BASIC EXPERIMENTS ON A HEXAPOD WALKING MACHINE(MELWALK-III) WITH AN APPROXIMATE STRAIGHT-LINE LINK MECHANISM

M.KANEKO, M.ABE, K.TANIE, S.TACHI, S.NISHIZAWA

Cybernetics Division, Mechanical Engineering Laboratory
1-1 Namiki, Tsukuba Science City, Ibaraki, Japan

ABSTRACT

Legged locomotion over irregular terrain is composed of body propelling motion and terrain adapting motion. Although conventional walking machines with three degrees of freedom for each leg can adapt their feet on irregular ground using flexible leg freedom, such machines generally require a tremendously complex control scheme for the body propelling motion. To cope with this problem, a hexapod walking machine with an approximate straight-line link mechanism is developed on the idea that body propelling motion is realized by only one degree of freedom and this freedom can be perfectly decoupled from the freedom for terrain adaptability, and several basic experiments are performed to make clear the features of this type of walking machines.

1. INTRODUCTION

Legged locomotion over irregular terrain is composed of body propelling motion and terrain adapting motion. In general, each motion control may be required alternately. The conventional walking machine with three degrees of freedom for each leg [1-4] has great flexibility during terrain adaptive motion, because each foot can select a suitable foothold in three dimensional space. Such machines, however, are very difficult to control during body propelling motion, because a cooperational actuator control in stance legs is required for the system, with several closed kinematic chains between the body and the ground, even though gravitationally decoupled actuator (GDA) system [4],[5] is introduced in leg mechanism. This situation is similar to the cooperational motion control using more than two manipulators [6]. Therefore, If it were possible to realize body propelling motion by one degree of freedom and to make this freedom perfectly decouple from the freedoms for terrain adaptive motion, the control system would become surprisingly simple. The eight-legged walking machine for underwater construction [7] is known as a first trial of this type of walking machine. This machine, however, requires leg length changing motion as well as body propelling motion even when it proceeds on a flat plane or a gentle irregular terrain.

Now, let us consider human walking. Although human walking is regarded as voluntary motion, when limited to steady walking, it can be considered as autonomic motion because the steady walking pattern is fixed [8], and a walking pattern is changed only when facing an obstacle. Therefore it can be interpreted that irregular terrain by leg motion is realized by mixing the basic leg motion with a supplemental motion to adapt to the irregular terrain. This interpretation may be applied to animal locomotion. On the basis of these considerations, the authors have been studying on a hexapod walking machine (MELWALK) with a basic leg motion pattern using an approximate straight-line link mechanism [9],[10].

In this paper, the authors discuss an eight degrees of freedom, hexapod walking model (MELWALK-III) capable of adapting for irregular terrain and capable of changing body direction. First, the system structure and the fundamental control algorithm are described precisely. Next, some features of this proposed walking machine are made clear through some basic walking experiments.

2. SYSTEM STRUCTURE OF MELWALK-III

2.1 Two basic walking motions and introduction of an approximate straight-line mechanism

(a) Terrain adaptive motion

This motion is realized in support leg alternating phase.

(b) Body propelling motion

This motion is realized except all legs supporting phase. Body is propelled along an approximate straight line link mechanism that is produced by one d.o.f.

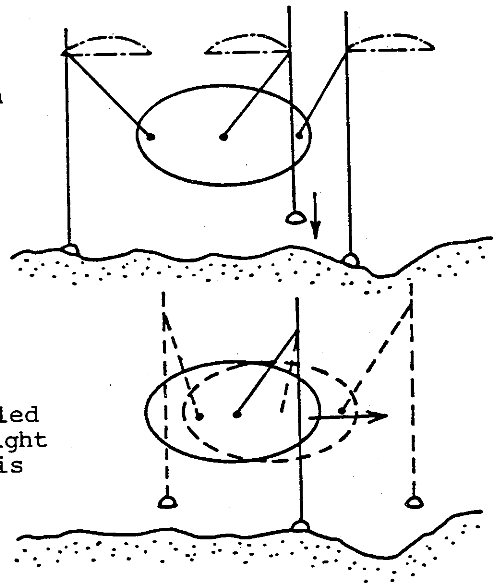

Fig.1 Two basic walking motions

The proposed machine here is illustrated as shown in Fig.1. Terrain adaptive motion is realized by changing leg length as shown in Fig.1(a). Although more than two degrees of freedom for each leg are desirable for terrain adaptability, the proposed walking machine has only one degree of freedom for simplicity.

