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Experimental Study on Energy Efficiency for Quadruped Walking Vehicles

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***Abstract*— Though a legged robot has high terrain adaptability as compared with a wheeled vehicle, its moving speed is considerably low in general. For attaining a high moving speed with a legged robot, a dynamically stable gait, such as running for a biped robot and a trot gait or a bound gait for a quadruped robot, is a promising solution. However, the energy efficiency of the dynamically stable gait is generally lower than the efficiency of the stable gait such as a crawl gait. In this paper, we present an experimental study on the energy efficiency of a quaduped walking vehicle. Energy consumption of two walking patterns for a trot gait is investigated through experiments using a quadruped walking vehicle named TITAN-VIII. The obtained results show that the 3D sway compensation trajectory proposed in our previous paper [10] has advantages in view of energy efficiency as compared with the original sway compensation trajectory.**

I. Introduction

A legged robot has high terrain adaptability as compared with a wheeled vehicle. It enables not only to aviod an obstacle by going round, but also to stand on or even step over an obstacle. Climbing a steep sloop by hooking its soles, or jumping across a ditch are also possible. However, a moving speed of a legged robot is considerably lower than the speed of a wheeled vehicle in general.

For attaining a high moving speed with a legged robot, a dynamically stable gait, such as running for a biped robot and a trot gait or a bound gait for a quadruped robot, is a promising solution. However, since a robot body has to be supported by few legs in the dynamically stable gait, special attitude control is requisite for keeping a posture of the robot stable.

For a quadruped walking vehicle, a trot [16],[8],[18],[17], a pace [13], and a bound [12],[3],[4] gaits have been widely noted as fundamental dynamically stable gaits. Amang these gaits, we have particularly noticed the trot gait since it has close affinity to a crawl gait, which is a typical standard statically stable gait. In addition, the trot gait has an advantege that it can be classified as a "safety gait" [7] which avoids complete tumbling by touching a swing leg to ground. However, in the trot gait, the body of a robot has to be supported by diagonal legs, and its posture becomes unstable.

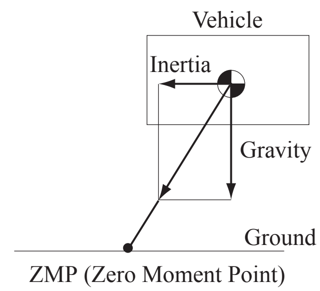


Fig. 1. Zero moment point(ZMP)

For realizing a "stable" trot gait, we have proposed the sway compensation trajectory[16]. This method utilizes its body motion along a lateral direction to keep its body balance. By this body motion, a zero moment point (ZMP) is controled to move on a desired trajectory. The ZMP is the projection onto the ground of the force acting on the body as shown in **Fig.1**. At this point, no moment exists. Therefore, by keeping this point on the diagonal line of the supporting legs, the robot enables to maintain a walking stability, since there is no moment around this line which causes the inclination of the robot body. The proposed sway compensation trajectory uses lateral (along y axis) body motion to keep the ZMP on a diagonal line between the supporting legs as shown in **Fig.2**.

In general, energy efficiency of the dynamically stable gait is lower than the efficiency of a statically stable gait such as a crawl gait. This is mainly due to the fact that much power has to be supplied at each joint to support a body by few legs. This problem is quite critical, especially if the robot has to carry its own energy source such as a

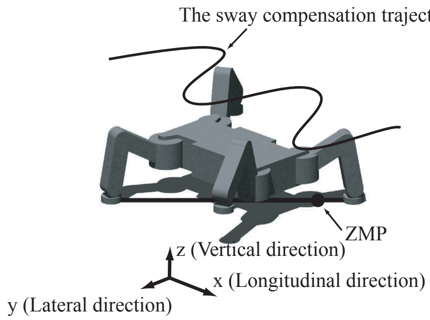


Fig. 2. The sway compensation trajectory

battery.

The energy efficiency of various legged robots including a monopod[6], a quadruped robot[1], and a hexapod[11],[14], [15] has been investigated in the past. However, the most of these studies limits their discussion in computer simulation and qualitative analysis.

