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Study on Roller-Walker
(System Integration and Basic Experiments)

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Abstract

We have proposed a new leg-wheel hybrid mobile robot named "Roller-Walker". Roller-Walker is a vehicle with a special foot mechanism which changes to a sole in walking mode and a passive wheel in skating mode. On rugged terrain the vehicle walks in leg mode, and on level or comparatively smooth terrain the vehicle makes wheeled locomotion by roller-skating using the passive wheel. The characteristics of Roller-Walker are: 1) it has a hybrid function but is lightweight, 2) it has the potential capability to exhibit high terrain adaptability in skating mode if the control method for roller-walking is fully investigated in the future. In this paper, the 2 leg trajectory for straight roller-walking is optimized in order to achieve the maximum constant velocity. Also a changeable ankle mechanism was integrated into the Roller-Walker system. Experiments were performed to demonstrate the validity of the concept of Roller-Walker and the results of straight roller-walk experiments are compared with those derived through simulation.

1. Introduction

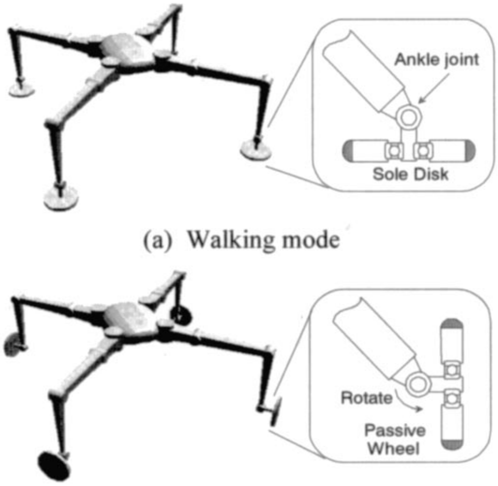
A walking robot which can select discrete foot placements with articulated legs has several advantages: 1) it can move adaptively on rugged terrain, 2) it has higher energy efficiency than a wheeled vehicle especially on soft terrain because it leaves discrete footprints rather than a continuous furrow thus minimizing soil deformation resistance, 3) it makes holonomic and omnidirectional motion without slippage, 4) it can be a stable and at the same time dynamic base for a manipulator even on rugged terrain when it is not moving.

However on flat terrain, wheeled locomotion is absolutely better than legged locomotion in terms of speed and energy efficiency. Therefore attempts have been made to combine the advantages of these two means of locomotion through leg-wheel hybrid vehicles.

A hexapod vehicle of KOBE Steel Ltd., designed to perform tasks in a disaster area is one example[1]. A quadruped walking vehicle of Mechanical Engineering Laboratory designed for underground excavating had a crawler on the body[2]. And vehicles made by Hitachi Ltd. and KAIST of Korea have prismatic legs with driven wheels at the end[3][4].

In these previous studies, hybrid vehicles have been

Fig.1 Previous typical hybrid vehicle



(a) Walking mode

(b) Skating mode

Fig.2 Basic concept of Roller-Walker in two modes

equipped with driven wheels and steering and braking mechanisms. (Fig.1) In such hybrid vehicle with active wheels, there is a serious defect. It is the problem of the weight. Drive wheels are usually extremely heavy and bulky because the require driving actuators and steering and braking mechanisms. Therefore installation of the active wheels usually increases the total weight of the walking vehicle which is already heavy enough, limiting the versatility of the leg mechanism.

By the installation of passive wheels, or casters, this problem can be avoided. So we have proposed a new leg-wheel hybrid vehicle named "Roller-Walker" that performs wheeled locomotion using passive wheels. The fundamental characteristics of its mobility will be discussed in the following section.

2. Introduction of "Roller-Walker"

2.1 Basic concept of Roller-Walker

Roller-Walker has special foot mechanisms which act as wheels as well as soles. While the foot mechanisms are in the state shown in Fig.2(a), Roller-Walker makes normal walking motions. When the feet are rotated 90[deg] they become wheels as shown in Fig.2(b), and Roller-Walker makes wheeled locomotion.