Next, let us consider body propelling motion. During this phase, body motion is perfectly determined by the basic leg motion pattern against the body. For living things such as horses, dogs, the front leg motion trajectory against the body forms a closed trajectory including a partial straight line [11]. Although the straight line is not exactly straight, a walking machine is considered desirable from the following two points when the straight line is closer to an exact straight line. The first point is that reduced up-and-down movement of the center of gravity during walking increases the energy efficiency of the walking machine. Improvement of the energy efficiency is an important factor to be taken into consideration especially for energy self-sustaining mobile robot. The second point is that a gravitationally decoupled actuator (GDA) system becomes possible by adding a leg length changing mechanism, which also relates to energy saving. Although it is ideal to make the foot trajectory of the stance phase exactly straight, it is generally difficult to get such a trajectory using a limited number of actuators. Therefore for a practical application, an approximate straight line instead of an exact straight line is sufficient to realize GDA system, if degree of an approximate straight line is fine.

2.2 Body propelling mechanism

A four bar linkage mechanism as shown in Fig.2 [12] is considered here. The trajectory of point T(x,y) in Fig.2 is represented by Eqs.(1),(2),(3).

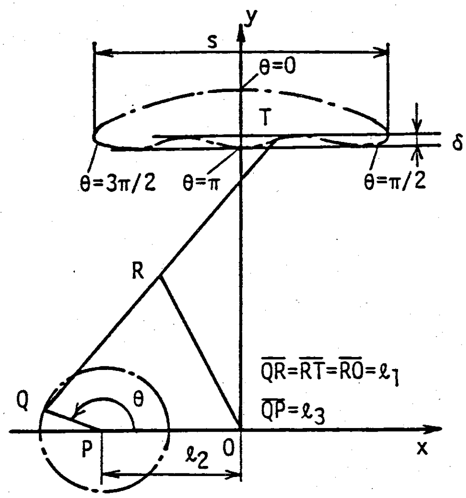

Fig.2 A four bar linkage mechaism to produce an approximate straight line and its coordinate system

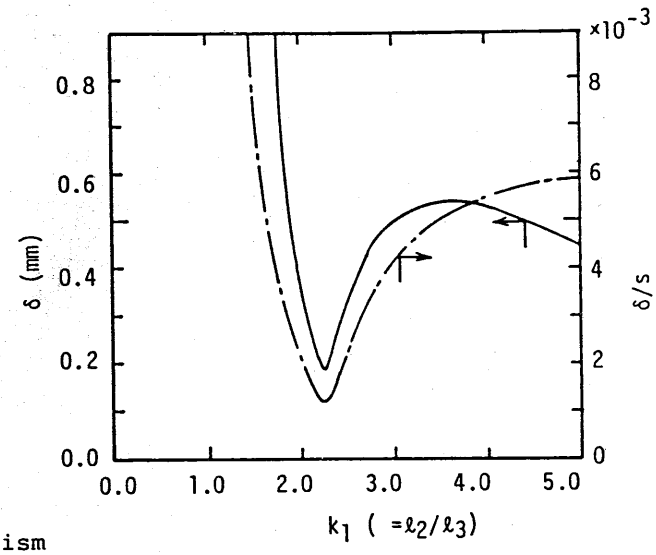

Fig.3 Relationship between δ, δ/s

$$x^2 + y^2 + k_2{}^2(k_1{}^2 - 2k_1\cos\theta + 1)\ell_1^2 = 4\ell_1^2 \quad (1)$$

$$\frac{x}{y} = \frac{\sin\theta}{k_1 - \cos\theta} \quad (2)$$

$$k_1 = \frac{\ell_2}{\ell_3} \qquad k_2 = \frac{\ell_3}{\ell_1} \quad (3)$$

Now, let us assume $y(\pi)=y(\pi/2)$ as a necessary condition for an approximate straight line. Due to symmetrical features, this assumption is equivalent to $y(\pi)=y(\pi/2)=y(3\pi/2)$. Therefore, Eq.(4) is obtained from Eq.(1) thru (3).

