論文 / 著書情報
Article / Book Information

Title	Study on Roller-Walker (Multi-mode Steering Control and Self-contained Locomotion
Author	Gen Endo, Shigeo Hirose
Journal/Book name	Proc. of the IEEE International Conference on Robotics and Automation '00, Vol. , No. , pp. 2808-2814
発行日 / Issue date	2000,
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Proceedings of the 2000 IEEE
International Conference on Robotics & Automation
San Francisco, CA • April 2000

Study on Roller-Walker
(Multi-mode Steering Control and Self-contained Locomotion)

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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 wheels. 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 4 leg trajectory of Straight Roller-Walk is optimized in order to achieve maximum constant velocity. Also steering roller-walk control method is proposed. It is obtained by the expansion of the straight roller-walk trajectory theory adding an offset to the swinging motion. This steering method resembles that of a car. The control system was modified into an untethered system, and control experiments were performed. The realization of the steering motion was verified by them.

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].

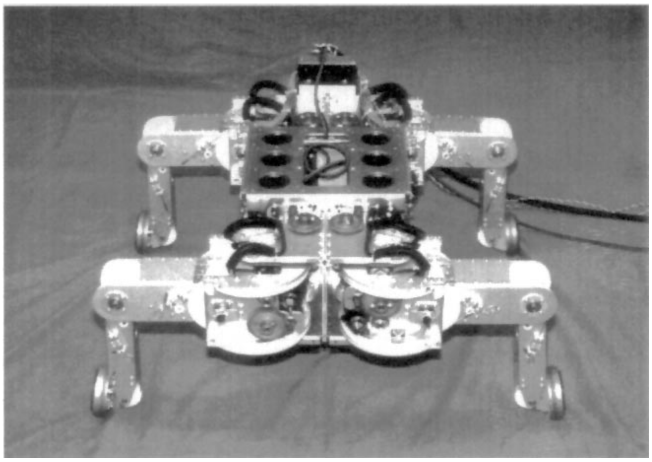

Photo.1 Roller-Walker

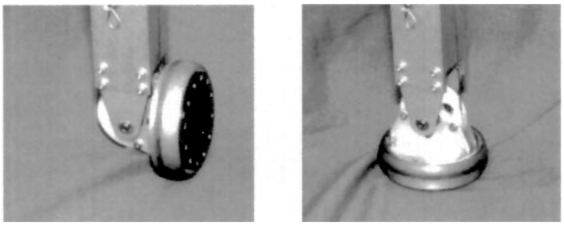

Photo.2(b) Skating mode Photo.2(a) Walking mode

In these previous studies, hybrid vehicles have been equipped with driven wheels and steering and braking mechanisms. 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 they 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.(Photo.1) The fundamental characteristics of its mobility will be discussed in the following section.

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2. Introduction of "Roller-Walker"

2.1 Basic concept of Roller-Walker

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

Fig.1 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.2. 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 many advantages in terms of practical robotics.

We have already derived the optimized frontal 2 legs' trajectory that produces maximum straight constant velocity. An experimental model was integrated by modifying quadruped walking vehicle TITAN VIII [8]. The results were compared with the simulations. In the following chapter we would like to discuss straight propulsion using 4 legs, rotational motion, steering motion and inclined propulsion.

Fig.1 Skating locomotion

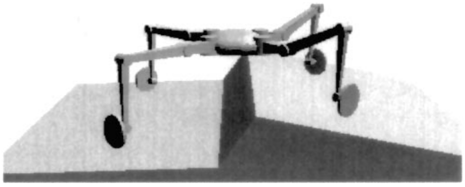


Fig.2 Roller-Walker on uneven terrain

3. Kinematic model

At first, we discuss the kinematics model that is used by all the following simulations.

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][7].

The straight roller-walk using fixed symmetric motion of both of the front legs is analyzed. Fig.3 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.

Since both right and left legs are moves symmetrically, the lateral reaction forces are canceled and only the sagital

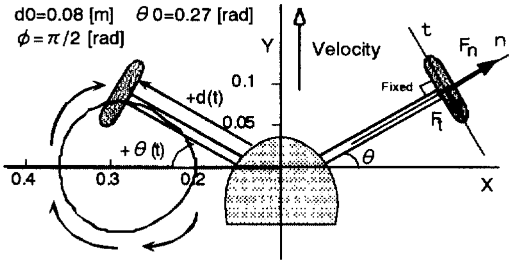


Fig.3 Simulation model and parameters

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 $\theta(t)$. 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;

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

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

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:

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

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

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.