Gregorio et al.[6] experimentally investigated the energy consumption of their single legged robot named the ARL Monopod. They also showed comparison of the specific resistance[5] for several walking vehicles developed in the past, and human and car.

Kimura[9] examined the energy efficiency of a quadruped vehicle and showed the relation between the walking cycle and energy consumption for trot and pace gaits. However, a quadruped walking vehicle was modelled as an inverted pendulum and the dynamically stable gait which always maintains the equilibrium state, such as the gait performed by the sway compensation trajectory, was not examined.

If the sway compensation trajectory is examined from a viewpoint of energy efficiency, the energy consumption is expected to be larger than in the case without specific controls of body trajectory, since acceleration and deceleration of the body in the lateral direction has to be repeated periodically.

However, the position of the ZMP is controllable not only by the lateral motion but also by the sagittal and vertical motion, respectively. Thus, by combining these motions, it may be possible to improve the energy efficiency against the conventional sway compensation trajectory which controls the position of the ZMP only by the lateral motion.

From these consideration, we proposed the 3D sway compensation trajectory [10]. This method utilizes the body motion along not only a lateral direction but also a sagittal and a vertical directions. The 3D sway compensation trajectory make it possible to move the robot body more smoothly in terms of acceleration. Thus, the 3D sway compensation trajectory was considered to give higher energy efficiency than the original sway compensation trajectory.

In this paper, we present an experimental study on the energy efficiency of a quaduped walking vehicle. Energy consumption of the sway and 3D sway compensation trajectories is investigated through experiments using a quadruped walking vehicle named TITAN-VIII, which is commonly used in many research groups. The obtained results show that the proposed 3D sway compensation trajectory has advantages in its energy efficiency as compared with the original sway compensation trajectory.

II. The 3D sway compensation trajectory

In this section, we give formulation of the conventional sway compensation trajectory and the 3D sway compensation trajectory which is the expansion of the conventional one to a sagittal direction.

A. Conventional sway compensation trajectory

First, the formulation of the conventional sway compensation trajectory is presented. Here, we consider a vehicle as a point mass at (x_g, y_g, z_g). If the ground is flat and the height of the body from the ground, z, is constant, the position of the ZMP $(x_z, y_z, 0)$ is given as

$$\begin{pmatrix} x_z \\ y_z \end{pmatrix} = \begin{pmatrix} x_g \\ y_g \end{pmatrix} - A \begin{pmatrix} \ddot{x}_g \\ \ddot{y}_g \end{pmatrix} \quad (1)$$

where, $A = \frac{z_g}{g}$. And, the diagonal line of the support legs is defined as

$$\cos\theta \ x + \sin\theta \ y = d \quad (2)$$

Then, in order to stay the ZMP on this line, the center of gravity has to satisfy

$$\cos\theta(x_g - A\ddot{x}_g) + \sin\theta(y_g - A\ddot{y}_g) = d \quad (3)$$

Assuming that the vehicle moves along the x axis and acceleration of the center of gravity along the moving direction is constant, the position of the body along the x axis is expressed as

$$x_g = a_2^x t^2 + a_1^x t + a_0^x \quad (4)$$

By substituting this equation into Eq.(3), we get

$$\cos\theta(a_2^x t^2 + a_1^x t + a_0^x - 2Aa_2^x) + \sin\theta(y_g - A\ddot{y}_g) = d \quad (5)$$

The solution of this differential equation, y_g, is given as the addition of the solutions of the next equation

$$y_g - A\ddot{y}_g = 0 \quad (6)$$

that is,

$$y_g = C_1^y e^{\frac{t}{\sqrt{A}}} + C_2^y e^{-\frac{t}{\sqrt{A}}} \quad (7)$$

and one particular solution that satisfies Eq.(5). Here, we assume that the general form of the particular solution is expressed by a polynomial expression of time t; then the solution of Eq.(5) is derived as

$$y_g = C_1^y e^{\frac{t}{\sqrt{A}}} + C_2^y e^{-\frac{t}{\sqrt{A}}} + a_2^y t^2 + a_1^y t + a_0^y \quad (8)$$

