# Feedforward and feedback dynamic trot gait control for a quadruped walking vehicle

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## Abstract

*To realize dynamically stable walking for a quadruped walking robot, the combination of the trajectory planning of the body and leg position (feedforward control) and the adaptive attitude control using sensory information (feedback control) is indispensable. In this paper, we initially propose a new trajectory planning for the stable trot gait named 3D sway compensation trajectory, and show that this trajectory has lower energy consumption than the conventional sway trajectory that the authors have proposed. Next, as the adaptive attitude control method used during the 2-leg supporting phase of the trot gait, we consider four methods: a) rotation of body along the diagonal line between supporting feet, b) translation of body along the perpendicular line between supporting feet, c) vertical swing motion of recovering legs, and d) horizontal swing motion of recovering legs. The stabilization efficiency of each method is verified through computer simulation and the damping experiment using a quadruped walking robot, TITAN-VIII. Furthermore, the dynamic trot gait control that combines the feedforward control based on the proposed 3D sway compensation trajectory and the adaptive feedback control using body translation and vertical motion of swing legs is developed, and the walking experiment on rough terrain using TITAN-VIII is carried out.*

## 1 Introduction

To increase the walking speed and the energy efficiency of a quadruped walking vehicle, it is indispensable to realize dynamically stable walking that has a phase when the vehicle body is supported by less than 2 legs and the body attitude becomes unstable.

Within a trot [2],[3],[4],[7], pace[12], and bound [13],[14],[15] gaits that are fundamental dynamically stable gaits, the authors have studied the trot gait in paticular. This gait is attractive because it has a close affinity to the crawl gait, which is one of the standard statically stable gaits, and can be classified as a "safety gait" [1] that avoids complete tumbling by touching a swing leg to ground. Then, the authors have proposed a generalized trot gait [2],[3] that can smoothly shift from the crawl gait to the trot gait in proportion to walking speed, and an intermittent trot gait [4] that makes the diagonal legs as swing and support legs simultaneously to reduce dynamic effect of the recovering swing legs on the body.

Furthermore, the sway compensation trajectory of the vehicle body [2], which uses lateral body motion to keep a zero momentum point (ZMP) on a diagonal line between the support legs, was proposed and the effectiveness of this trajectory control to realize a dynamically stable walk was verified through walking experiments using TITAN-IV and TITAN-VI.

In the environment where the unknown roughness or inclination exists, however, dynamically stable walking is difficult using feedforward gait control such as the sway compensation trajectory only, and the adaptive feedback control system that stabilizes the body attitude using mounted attitude sensors, gyroscope sensors, etc. is requisite.

In this regard, for the realization of the practical dynamically stable trot gait for a quadruped walking vehicle, authors believe that the combination of feedforward control based on the sway compensation trajectory and feedback control based on the adaptive attitude control is one possible effective control method. The basic ideas underlying this feedforward and feedback dynamic trot gait control are as follows: First, the state of the system is generously transferred adjacent to the unstable equilibrium point by off-line, feedforward gait planning such as the sway compensation trajectory. Then, the remaining small deviation from the equilibrium point is adaptively compensated by a simple, linear feedback control system.

In this paper, first, we propose the new sway trajectory of the vehicle body named 3D sway compensation trajectory that uses lateral, longitudinal, and vertical motion of the vehicle body to keep ZMP on the diagonal line of the support legs. With the proposed trajectory, it is possible to improve the energy efficiency against the conventional sway compensation trajectory that controls the position of ZMP by the lateral motion only.

Next, as the adaptive feedback control method, several attitude control methods using the body translation and swing leg waving motion are proposed. The control performance of each method is examined through computer simulation and damping control experiments in the two-leg supporting phase using the quadruped walking vehicle named TITAN-VIII [11].

Furthermore, the feedforward and feedback dynamic trot gait control system that combines the 3D sway compensation trajectory and the adaptive body position and swing leg motion control is developed and the walking experiment on rough terrain using TITAN-VIII is carried out.

# 2 3D sway compensation trajectory

## 2.1 Conventional sway compensation trajectory

First, we show the formulation of the conventional sway compensation trajectory. Here, we consider a vehicle as a mass point 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 ZMP $(x_z, y_z, 0)$ is given as

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

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

$$\cos\theta\ x + \sin\theta\ y = d \tag{2}$$

Then, in order for ZMP to keep on this line, the center of gravity has to be satisfied

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

Assuming that the position of the body along the $x$ axis is expressed as

$$x_g = x_0 + vt + \frac{1}{2}at^2 \tag{4}$$

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

$$\cos\theta(x_0 - Aa + vt + \frac{1}{2}at^2) + \sin\theta(y_g - A\ddot{y}_g) = d \tag{5}$$