In the following sections, we set the locomotion velocity as a criterion of optimization because it is the most fundamental characteristics of the mobile robots.

4. Straight Roller-Walk

4.1 Frontal 2 legs' trajectory

In this section, the front leg trajectory is optimized in order to achieve maximum constant velocity. 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.

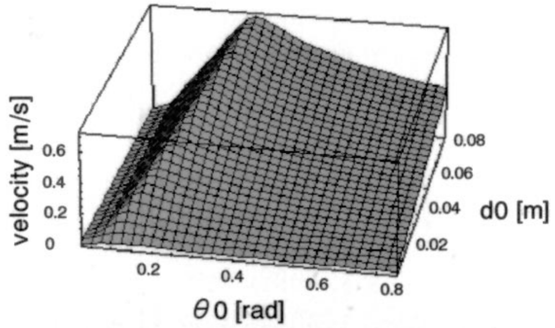
The parameters d_0, θ_0 and ϕ are varied from 0.01 to 0.08[m], from 0.1 to 1.0[rad], and from 0 to 2π[rad], respectively. Through velocity simulations using all combinations, the optimum parameters were found as follows:

1) $\phi = \pi/2$ maximizes the constant velocity and minimizes the speed fluctuation over each cycle.

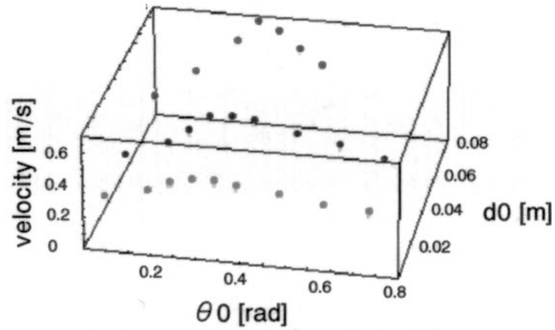
2) The maximum d_0 within the leg's work space is the optimal value.

3) θ_0 is optimized at approximately 0.3 [rad].

Fig.4(a), Fig.4(b) show the relationship between the amplitudes and average constant velocity. The propulsive velocity was measured by a tacho generator equipped with an extra measuring caster. The distribution map of the velocity simulation follows the experimental results well. The optimal trajectory is illustrated on the left side of Fig.3, and its propulsive velocity is shown in Fig.5. There are two



(d_0, θ_0 : parameter $\phi=\pi/2$,T=2.0)
Fig.4(a) Simulated velocity



(d_0, θ_0 : parameter $\phi=\pi/2$,T=2.0)
Fig.4(b) Experimental velocity

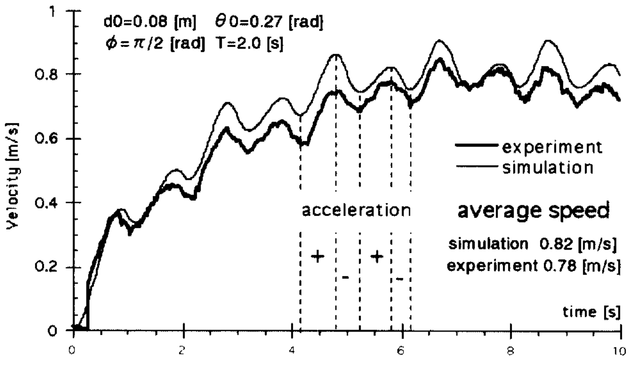


Fig.5 Velocity at optimized trajectory

times acceleration/deceleration in a period, however 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.

We also verified that the constant velocity was proportional to inverse of period T. Thus the velocity can be easily controlled by adjusting the leg trajectory period T regardless of the trajectory shape.

4.2 4 legs' trajectory

The rear leg's trajectory is also analyzed by using the same algorithm and coordinates. Here, we introduced a phase difference ϕfr between front and rear cyclic function. According to the results of former section and the physical consideration that the frictional force only depends on the velocity, it is expected that the rear 2legs' trajectory takes the same optimum parameters. So in this section, ϕfr is optimized by the simulation. The results shows that ϕfr=$\pi/2$ or $3\pi/2$[rad] minimize the acceleration/deceleration fluctuation and at the same time they maximize the constant velocity. It is increased 12% compared with the frontal 2legs trajectory. The reason is considered as follows.