Fig.3 illustrates the motion of the Roller-Walker in skating mode. The principle by which thrusting motion is produced accords with that of roller skating. By means of leg motion, the wheels are made to slide along the ground at some inclination to the axis of rotation and the force component in the direction of wheel rotation drives the vehicle.

Although several leg-wheel hybrid vehicles have been proposed, as far as the authors are aware, no vehicle based on the locomotion principle mentioned above has ever been studied. Thus we named the concept of the newly introduced vehicle "Roller-Walker", and its locomotion method as "roller-walk". The number of the legs of Roller-Walker is not limited to four. It can be a biped or hexapod.

2.2 Characteristics of Roller-Walker

Let us summarize the characteristics of Roller-Walker introduced here.

1) Roller-Walker produces a thrusting force from the leg actuators, and the installation of additional actuators to drive the wheels is not required for the walking vehicle to have a hybrid function. Moreover the wheels of Roller-Walker serve as feet in walking mode, and thus it can be said that extra single purpose wheels are not added to the walking vehicle to roller-walk. The ankle joint rotational mechanism, which can be made lightweight, is the only additional mechanism for the walking vehicle. Therefore Roller-Walker avoids the biggest problem with most hybrid vehicles, that is the weight.

2) Future studies about the control method for the roller-walk will enable Roller-Walker to generate a wide variety of terrain adaptive wheeled locomotion even on uneven terrain as shown in Fig.4. Because the wheels are installed on the tips of the each leg which has large work space for walking.

Thus it might safely be said that Roller-Walker and its motion, the roller-walk, have significant advantages. In the following chapter we would like to discuss straight propulsion at constant velocity, which is considered as the most basic form of the roller-walk.

3. Computer simulation

To clarify the overall structure of the roller-walk control method, considerable study is necessary. In this chapter, we investigate the most fundamental motion, straight

Fig.3 Skating locomotion

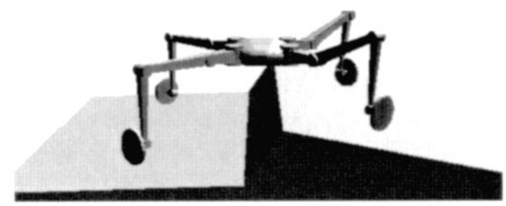


Fig.4 Roller-Walker on uneven terrain

roller-walk, by computer simulation. The leg trajectory is optimized in order to achieve maximum constant velocity. The derived results are compared with experimental results in the last chapter.

3.1 Kinematic model

There are an infinite number of possible trajectories in the legs' work space. Let us assume that: 1) every legs are on the ground, 2) each leg produces cyclic motion on a fixed trajectory. The advantages of introducing these assumptions are: 1) high stability, 2) easy analysis, 3) independence from payload. However it has also disadvantage that the velocity and energy efficiency decrease because continuous acceleration and deceleration are generated by cyclic thrusting motion. Nevertheless it seems that simulations using these assumptions provide the most fundamental information, so we performed these simulations in previous work[5][6].

The straight roller-walk using fixed symmetric motion of both of the front legs is analyzed. Fig.5 shows the kinematic model and the body coordinates. The axis of the passive wheel is fixed at a right angle to the leg and its yaw rotation is restricted. The body weight is carried equally by all the legs and the camber angle is always kept perpendicular to the ground.