The solution of this differential equation, $y_g$, is given as

$$y_g = C_1^y e^{\frac{t}{\sqrt{A}}} + C_2^y e^{-\frac{t}{\sqrt{A}}} + a_2^y t^2 + a_1^y t + a_0^y \tag{6}$$

From the boundary condition for the continuity of the 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

$$C_1^y = \sqrt{A}\cot\theta \frac{T\frac{a}{2} + (1 - e^{-\frac{T}{2\sqrt{A}}})v}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \tag{7}$$

$$C_2^y = \sqrt{A}\cot\theta \frac{T\frac{a}{2} + (1 - e^{\frac{T}{2\sqrt{A}}})v}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \tag{8}$$

$$a_2^y = -a\cot\theta \tag{9}$$

$$a_1^y = -v\cot\theta \tag{10}$$

$$a_0^y = -x_0\cot\theta + d\csc\theta \tag{11}$$

$$x_0 = \frac{d}{\cos\theta} + \frac{1}{4}\left(\frac{\sqrt{A}T(e^{\frac{T}{2\sqrt{A}}} + e^{-\frac{T}{2\sqrt{A}}} + 2)}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} - \frac{T^2}{4}\right)a - \frac{T}{4}v \tag{12}$$

Where, $T$ is a walking cycle. This trajectory of the center of gravity, which is given as Eqs.(4) and (6), is defined as the (conventional) sway compensation trajectory [2].

## 2.2 Expansion for longitudinal motion

The conventional sway compensation trajectory mentioned above can be expanded to include a sway toward the longitudinal 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.(6) and

$$x_g = C_1^x e^{\frac{t}{\sqrt{A}}} + C_2^x e^{-\frac{t}{\sqrt{A}}} + a_2^x t^2 + a_1^x t + a_0^x \tag{13}$$

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

$$C_1^x = -\frac{(T^2 + 4\sqrt{A}T)a_2^x + 2Ta_1^x - 2L}{8(e^{\frac{T}{2\sqrt{A}}} - 1)} \tag{14}$$

$$C_2^x = -\frac{(T^2 - 4\sqrt{A}T)a_2^x + 2Ta_1^x - 2L}{8(e^{-\frac{T}{2\sqrt{A}}} - 1)} \tag{15}$$

$$C_1^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1 - e^{-\frac{T}{2\sqrt{A}}})a_1^x}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \tag{16}$$

$$C_2^y = \sqrt{A}\cot\theta \frac{Ta_2^x + (1 - e^{\frac{T}{2\sqrt{A}}})a_1^x}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} \tag{17}$$

$$a_2^y = -a_2^x \cot\theta \tag{18}$$

$$a_1^y = -a_1^x \cot\theta \tag{19}$$

$$a_0^y = -a_0^x \cot\theta + d\csc\theta \tag{20}$$

$$a_0^x = \frac{d}{\cos\theta} + \frac{1}{2}\left(\frac{\sqrt{A}T(e^{\frac{T}{2\sqrt{A}}} + e^{-\frac{T}{2\sqrt{A}}} + 2)}{(e^{\frac{T}{2\sqrt{A}}} - e^{-\frac{T}{2\sqrt{A}}})} - \frac{T^2}{4}\right)a_2^x - \frac{T}{4}a_1^x \tag{21}$$

Where, $L$ is the body stroke in one walking cycle.

## 2.3 Expansion for vertical motion

Moreover, the above equations can be expanded to the form including a sway in the vertical direction.

Considering $A = \frac{z_g}{g+\ddot{z}_g}$, we assume the trajectory to the vertical direction, $z_g$, is given as

$$z_g = C_1^z e^{\frac{t}{\sqrt{A}}} + C_2^z e^{-\frac{t}{\sqrt{A}}} + A\ g \tag{22}$$

Where, $A$ is an arbitrary constant. By substituting the boundary condition about the continuity of trajectory, coefficients with the parameter $A$ are derived as

$$C_1^z = -\frac{Ag - H}{1 + e^{\frac{T}{2\sqrt{A}}}} \tag{23}$$

$$C_2^z = -\frac{(Ag - H)e^{\frac{T}{2\sqrt{A}}}}{1 + e^{\frac{T}{2\sqrt{A}}}} \tag{24}$$

Where, $H$ is the body height at $t = 0, \frac{T}{2}$.

We define these expansions of conventional sway compensation trajectory toward longitudinal and vertical direction as "**the 3D sway compensation trajectory**".