When mobile robot moves at constant velocity, each leg produces same magnitude of acceleration and deceleration and they are always balanced in one cycle. Thus it can be considered that each leg has no frictional drag against the propulsive direction. In case of frontal 2 leg propulsion, the rear passive wheels produce rolling resistance. Therefore 4 leg propulsion increases the velocity for this resistance.

The effect of ϕfr=$\pi/2$ levels the velocity fluctuation because each leg produces acceleration/deceleration every $\pi/2$ phase in one cycle. If ϕfr=$\pi/2$ (or $3\pi/2$), frontal acceleration is canceled by rear deceleration. In this case, frictional forces are consumed by inner forces. So it is not effective propulsion in terms of energy efficiency. However, the body activated forces are doubled and it is sustained by inner force steadily. Since it is much more stable propulsion. Fig.6 illustrates the optimum velocity using 4 legs.

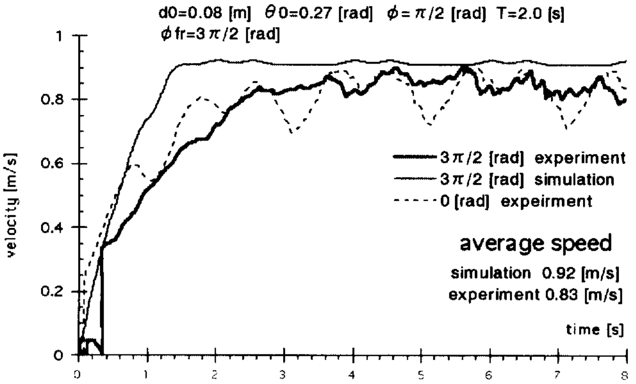


Fig.6 Velocity using 4 legs

5. Rotational Roller-Walk

In this section, the former results are expanded into rotational motion.

At first, we discuss qualitative considerations. In the case of straight propulsion, if the passive wheels are moved symmetrically along the optimized trajectory, the propulsive velocity that depends on the cyclic period are generated. Assuming that this velocity is supplied by the usual driven wheels equivalently, the standard posture of the legs will be radially shown in Fig.7. If diagonal leg pairs, (Leg1,Leg3) and (Leg2,Leg4), are moved symmetrically, the radius reaction forces are canceled and only rotating forces remain as rotational force.

The simulations of the angular velocity around the center of the body were made and parameter optimization were done same as the straight propulsion. Inertia I=2.28[kgm2] that was used in the simulation was obtained by the preliminary experiments. As the results derived through the simulation, angular velocity distribution was almost the same as straight propulsion. The optimized parameters were also the same though θ_0=0.28 was slightly increased.

Experiments were then done over 50 times by the various trajectory parameters. (Photo.3)

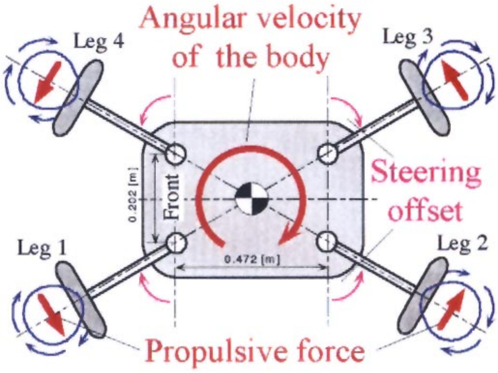


Fig.7 Standard posture of the rotational roller-walk

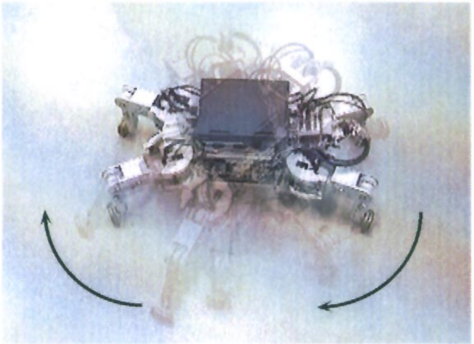


Photo.3 Rotational experiment

It was verified that the experimental angular velocity distributed same as the simulation and optimized parameters were obtained experimentally . Fig.8 shows the angular velocity at the optimized trajectory. The maximum average velocity is 2.25[rad/s] that cannot realize by walking.