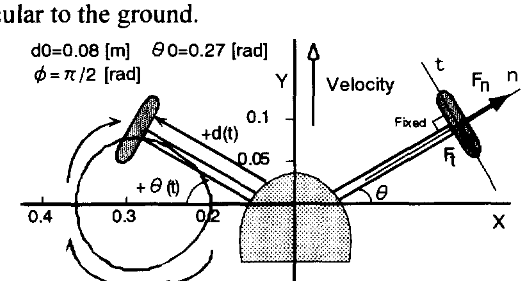


Fig.5 Simulation model and parameters

Since both right and left legs are moves symmetrically, the lateral reaction forces are canceled and only the sagital reaction forces remain as a driving force. The motion of the contact point between the wheels and the ground is assumed as follows:

$$d(t) = d_{offset} + d_0\left(\sin\left(\frac{2\pi}{T}t + \frac{3}{2}\pi\right) + 1\right) \quad (1)$$

$$\theta(t) = -\theta_0 \sin\left(\frac{2\pi}{T}t + \frac{3}{2}\pi + \phi\right) \quad (2)$$

In equations (1),(2), there are 4 variable parameters d_0, θ_0, ϕ, T. Here, d_0 and θ_0 are the amplitudes of the prismatic motion and swing motion of the leg. ϕ is the phase difference between d(t) and θ(t). T is the period of cyclic motion. A phase offset of $3\pi/2$ and a length offset 1 are added under consideration of the leg's work space.

Coulomb friction is presumed between wheel and ground, and viscous resistance is also presumed in the tangential direction of the wheel caused by the bearing and its lubricating oil. Thus the tangential and normal forces Ft, Fn of the wheel resulting from this cyclic motion can be expressed as follows;

$$F_t = -\,\mathrm{sign}\left(V\cos\theta(t) + d(t)\,\dot{\theta}(t)\right)\cdot \mu_t \cdot \frac{W}{4} - \mu_{tc}\cdot\left(V\cos\theta(t) + d(t)\,\dot{\theta}(t)\right) \quad (3)$$

$$F_n = -\,\mathrm{sign}\left(V\sin\theta(t) + \dot{d}(t)\right)\cdot \mu_n \cdot \frac{W}{4} \quad (4)$$

The Coulomb frictional coefficient μ_t and viscous coefficient μ_{tc} to the tangential direction of the wheel, that of rotational friction, and the frictional coefficient in the normal direction, μ_n, are set as follows:

$$\mu_t = 0.01 \quad , \quad \mu_{tc} = 5.5 \quad (5)$$

$$\mu_n = 0.560 \quad \left(|V_n| \geq 0.01\ [\mathrm{m/s}]\right) \quad (6)$$

These values were obtained by experiment. In order to prevent resultant vibration, viscous resistance is presumed when the velocity in the normal directions very low.

3.2 Optimization of the trajectory

In this chapter the front leg trajectory is optimized in order to achieve maximum constant velocity as one example of motion analysis. The tangential direction of the rear passive wheels is aligned with the direction of motion and the thrusting forces are supplied by the front 2 legs. If cyclic period T is decreased, the velocity increases because the supplied thrusting power increases in a unit time interval. Thus T is fixed at 2.0[s] and d_0, θ_0, ϕ are optimized to obtain the shape of the trajectory.

The parameters d_0, θ_0 and ϕ are varied from 0.01 to 0.08[m], from 0.1 to 1.0[rad], and from 0 to 2π[rad], respectively. Through velocity simulations using all combinations, the optimum parameters were found as follows:
1) $\phi = \pi/2$ maximizes the constant velocity and minimizes the speed fluctuation over each cycle.
2) The maximum d_0 within the leg's work space is the optimal value.
3) θ_0 is optimized at approximately 0.3 [rad].
Fig.6, Fig.7 show the results of the simulation while the optimal trajectory is illustrated on the left side of Fig.5. The maximum average velocity is 0.82 [m/s] which is 2.3 times faster than the maximum speed of the leg's end. This result shows the advantage of wheeled locomotion compared with walking in terms of locomotion velocity.