From the boundary condition about the continuity of a trajectory ($\dot{y}_{g,t=0} = \dot{y}_{g,t=\frac{T}{2}} = 0, y_{g,t=0} = -y_{g,t=\frac{T}{2}}$), each coefficient is determined as

$$C_1^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1-e^{-\frac{T}{2\sqrt{A}}})v}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \quad (9)$$

$$C_2^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1-e^{\frac{T}{2\sqrt{A}}})v}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \quad (10)$$

$$a_2^y = -2a_2^x \cot\theta \quad (11)$$

$$a_1^y = -a_1^x \cot\theta \quad (12)$$

$$a_0^y = -a_0^x \cot\theta + d\csc\theta \quad (13)$$

$$a_0^x = \frac{d}{\cos\theta} + \frac{1}{2}\left(\frac{\sqrt{A}T(e^{\frac{T}{2\sqrt{A}}} + e^{-\frac{T}{2\sqrt{A}}} + 2)}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} - \frac{T^2}{4}\right)a_2^x - \frac{T}{4}a_1^x \quad (14)$$

where, T is a walking cycle. This solution is a trajectory of the center of gravity that always keeps the ZMP on the diagonal line of the support legs, and this trajectory is defined as the (conventional) sway compensation trajectory.

B. Expansion for sagittal motion

The conventional sway compensation trajectory mentioned above is expanded to the form including a sway along the sagittal direction.

First, Eq.(3) is decomposed into two equations for the x and y directions, and each solution trajectory is assumed to be given as Eq.(8) and

$$x_g = C_1^x e^{\frac{t}{\sqrt{A}}} + C_2^x e^{-\frac{t}{\sqrt{A}}} + a_2^x t^2 + a_1^x t + a_0^x \quad (15)$$

By substituting the boundary condition about the continuity of a trajectory, the following equations with two parameters a_2^x and a_1^x are derived.

$$C_1^x = -\frac{(T^2 + 4\sqrt{A}T)a_2^x + 2Ta_1^x - 2L}{8(e^{\frac{T}{2\sqrt{A}}} - 1)} \quad (16)$$

$$C_2^x = -\frac{(T^2 - 4\sqrt{A}T)a_2^x + 2Ta_1^x - 2L}{8(e^{-\frac{T}{2\sqrt{A}}} - 1)} \quad (17)$$

$$C_1^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1-e^{-\frac{T}{2\sqrt{A}}})a_1^x}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \quad (18)$$

$$C_2^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1-e^{\frac{T}{2\sqrt{A}}})a_1^x}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \quad (19)$$

$$a_2^y = -a_2^x \cot\theta \quad (20)$$

$$a_1^y = -a_1^x \cot\theta \quad (21)$$

$$a_0^y = -a_0^x \cot\theta + d\csc\theta \quad (22)$$

$$a_0^x = \frac{d}{\cos\theta} + \frac{1}{2}\left(\frac{\sqrt{A}T(e^{\frac{T}{2\sqrt{A}}} + e^{-\frac{T}{2\sqrt{A}}} + 2)}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} - \frac{T^2}{4}\right)a_2^x - \frac{T}{4}a_1^x \quad (23)$$

where, L is the body stroke in one walking cycle.

We define this expansion of conventional sway compensation trajectory along a sagittal direction as “the 3D sway compensation trajectory”. Expansion to a vertical direction is also possible[10] in the same way as the formulation to a sagittal direction.

C. Evaluation from a viewpoint of acceleration

The energy consumption of a walking vehicle is affected by many factors such as mass of the body and legs, configuration of the degrees of freedom, trajectories of body and legs, the negative power at each actuator, etc [11],[1]. In this section, the trajectory which minimizes the total of the external force applied dynamically, that is, the sum of squared acceleration through the entire trajectory as defined below, is considered.

$$\rho = \int_0^{\frac{T}{2}} (\ddot{x}_g{}^2 + \ddot{y}_g{}^2 + \ddot{z}_g{}^2)dt \quad (24)$$

Here, only a regular walk ($a_2^x = 0$) is considered for simplicity.