ϕfr was introduced between (Leg1,Leg3) and (Leg2,Leg4), and also optimized at ϕfr=π/2 same as the straight motion. In this case, the angular velocity was increased 11% compared with ϕfr=0, however there was a moment that the rotational center was easily disturbed by a little disturbance. Because every wheels' rotational direction were aligned with the almost same direction geometrically at the moment. In terms of statically indeterminate problem caused by 4 point contact, ϕfr=0 is appropriate because of the equality of the every leg's condition.

6. Steering Roller-Walk

Steering roller-walk is also obtained using the same method. If a steering offset which is calculated geometrically, is added in the center value of the swinging motion, the body propels along the circular trajectory.(Fig.9) The reaction force caused by adding the offset is negligibly small because swinging direction is the rotation direction of the passive wheel. Therefore the steering offset can be added regardless of leg's position anytime. There are moments because of the leg's root position, however that they hardly effect the body's rotation. Because the radius reaction forces change the direction, so the integration of it in a period is negligibly small.

The body coordinate velocity Vx, Vy and ω were simulated at circular radius R=0.5[m]. The optimizing criterion was set as follow:

$$\left| \bar{V}_y / \bar{\omega} - R \right| \leq 0.02 \quad \text{and} \quad \text{Maximize } V_y \qquad (7)$$

The optimum parameters were inner legs' θ_0=0.21 (Leg2,Leg3), outer legs' θ_0=0 (Leg2,Leg3), ϕfr=11π/6, and other parameters were the same. (In this simulation, maximum d$_0$ was set at 0.05 to avoid inner legs' interference.) Simulations were also done by changing R as a parameter. As for the results, inner side θ_0 increases as R increases though d$_0$=0.05 is constant. This result can be explained qualitatively that the velocity difference between the inner legs and the outer legs in the circular trajectory is absorbed by changing amplitude of the swinging motion θ_0 and radius reaction forces are canceled by prismatic motion d$_0$.

Experiments were carried out to compare these results. V_y was measured by a tacho generator and the body position and its angle were measured by a 3D position measurement system OPTOTRAK (Northern Digital Inc.). It tracked 4 markers that were fixed on the body and the body center position and its angle were derived by their posi-