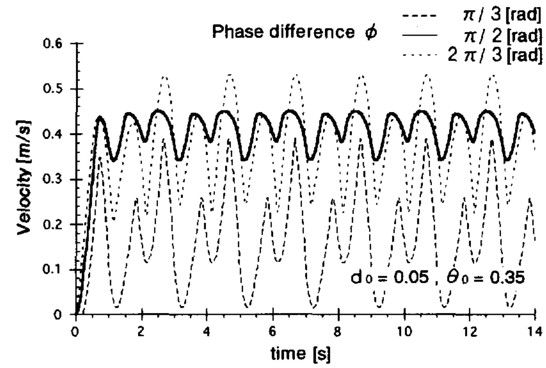


Fig.6 Optimization of ϕ

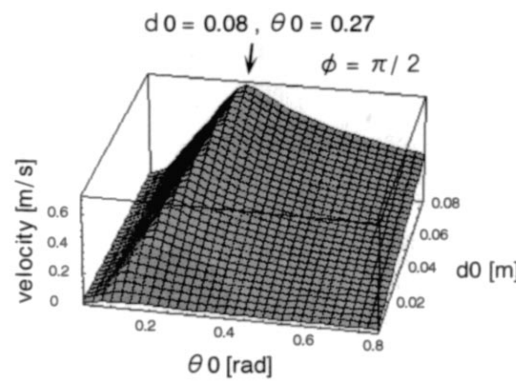


Fig.7 Optimization of d_0 and θ_0

4 Experimental model

A prototype model of Roller-Walker was developed by modifying a quadruped walking robot, TITAN VIII. TITAN VIII uses a wire and pulley drive system to realize not only high performance of the movement but also low price, simple maintenance, simple modification[7]. The mechanical improvements for Roller-Walker are: 1) addition of a changeable ankle mechanism, 2) installation of passive wheels, 3) changes to the body dimensions.

4.1 Changeable ankle mechanism

As shown in Fig.8, a parallel link mechanism was introduced to the ankle joint of TITAN VIII in order to keep foot's sole parallel to the body. This mechanism is composed of three equal diameter pulleys which are free to rotate and a wire fixed to the rotational Z axis by winding. If the leg moves with respect to the Z axis, the ankle joint is always kept at the same angle relative to the body regardless of the leg's posture because all pulleys are connected by a wire. We utilized this mechanism for the ankle mode change. If the leg is fixed in the same position and only the wire is driven, the ankle rotates to transform from a foot into a passive wheel. These two mechanisms, the parallel link mechanism and the ankle changing mechanism, are fully independent of each other mechanically if the wire driving mechanism is installed within the leg's structure so that it rotates with the leg. Therefore in wheeled mode the camber angle of the passive wheel is always kept the same.

Assuming that the ankle change is restricted only performed with the leg lifted up, the power required of the actuator can be very small. However the reaction force from contact with the ground is transmitted to the output of the actuator due to the offset of the passive wheel. This force is larger than the perpendicular reaction force because the prismatic motion generates an additional friction force, so its magnitude is very large. To solve this problem, we used a worm gear to make the system non-backdriveable. This mechanism is very compact and light so we could install it within the leg structure. The output power of the installed small actuator is 2.7 [w]. The ankle angles for the 2 modes are set by limit switches.

4.2 Passive wheel

The characteristics of the passive wheel's friction directly effect the movements of Roller-Walker, so it is important to understand them well. It is generally known that the friction characteristics of rubber tires do not follow the Coulomb friction model[8][9]. This difference is caused mainly by the large stuructual deformation of the wheel in the axial direction and the surface rubber deformation at the contact point with the ground. Thus if we design a wheel which has high stiffness and harder rubber, it will follow the Coulumb friction model more closely. With this consideration in mind, we attached the passive wheels shown in Fig.9

4.3 Mechanical integration

Photo.1 shows the completed Roller-Walker and Photo.2(a),(b) indicates the two modes of the passive wheel. The body front/back length was extended 70 [mm] in order to fit the Titech robot driver[10] inside the body. As a result, there is enough space on the body top for mounting the computer and other instruments. This extension also prevents the front and rear legs from interfering with each other. The batteries are mounted on the center of the body and it can be exchanged from the body top.