First, for the conventional sway compensation trajectory in which the body is moved only in a sagittal direction, the sum of squared acceleration through the entire trajectory, ρ, is obtained by substituting $a_1^x = \frac{L}{T}$ into Eq.(24) as

$$\rho = \frac{L^2(\sqrt{A}(-1+e^{\frac{T}{\sqrt{A}}}) - e^{\frac{T}{2\sqrt{A}}})\cot^2\theta}{A(1+e^{\frac{T}{2\sqrt{A}}})^2 T^2} \quad (25)$$

Next, the proposed 3D sway compensation trajectory including a sway in the sagittal direction is considered. Since the parameter that can be designed is a_1^x, a_1^x that minimizes sum of squared acceleration through the entire trajectory is given by solving

$$\frac{\partial\rho}{\partial a_1^x} = 0 \quad (26)$$

as

$$a_1^x = \frac{(1+e^{\frac{T}{2\sqrt{A}}})^2 LT}{(1+e^{\frac{T}{2\sqrt{A}}})^2 T^2 + 16A(-1+e^{\frac{T}{2\sqrt{A}}})^2\cot^2\theta} \quad (27)$$

And the minimum of the sum of squared acceleration ρ is derived as

$$\rho = \frac{L^2(\sqrt{A}(-1+e^{\frac{T}{\sqrt{A}}}) - e^{\frac{T}{2\sqrt{A}}})\cot^2\theta}{A((1+e^{\frac{T}{2\sqrt{A}}})^2 T^2 + 16A(-1+e^{\frac{T}{2\sqrt{A}}})^2\cot^2\theta)} \quad (28)$$

By comparing Eqs.(25) and (28), the sum of the squared acceleration for the 3D sway compensation trajectory is smaller than the sum for the conventional sway compensation trajectory except $T = 0$, $\theta = \frac{\pi}{2}$, or $A = H/g = 0, \infty$. Therefore, the energy consumption is also expected to be reduced by the 3D sway compensation trajectory.

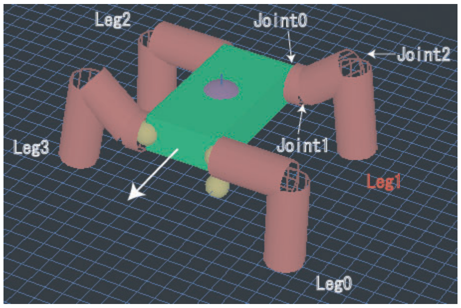


Fig. 3. A simulation model

III. Computer Simulation and Power Measurement Experiments

A. Computer simulation

To illustrate the advantage of the energy efficiency of the 3D sway compensation trajectory, we develop a set of computer simulation. The configuration of degrees of freedom, weight, etc. of a quadruped walking vehicle model for computer simulation is the same as the TITAN-VIII [2] (**Fig.3**) which is used in following experiments.

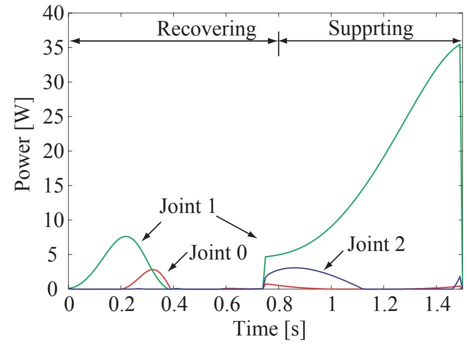
Fig.4 shows the power consumption of leg 2 for the conventional sway compensation trajectory and the 3D sway compensation trajectory. It is clear that the power consumption of the 3D sway compensation trajectory at joint 2, which mainly produces the lateral sway motion, becomes lower than the power consumption of the conventional sway compensation trajectory.

Fig.5 depicts the total energy consumption for a walking cycle in the cases where walking speed is changed from 0.05 to 0.20 [m/s], and $\gamma = a_1^x/v_0$ $(v_0 = \frac{L}{T})$ is changed from 0.2 to 1.0. $\gamma = 1.0$ is for the conventional sway compensation trajectory, and $0 \leq \gamma < 1.0$ is for the 3D sway compensation trajectory. As γ decreases, the sagittal sway body motion increases. In all the cases, it is verified that the energy consumption of the 3D sway compensation trajectory is lower than the energy consumption of the conventional sway compensation trajectory.