$$k_2{}^2(1 + k_1{}^2)(1 + 2k_1) = 4 \quad (4)$$

As Eq.(4) contains two unknown parameters k_1 and k_2 for one equation, one definite solution will not exist. Fig.3 shows the results of the linearity δ/s obtained by changing k_1, where δ,s are the maximum height of irregularity of the foot trajectory and stride length, respectively. Where δ is a value with link parameter ℓ_1=100mm. In Fig.3, as $\delta/s<0.01$ with $1.5<k_1<5.0$, the sufficient condition of an approximate straight line is considered satisfied. Since stride length converges asymptotically to zero as k_1 becomes greater, it is not advantageous to select a large value for k_1. In the proposed machines, MELWALK-I,II,III, a linkage parameter(k_1=2.22) having an outstanding desirable linearity of 0.001 for a four bar linkage mechanism is selected for the leg system. In addition, as the phase of the approximate straight section corresponds to approximately 180°, the four bar linkage system permits an easy realization of the alternating tripod gait, a typical insect gait, by driving three sets of four bar linkage mechanisms in pairs with the phase shifted 180°. Actually, to realize this gait, all legs are linked by timing belts. Therefore, body propelling motion is generated by only one degree of freedom. Although the gait is fixed to one possible gait, the control system is perfectly released from the cooperational control of closed kinematic chains.

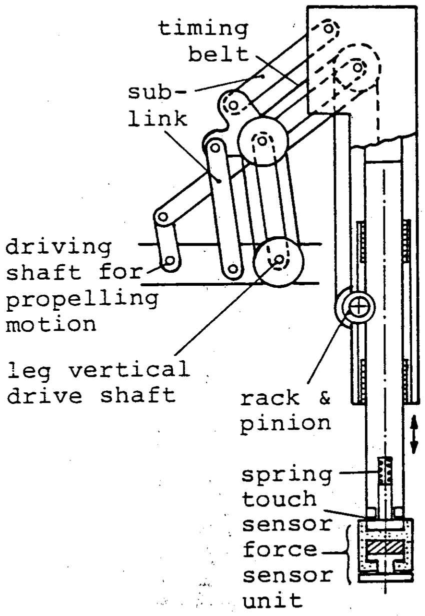

Fig.4 The leg mechanism of MELWALK-III

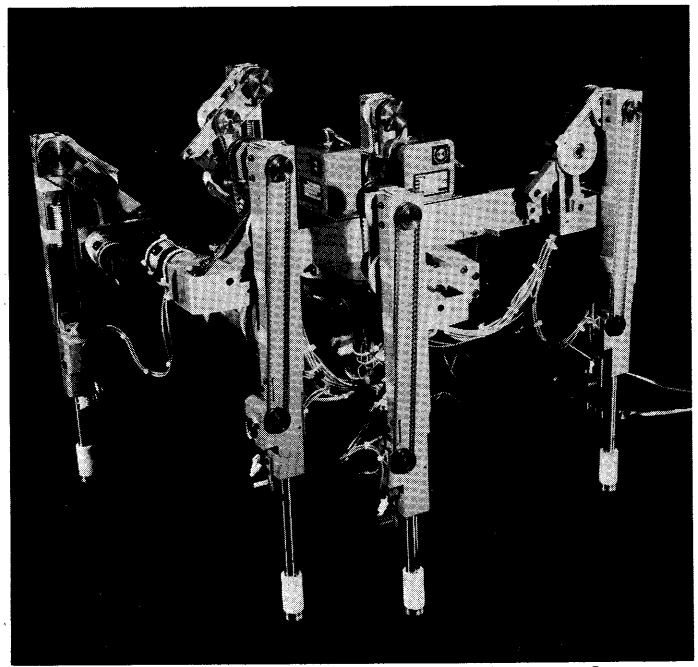

Photo 1 An overall view of MELWALK-III

2.3 Terrain adaptive mechanism

Leg mechanism having terrain adaptability is shown in Fig.4. In an attempt to reduce the energy consumption using reduced weight legs, a leg vertical drive motor(30W) is installed on the body. The drive power is transmitted to the gearbox, not illustrated in Fig.4, via pully and belt system. In the gearbox, the drive power is transmitted to a rack, through a worm, worm wheel and pinion, to move the leg vertically. The worm and worm wheel are used to realize the body self-sustaining system when the output of the DC motor is zero, that is to say, to make use of the advantage of the GDA system. A power transmission mechanism completely eliminate the interference between the propelling DC motor and the vertical drive DC motor, and permits independent control of those two motors. Two sub-linkages in Fig.4 composed of two sets of parallelogram linkages are used to constantly maintain the leg perpendicular to the body.