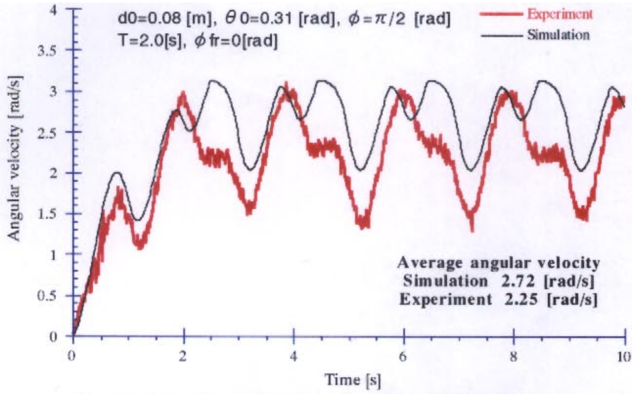


Fig.8 Angular velocity at optimized trajectry

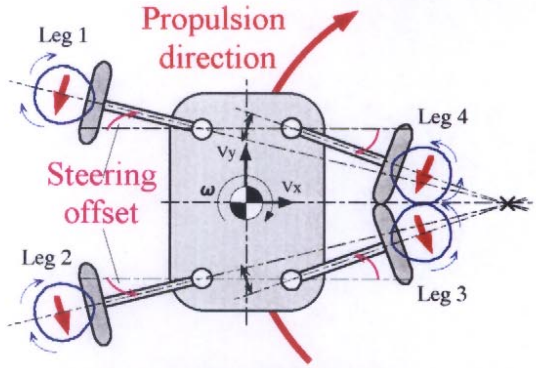


Fig.9 Steering Roller-Walk

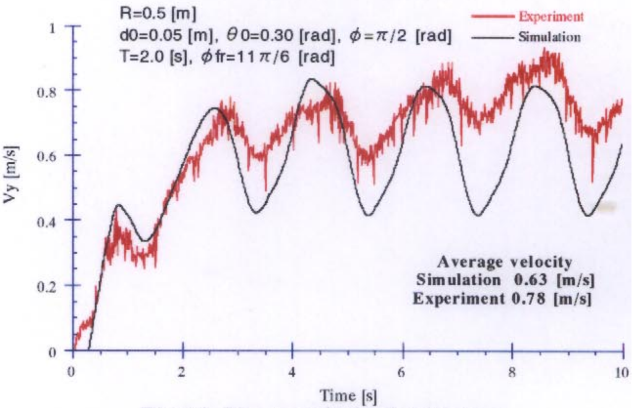


Fig.10 Vy at optimized trajectory

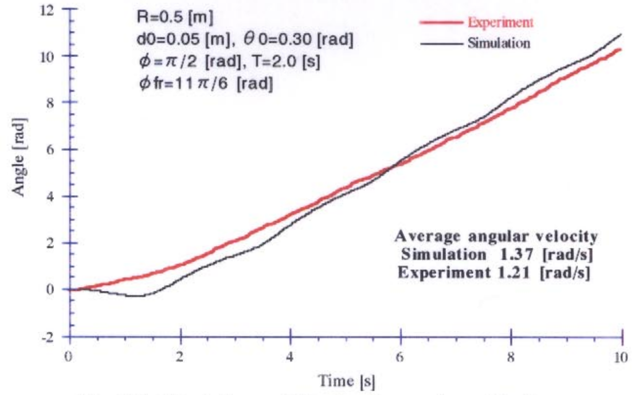


Fig.11 Variation of the body angle with time

tions. The total position error is estimated at about15[mm] including the calibration error of the propulsion plane.

The experiments at R=0.5[m] were carried out over 30 times and the experimental optimum parameters were found. They were the same as the simulation though θ_0 was slightly increased to 0.30. Experimental velocity at optimized parameters is illustrated in Fig.10.

Experimental average velocity Vy is 30% larger than the simulation. In the simulation, static friction force is not included by assuming eqn.(6). By the careful observation, inner leg hardly made slide in the normal direction relative to the ground. Therefore the difference between the simulation and the experiment was effected by the static friction force.

Fig.11 shows the angle and Fig.12 illustrates the position trajectory of the body for 3 period at constant state. It is difficult to assert that the simulation is appropriate at the position level, however high steering ability of Roller-Walker was demonstrated. The experimental radius is about 0.6[m] and the angular velocity is almost constant. Minimum radius is about 0.4[m] calculated by legs' workspace.

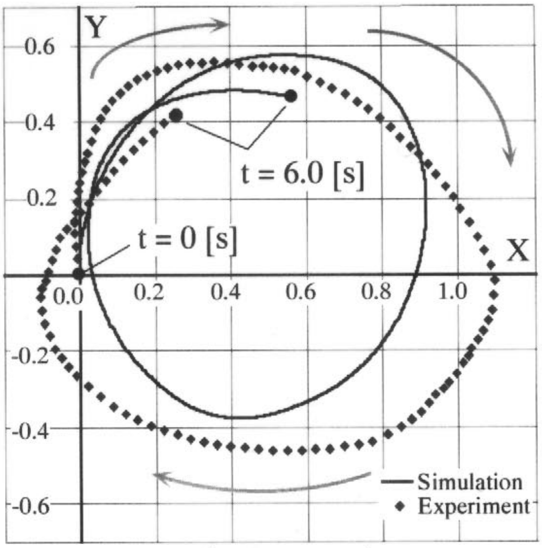
7. Crab Roller-Walk

In the former section, front and rear added steering offset are opposite. If they are added to the same direction, Roller-Walker makes diagonal motion.(Fig.13) It was demonstrated by the experiment in which offset angle set 30[deg]. This control method resembles 4WS(4 wheel steering) of a car.

8. Self-contained system

The control system should be untethered so as not to impede the movement such as high speed wheeled locomotion. We modified wired control system into a self-contained system by using a notebook PC mounted on the top of the body. The ankle angles are changed by digital values from the control computer. The parameters of propulsive velocity, direction and locomotion mode are transmitted by radio wave and the cyclic period and steering offset are calculated. When Roller-Walker takes standard posture, it can select walking or skating mode indicated by mode change command. It changes the legs' placements and ankle angles sequentially.

All electric power is supplied by the lead acid battery that produces 25[min] untethered movements. The system configuration is illustrated in Fig.14.