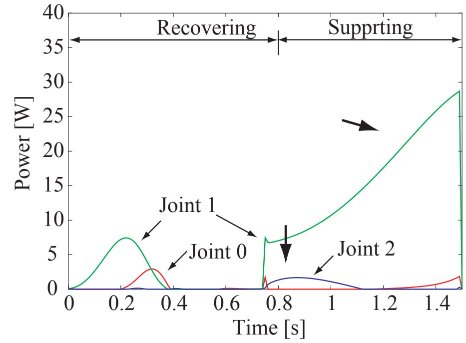
B. Experiments with TITAN-VIII

Next, we develop power measurement experiments using a quadruped walking vehicle, TITAN-VIII[2] (**Fig.6**). The TITAN-VIII was designed at Tokyo Institute of Technology in 1996, and since it was released, it has been widely used as the common platform of a quadruped waking vehicle in many research groups in Japan.

In order to measure the power consumption at each actuator, we designed an analog circuit (**Fig.7**), and installed it in each motor driver. Voltage and current supplied to actuators are multiplied by an analog multiplier via low pass filters, and stored in a PC via an A/D converter.



(a) The sway compensation trajectory



(b) The 3D sway compensation trajectory

Fig. 4. Power consumption of leg 2. (cycle time is 1.5 [sec.])

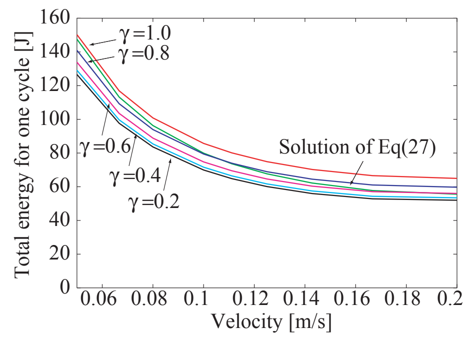


Fig. 5. Total energy consumption for various waking patterns. ($\gamma = a_1^x/v_0$)

Fig.8 shows the power consumption of the leg 2 for the sway compensation trajectory and the 3D sway compensation trajectory In the same way as the simulation results, the power consumption of the 3D sway compensation trajectory at joint 2 is lower than the power consumption of the conventional sway compensation trajectory. Though the energy consumption at each actuator seems to be different between **Fig.4** and **Fig.8**, this is mainly due to the difference of joint configuration, that is, TITAN VIII utilizes the interfere mechanism[2] to improve the efficiency of power consumption at each actuator.

Fig.9 depicts the total energy consumption for a walking

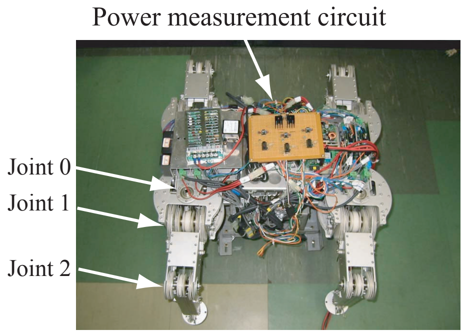


Fig. 6. TITAN VIII with a power measurement circuit

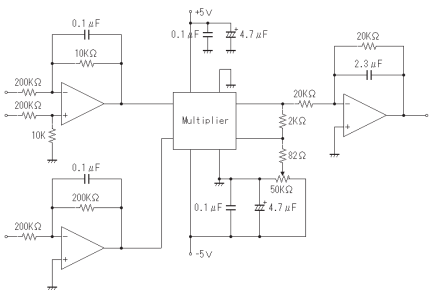


Fig. 7. A power measurement circuit diagram

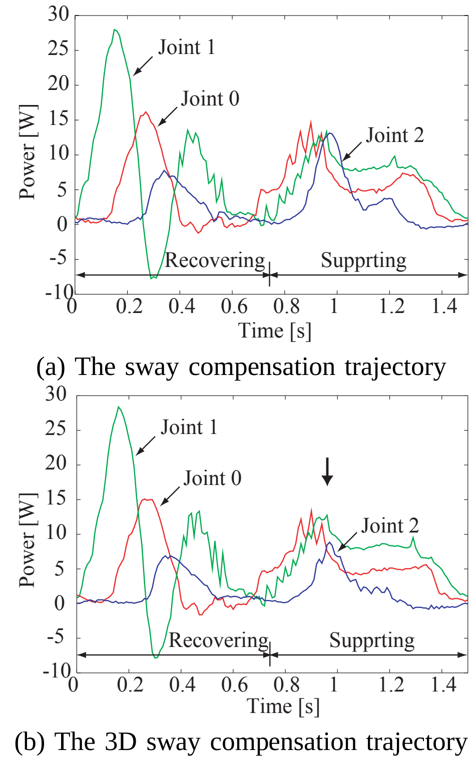


Fig. 8. Power consumption of leg 2. (cycle time is 1.5 [sec.])