Table.1 shows the specifications of Roller-Walker. The total additional weight that includes the complete mechanism and control circuit is 1.6 [kg]. This is only 7% of the weight of TITAN VIII so the Roller-Walker concept is clearly effective in terms of weight.

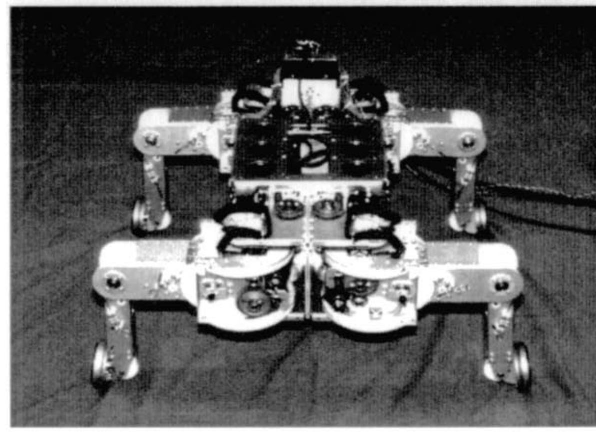


Photo.1 Roller-Walker

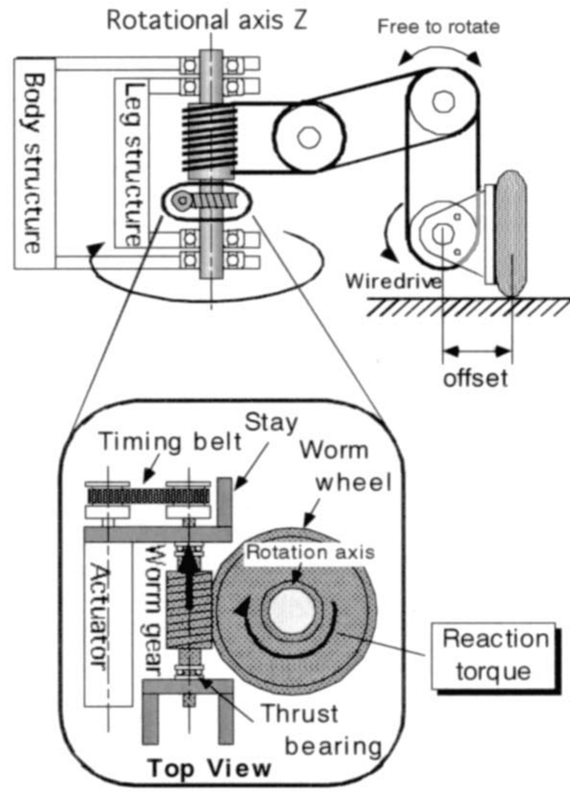
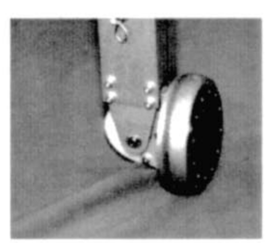


Fig.8 Ankle change mechanism



(a) Skating mode

(b) Walking mode

Photo.2 Wheel and sole disk

4.4 Control system

The control system should be untethered so as not to impede the movement such as high speed wheeled locomotion. However we produced a wired control system by open loop control as a first step for simplicity. The control computer sends only the command value of each joint angle to the motor driver which makes position control on board. The system configuration is illustrated in Fig.10.

Now we are in the first stage of investigating the basic movements of propulsion, so we did not introduce sensor systems such as a gyroscope posture sensor or CCD camera for visual feedback. We are considering it as future work.