2.4 Total system construction

Photo 1 shows an overall view of MELWALK-III. The body dimensions are 500x500x100mm (depth x width x height); maximum extension and contraction of the legs is 200mm; reference link parameter ℓ_1=70mm; and the body weight is 35kg.

This walking machine has two plates equipped with three legs which can rotate relative to each other ±18 around the center vertical shaft. A propelling DC motor(50W) and a steering DC motor(50W) are installed on the lower base plate. One spline joint and two universal joints installed at the ends of the joint transmit the propelling power from the lower base plate to the upper base plate. The three legs installed on the lower base plate are linked by timing belts with phase shifted by 180°, and driven for alternating tripod gait. The walking machine also designed so that its center of gravity always falls into the supporting triangle as long as the body is maintained horizontal.

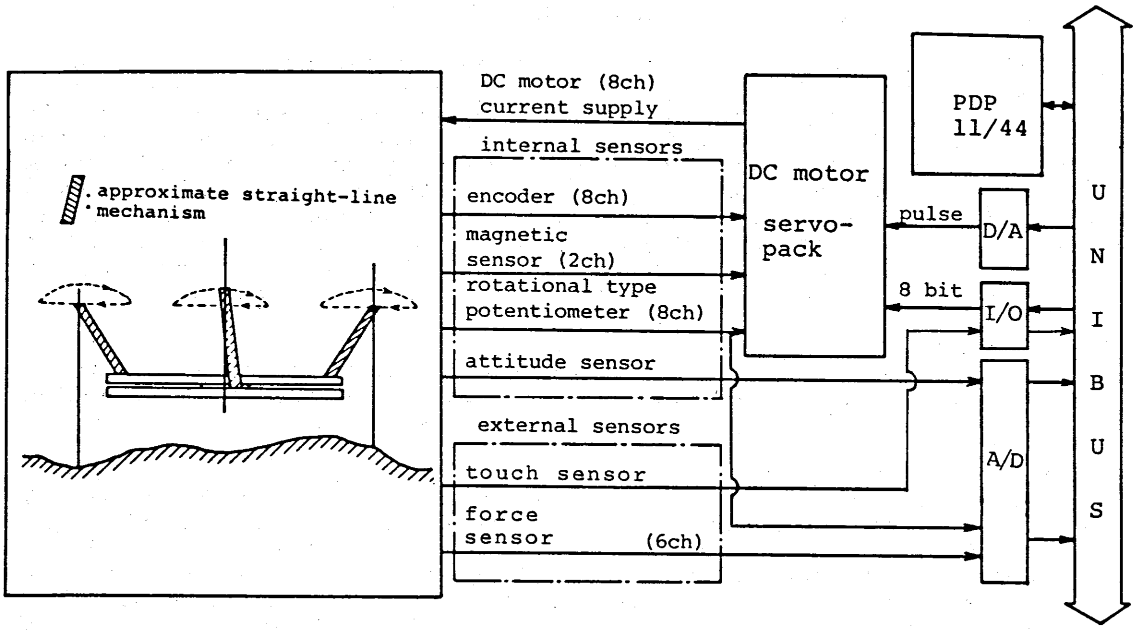

Fig.5 Total control system

Two kinds of sensors, internal and external, are in general, necessary devices for an intelligent robot. Internal sensors are used to detect the condition of the robot itself, and in the case of MELWALK-III, the internal sensors include rotary potentiometers (6 ch) to detect the leg length seen from the body, encoders (8 ch) to detect the rotational angle of the DC motor, a potentiometer (1 ch) to detect the rotational angle of the body when steered, a potentiometer (1 ch) to detect the phase of the legs, magnetic sensors (2 ch) to detect the rotational limitation of the body, and two attitude sensors with pendulum to detect the inclination of the body.

In this walking machine, as the approximate straight-line mechanism maintains the body horizonral, attitude sensors are basically not required for that purpose but are used only to correct errors accumulated due to backlash of leg length changing mechanism and so on. As for external sensors, or sensors to gather environmental information, MELWALK-III is equipped with two types of tactile sensors. One is ground touch sensor (6 bits for six legs) and another is force sensor (6 ch). Although an obstacle sensor is an important sensor for a walking machine, it is not an essential one to evaluate the fundamental functions of walking machine. Therefore this paper does not touch on the obstacle sensor. Fig.5 shows the overall control system comprising the abovementioned sensors and the motor drive system.