(d_0=0.05 [m], θ_0=0.30 [rad], $\phi=\pi/2$ [rad] T=2.0 [s], $\phi_{fr}=11\pi/6$ [rad])

Fig.12 Trajectory of the body position

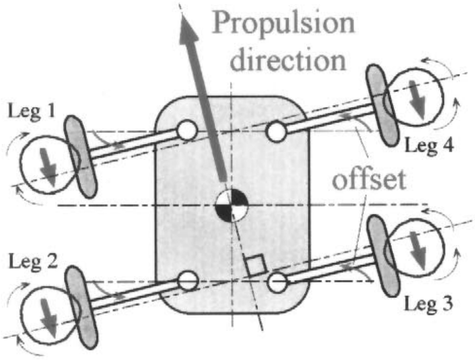


Fig.13 Crab Roller-Walk

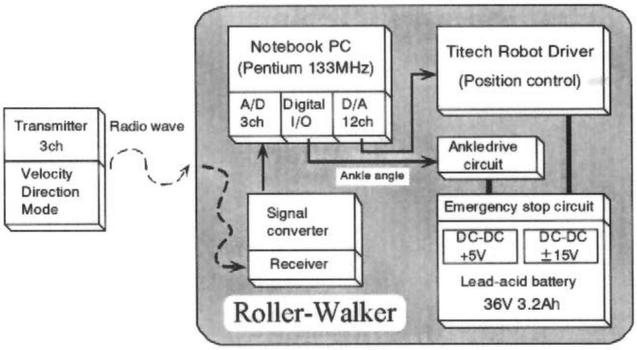


Fig.14 System configuration

9. Maneuvering experiment

By using derived results, maneuvering experiments were demonstrated in order to verify its controllability. The trajectory parameters were set for optimum straight propulsion. Roller-Walker made very smooth velocity change from 0 to 0.5[m/s]. And backward propulsion was demonstrated by making the leg trajectory opposite against time scale.

Steering motion was also extremely controllable by operator's command. One example of the maneuvering experiments, a result of figure 8 propulsion is shown in Photo.4. (It was captured every 2[s]. The distance of two poles was 2.0[m].) Roller-Walker demonstrated the slalom propulsion at regular distance 0.9[m]. Average locomotion velocity was 0.3[m/s]. The front/back length of Roller-Walker is 0.6[m], so it has enough ability to steer.

It followed very well against quick change of operator's command. We confirm that the Roller-Walk propulsion bears comparison with a locomotion of a normal driven wheel.

10. Conclusions

In this paper, straight motion using 4 legs, rotational motion, steering motion and diagonal motion by roller-walk were proposed. These movements were verified by the simulation and experiments quantitatively. And experimental system was modified into untethered system, and then maneuvering experiments was demonstrated. We confirmed that Roller-Walk had enough controllability.

In the each optimization, propulsive velocity was used for the optimizing criterion. However it is necessary to optimize in terms of energy efficiency. We will also investigate the trajectory considering the lifting up of the leg and terrain adaptive roller-walk method.

Acknowledgments

This research is supported by JSPS Research Fellowships for Young Scientists and The Grant-in Aid for COE Research Project of Super Mechano-Systems by the Ministry of Education,Science, Sport and Culture.

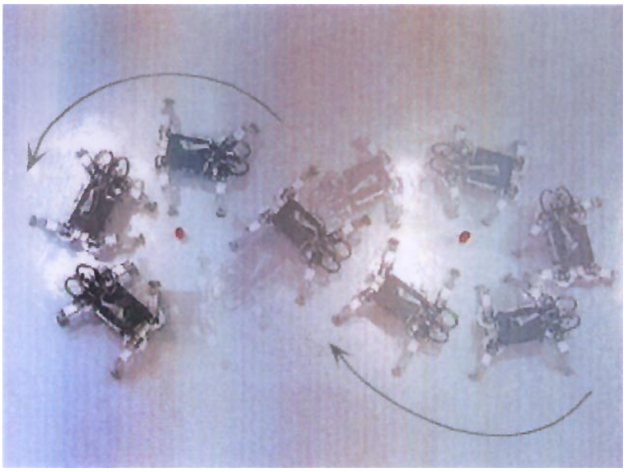


Photo.4 Figure 8 propulsion

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