5. Experiments

In order to measure the friction coefficient, some experiments were done as shown in Fig.11. The velocity was measured when the body with the passive wheels was sliding on the ground. The friction coefficient was derived from the deceleration. The slip angle was changed by adjusting the leg angle θ, and the perpendicular reaction force due to the body weight was changed by mounting some payload on the top. The results of the experiments indicate that the Coulomb friction assumption held true for this wheel. This method of measuring the friction coefficient is very effective and practical on various surfaces.

Control experiments were done to demonstrate the performance of the total Roller-Walker system. The sequence is: 1) walking, 2) changing the foot placement, 3) changing the sole to wheel, 4) straight roller-walk.

The details of the ankle changing sequence are: 1) move the body center of gravity to maintain some stability margin, 2) lift up the leg, 3) change the ankle angle, 4) set down the leg. This sequence took 9.0[s] to carry out for all 4 legs in the order 1,4,3,2. A smooth change was demonstrated by the experiments.

Straight roller-walking was also demonstrated smoothly in a straight line though the direction was disturbed a little by the imbalance of static friction force at the start time. Fig.12 indicates the experimental velocity with the optimal foot trajectory and Photo.5 shows the experiment. The body position was made low in order to maximize the legs' work space. As Fig.12 shows, the experimental velocity follows the simulation result very well for acceleration/declaration and the experimental velocity is 5% lower than the simulation. Careful straight roller-walk experiments were done over 50 times and the optimal trajectory derived by the simulation maximized the experimental constant velocity. Thus we confirmed that the kinematic model used for the simulation was very appropriate.

As shown in the left side of Fig.5, the left side clockwise trajectory produces a forward force. By experiment we confirmed that backward propulsion was produced by the

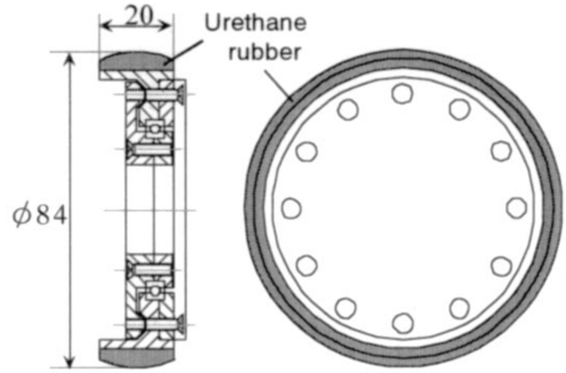


Fig.9 Passive wheel

Table 1 Specifications of Roller-Walker

Dimension	470×600×250 [mm]	
Weight	TITAN VIII	22.2 [kg]
	Additional Weight	+1.6 [kg]
	Roller-Walker (Including Battery)	23.8 [kg]
Payload	20~32 [kg]	
Battery	36V - 3.4 Ah	

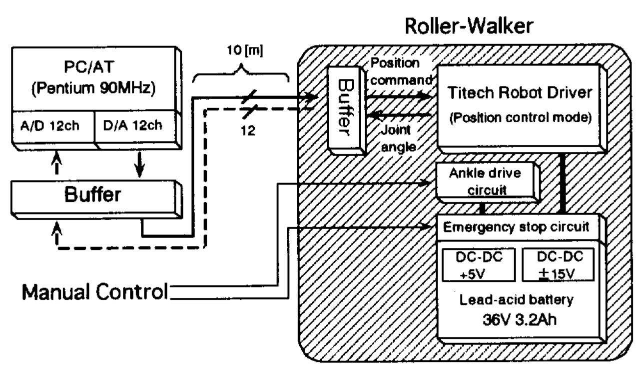


Fig.10 Configuration of the control system

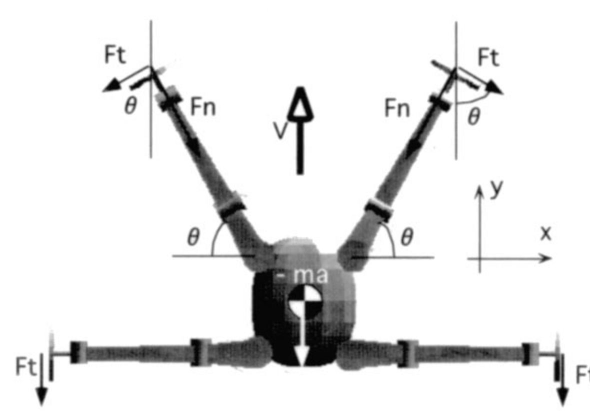


Fig.11 Measurement of the friction coefficient

counterclockwise trajectory.