Next, let us consider the motor servo system. Pulses from the computer drive the DC motor. The computer (DEC PDP 11/44) transmits drive pulses (8 ch) and motor rotational direction command ON-OFF signals (1bit x 8ch) to the motor servo system simultaneously for each channel. Then the DC motor servo pack sends an electric current, corresponding to the difference between the integrating value of the feedback signal of the encoder and the integrating value of the command pulse signals, to the DC motors. The advantage of this type of pulse control is that position control and speed control are available simultaneously. That is to say, the number of the command pulses in a unit of time determines the speed and the integrating value of the number of the pulses determining the position.

3. WALKING MOTION GENERATING ALGORITHM

A walking machine having three degrees of freedom on each leg is composed of control systems such as a gait generating subsystem to provide a stable gait, a basic motion regulation subsystem which controls the body attitude, body altitude and the leg condition using the information gathered by various kinds of sensors, and a central system which selects the gait mode and controls the speed. These forms a hierarchy system [4],[13]. Although the control systems of MELWALK-III basically form a hierarchy system, the structure and its core units are much simpler than those of systems proposed up to this time. Now, let us try an in-depth analysis of the basic motion regulation subsystem.

3.1 Body propelling control

This control is realized by computer sending predetermined drive pulses to the motor channel for body propelling control. As this motion control is realized by only one DC motor, it is very simple.

3.2 Terrain adaptive control

On support leg alternating phase, each of the three transfer legs is lowered until the output of the touch sensor installed behind the foot becomes "ON". Although it is desirable that each of transfer legs is so positioned that it contacts soft over irregular terrain using a kind of proximity sensor, ON-OFF type touch sensors are sufficient because leg length changing motion is not so fast due to the use of worm and worm wheel.

3.3 Steering control

Steering motion is implemented by two methods. One is to be realized by mixing forward propelling motion and body changing motion. Another is that to be realized with stepping. In this case, the turning radius can be reduced to approximately zero. For MELWALK-III, as the two base plates can turn maximum 18° relatively to each other about the vertical axis, the direction of the body can be changed approximately 90° over five steps.

3.4 Attitude control

As the body moves along an approximate straight line during a body propelling motion, the body attitude is constantly maintained. Therefore body inclination will theoretically not occur. However, there is possible body inclination resulting from the accumulated positioning errors and backlash in the leg system. Therefore the body attitude must be checked by the attitude sensor and attitude control must be executed when a body inclination exceeds a predetermined value. In this control the three support leg lengths are so adjusted that the body becomes horizontal.

Besides these controls, body altitude control, obstacle avoidance control are required, but this paper will not discuss this control system.

4. FUNDAMENTAL EXPERIMENT

As MELWALK-III is not equipped with an obstacle sensor, it cannot be used for a highly intelligent irregular terrain walking experiment, but if the height of the irregularity is less than the body height, a simplified intelligent irregular terrain walking performance incorporating the control method of Fig.6. This method, which raises the leg to the body height before realizing body forward motion, is not an efficient method, but it has a great advantage in that the transfer leg will never hit obstacles lower than the body.

This section describes the experiments of simple irregular terrain walking, steering motion, and payload characteristics using MELWALK-III.

