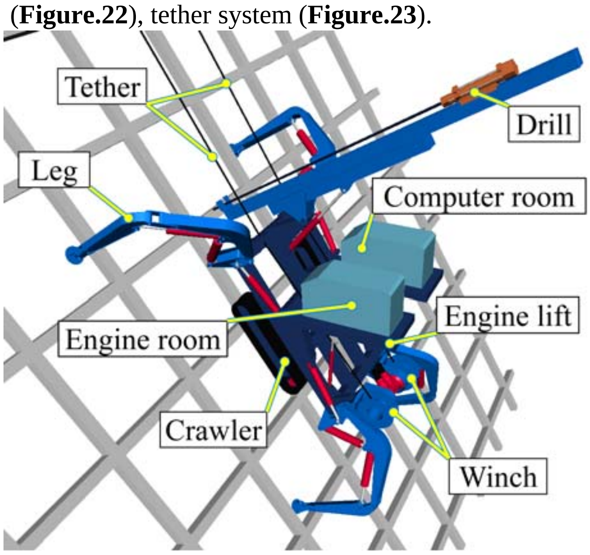

Figure.20: Concept of TITAN XI

Table.1: Specification of TITAN XI

Size [m]	4.8 x 5.0 x 2.0
Mass [kg]	7,000
Power [kW]	41.9

Figure.22: Snapshots of standard gait of TITAN XI.

Figure.23: Walking with tether on slope

As shown above, mechanism of TITAN XI was completed. However, there are still several technical challenges for practical application. They include:

1. Measure the slope and make the map using the optical system, and realize terrain-adaptive gait using the map information.
2. Travel from the level terrain to the slope.
3. Walk on the slope and transport the drilling machine to the work site (mainly crossings of concrete frames).
4. Control the posture of the drilling machine by using the multi DOFs legs and conduct drilling experiment.

We will examine these technical challenges soon and repeat experiments to build a machine for practical use.

4. Conclusion

We introduced two biologically inspired robots that we have developed. These robots will be used in wide application in the near future.
Snake-like robots can go in the narrow space like the interspaces of rock, rubble, pipes. So they will be used in rescue operation, or the inspection device inside the machines.
Spider-like robots can move on the rugged terrain like the rocky ground, construction site, staircases. So they will be used in off-road vehicle, robot for agriculture and forestly, vehicle for the construction works, and humanitarian demining robots.

Reference

[1] [1] Shigeo Hirose, Biologically Inspired Robots (Snake-like Locomotor and Manipulator), Oxford University Press, 1987.

[2] [2] G. Endo, K. Togawa, and S. Hirose, "Study on self-contained and Terrain Adaptive Active Cord Mechanism", Proc. of the IROS, pp1399-1405, 1999.

[3] [3] K. Togawa, M. Mori, and S. Hirose "Study on Three-dimensional Active Cord Mechanism: Development of ACM-R2", Proc. of the IROS, pp2242-2247, 2000.

[4] [4] Mark Yim et al. "PolyBot:a Modullar Reconfigurable Robot", Proc. of the ICRA, pp.514-520, 2000.

[5] [5] K.-U.Scholl et al. "Controlling a Multijoint Robot for Autonomous Sewer Inspection", Proc. of the ICRA, pp.1701-1706, 2000

[6] [6] Bernhard Klaassen et al. "GMD-SNAKE2:A Snake-Like Robot Driven by Wheels and a Method for Motion Control", Proc. of the ICRA, pp.3014-3019, 1999.

[7] [7] Kevin Dowling "Limbless Locomotion: Learning to Crawl", Proc. of the ICRA, pp.3001- 3006, 1999.

[8] [8] M.Mori, and S.Hirose "Development of Active Cord Mechanism ACM-R3 with Agile 3D mobility", Proc. of the IROS, pp1552-1557, 2001.

[9] [9] H. Ohno and S. Hirose, " Design of Slim Slime Robot and its Gait of Locomotion", Proc. of the IROS, pp707-715, 2001.

[10] [10] M.Mori, and S.Hirose "Three-dimensional serpentine motion and lateral rolling by Active Cord Mechanism ACM-R3", Proc. of the IROS, pp829-834, 2002.

[11] [11] T.Takayama, and S.Hirose "Amphibious 3D Active Cord Mechanism HELIX with Helical Swimming Motion", Proc. of the IROS, pp775-780, 2002.

[12] [12] T.Kamegawa, H,Matsuno, at el., "Development of the Sequentially Connected Multiple-unit Rescue Robot (KOHGA)", The 21nd Annual Conference of the Robotics Society of Japan, 2003, 1L14

[13] [13] R.Sasaki, S.Ma, K.Inoue, "Development of a 3-D Snake-like Robot based on 3-DOF Joints", The 21st Annual Conference of the Robotics Society of Japan, 2003, 1L12

[14] Shigeo Hirose, "A study of design and control of a quadruped walking vehicle," Int. J. Robotics Research, vol.3, no.2, pp.113-133, 1984.

[15] Ryuichi Hodoshima, Takahiro Doi, Yasushi Fukuda, Shigeo Hirose, "Development of TITAN XI: a QuadrupedWalking Robot to Work on Slopes - Design of system and mechanism," Proc. Int. Conf. on Intelligent Robots and Systems, Sendai, Japan, pp.792-797, 2004.

[16] Shigeo Hirose, Kan Yoneda and Hideyuki Tsukagoshi, "TITAN VII: Quadruped Walking and Manipulating Robot on a Steep Slope," Proc. Int. Conf. on Robotics and Automation, Albuquerque, New Mexico, pp.494-500, 1997