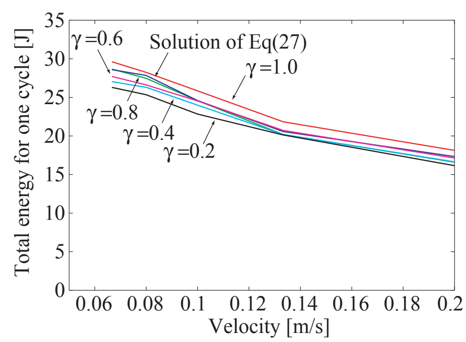


Fig. 9. Total energy consumption for various waking patterns. ($\gamma = a_1^x/v_0$)

cycle, which is obtained as the average of ten walking cycles, in the cases where walking speed is changed from 0.067 to 0.20 [m/s], and $\gamma = a_1^x/v_0$ ($v_0 = \frac{L}{T}$) is changed from 0.2 to 1.0. In all the cases, it is verified the energy consumption of the 3D sway compensation trajectory ($\gamma = 0.2 \sim 0.8$) is lower than the energy consumption of the conventional sway compensation trajectory ($\gamma = 1.0$). As γ decreases, the energy efficiency improves. However, it becomes difficult to keep body balance since large acceleration and deceleration toward a sagittal direction is demanded.

The solution of Eq.(27), that is, the parameter which minimizes the sum of squared acceleration, is also examined, and the energy consumption is plotted in **Fig.9**. Though the energy consumption is better than the conventional sway compensation trajectory, it is not an optimum parameter for low moving velocity. This is due to the actual leg structure, joint friction, or other various factors which is caused by simplification for analysis.

Next, we compare the energy efficiency between the proposed trot gait and a crawl gait, which is one of the typical statically stable gait. The specific resistance[5] has commonly been used to compare energy efficiency of various moving vehicles. The specific resistance is defined as $\varepsilon = \frac{E}{m\ g\ L}$, where E is the energy consumption, m is the mass of the vehicle, g is the gravitational acceleration, and L is the moving distance. In our case, these values are $m = 20.1[Kg]$ and $L = 0.2[m]$.

Fig.10 dipicts the experimental results for the cases where the duty factor β is changed from 0.5 to 0.9, that is, $\beta = 0.5 \sim 0.7$ for the trot gait with the 3D sway compensation trajectory, and $\beta = 0.75 \sim 0.9$ for a generalized trot gait[8],[16].

This figure shows that i) the energy efficiency of the crawl gait is better than the efficiency of the trot gait for the same moving velocity, and ii) the energy efficiency of the trot gait becomes worth as the duty factor increases.

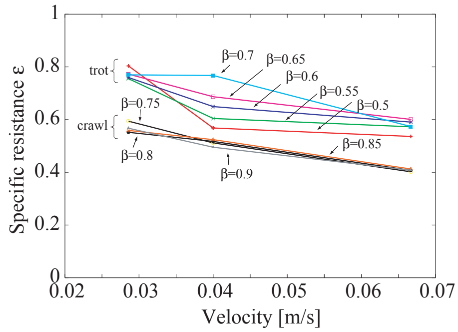


Fig. 10. Specific resistance for various walking patterns

IV. Conclusion

For a dynamically stable trot gait of a quadruped robot, we have proposed two control schemes; the sway compensation trajectory and the 3D sway compensation trajectory. In this paper, we examined power consumption of both control schemes experimentally using a quadruped walking vehicle, TITAN VIII. The experimental results shows that the 3D sway compensation trajectory has advantages in view of its energy efficiency as compared with the original sway compensation trajectory.

V. ACKNOWLEDGMENTS

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