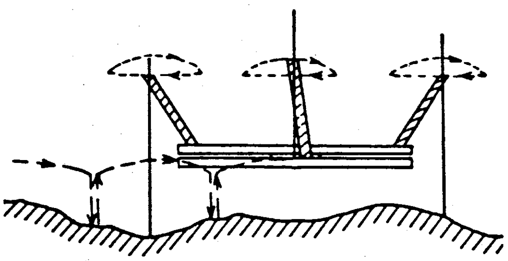

Fig.6 A control strategy for irregular terrain

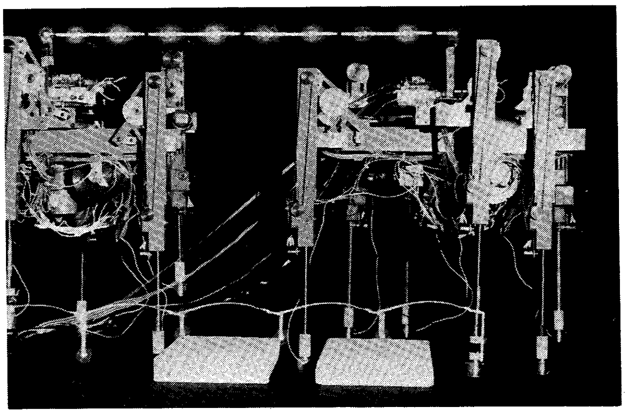

Photo 2 A walking experiment on simple irregular terrain

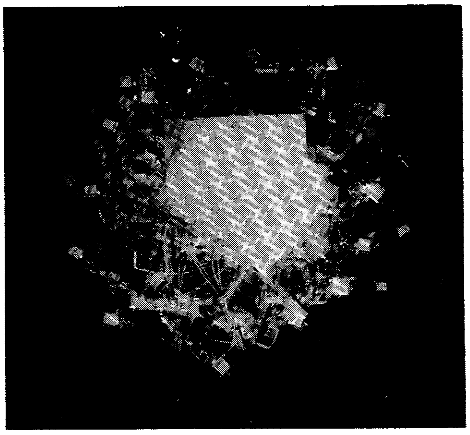

Photo 3 An experiment in changing the body direction (rotational radius r=0.0m)

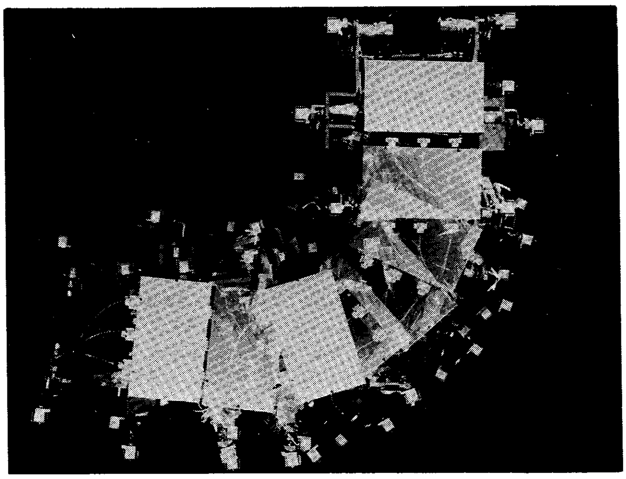

Photo 4 An experiment in changing the body direction (rotational radius r=0.8m)

4.1 Irregular terrain walking motion

Photo 2 is a chain photo of walking motions. The white line is the trajectory of the body with a LED installed at the reference point at the foot of one leg. The irregular terrain used for the experiment was produced by placing concrete blocks approximately 60mm high to simulate an irregularity smaller than 200mm which is the extension and contraction stroke of the legs. The control algorithm of Fig.6 is used as the basic algorithm. The average step time is 12 seconds. The extremely slow walking on irregular terrain is due to the extension and contraction speed of the legs.

4.2 Steering motion

Photo 3,4 are chain photos of 90° turn of turning radius r=0.8m, and 90° turn while stepping. The 90° turn takes approximately 20 seconds. This turning time is shorter than the 36 seconds of a quadruped walking machine with three degrees of freedom for each leg [14]. It is apparent that this type of walking machine has a potential capability of a simpler yet rapid steering motion resulting from its simple structure.

4.3 Load carring capability

The load carring capability is an important factor to evaluate the practicability of walking machine. In the case of MELWALK-III can load 24 kg for body weight 35 kg. In the case of MELWALK type walking machine, as the feet are always in the vicinity of the body, contrary to conventional walking machines, an excessive moment generated by the weight support reaction force will not be imposed on the hip. That feature is considered to contribute remarkably to an improved load carring performance from the viewpoint of material strength.

5. CONCLUSION

This paper propose a walking machine (MELWALK-III) which has a basic leg motion for body propulsion and additional freedoms for terrain adaptation. Although the gait of this type of walking machine is limited to one possible gait, its control system and control sheme become very simple due to the remarkable reduction of total degrees of freedom and due to independence between freedoms. Therefore walking speed essentially increases more than that of a conventional walking machine with three degrees of freedom per each leg. In constructing this type of walking machine, the introduction of a closed loop foot trajectory with an approximate straight line improves the energy efficiency during locomotion in the sense that the body has almost no up-and-down movement.

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