We also confirmed that driving diagonally opposite legs produces steering movements. When deceleration was needed in the movements of straight roller-walking, braking force was generated enough by changing the tangential direction of the passive wheel by adjusting the angle θ.

6. Conclusions

In this paper, the leg-wheel hybrid vehicle named "Roller-Walker" was proposed and it's concept and characteristics were introduced. The foot trajectory of straight roller-walk was optimized in order to attain the maximum constant velocity using the front 2 legs. The Roller-Walker experimental system was made by improving TITAN VIII and realization with a prototype Roller-Walker concept was demonstrated by experiments. The experimental velocity at the optimized trajectory was compared with the simulation.

Using this experimental system we will investigate the control method for various movements using all 4 legs such as steering motion, acceleration, terrain adaptive movements and so on.

7. Acknowledgments

The authors would like to thank Keisuke Arikawa for his help in the integration of the control system and the programing.

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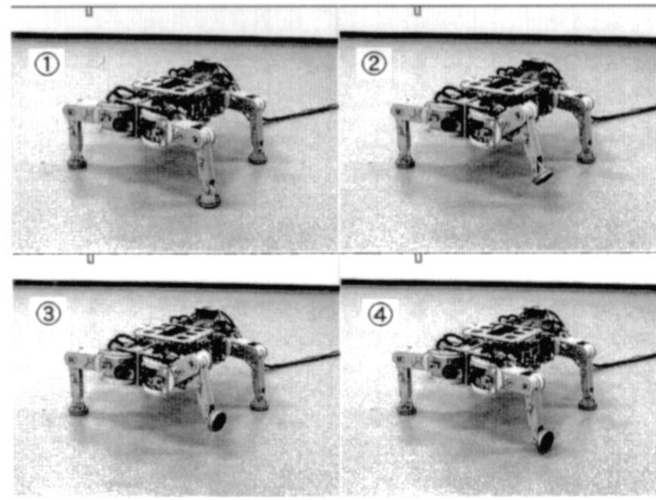

Photo.3 Experiment of the ankle change

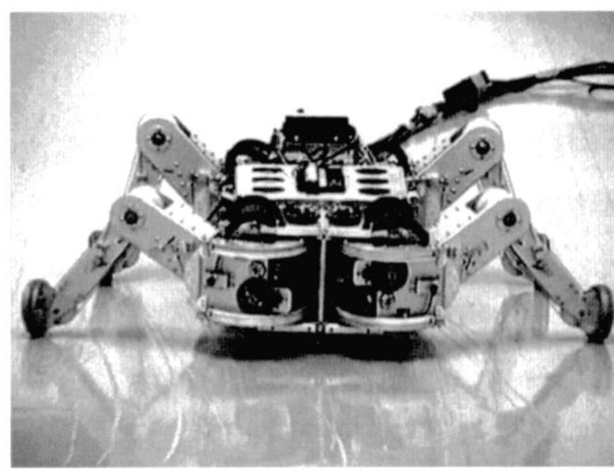

Photo.4 Straight propulsion experiment

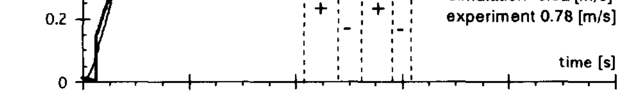

Fig.12 Experimental velocity at optimized trajectory

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