## 2.4 Energy efficiency of the 3D sway compensation trajectory

The energy consumption of a walking vehicle is affected by many factors such as the mass of body and legs, the configuration of the degrees of freedom, the trajectory of body and legs, the negative power at each actuator, etc [9],[10]. In this paper, however, the trajectory that minimizes the sum of squared acceleration through the entire trajectory is considered.

$$\rho = \int_0^{\frac{T}{2}} (\ddot{x}_g{}^2 + \ddot{y}_g{}^2 + \ddot{z}_g{}^2)dt \tag{25}$$

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

Simulation results that minimize the sum of squared acceleration are shown in **Table 1**. Here, $T = 1[s], H = 0.2[m], L = 0.2[m], \theta = 30[deg]$, and $d = 0$. **Figure 1** shows the obtained body trajectories for the conventional sway compensation trajectory, the expansion in the longitudinal direction, and the longitudinal and vertical direction, respectively. In **Fig.1**, the upper figure shows the trajectories projected on the ground (x-y plane), and the lower figure shows the trajectories projected on the x-z plane from the lateral direction in which the vertical axis is magnified 20 times.

From these figures, it is verified that the sum of the squared acceleration can be reduced by swaying not only in the lateral direction but also in the longitudinal and vertical directions.

Table 1: Minimum of squared acceleration

| | lateral only | lateral and longitudinal | lateral, longitudinal, and vertical |
|---|---|---|---|
| $\rho$ | 0.623 | 0.334 | 0.331 |
| $a_1^x$ | 0.2 | 0.107 | 0.107 |
| $A$ | 0.0204 | 0.0204 | 0.0207 |

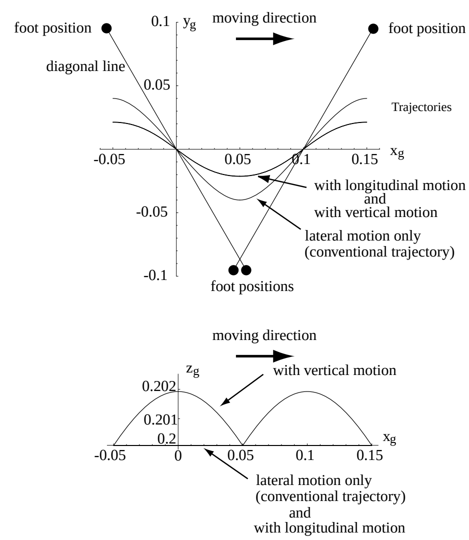



Figure 1: Trajectories of vehicle body

## 2.5 Computer simulation using the dynamic motion simulator, ADAMS

To verify the energy efficiency of the 3D sway compensation trajectory derived in section 2.4 in the actual robot system, the computer simulation using the dynamic motion simulator, ADAMS, is carried out.

The configuration of degrees of freedom, weight, etc.

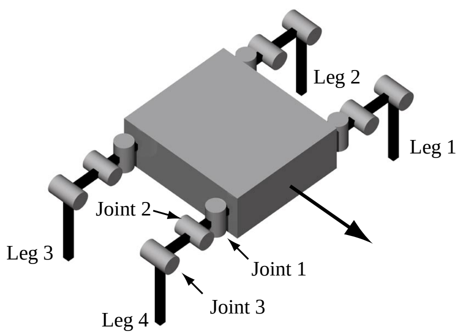



Figure 2: Simulation model for ADAMS

Table 2: Comparison of energy consumption

| | lateral only | lateral and longitudinal | lateral, longitudinal, and vertical | straight |
|---|---|---|---|---|
| E [J] | 142.0 | 114.6 | 108.6 | 96.8 |
| $\epsilon$ | 2.35 | 1.90 | 1.80 | 1.60 |

of a quadruped walking vehicle model for computer simulation is the same as the TITAN-VIII [11] developed in our laboratory.

**Figure 2** show the simulation model. The sum of power consumption at each joint, E, and specific resistance, $\epsilon$, [6] are shown in **Table 2**. In the simulation, the walking cycle is 1 [s], walking speed is 0.2 [m/s] and duty factor is 0.5. The columns show the results of the conventional sway compensation trajectory, the trajectory including lateral and longitudinal sway, the trajectory including lateral, longitudinal, and vertical sway, and straight line with no sway control. The trajectories that minimize the sum of squared acceleration derived in section 2.4 are used for the 3D sway compensation trajectories. Note that in case that the body moves on a straight line with no sway control, the body attitude cannot be maintained to be parallel to the ground, and the swing leg touches the ground unexpectedly.

From these results, power consumption and specific resistance can be improved by the 3D sway compensation trajectory that minimizes the sum of squared acceleration.

# 3 Adaptive attitude control

As mentioned above, in the environment where the unknown roughness or inclination exists, dynamically stable walking is difficult using only the feedforward gait control such as the 3D sway compensation trajectory. In addition, for example, when an extended trot gait is applied, the body attitude sometimes becomes unstable and oscillates due to the dynamic effect of the recovering motion of the swing legs [4]. Therefore, a feedback control system using mounted attitude sensors, gyroscope sensors, etc. which adaptively corrects body attitude are required. In this section, we propose the attitude control method during 2-leg supporting phase using the body translation and rotation, and swing leg waving motion.

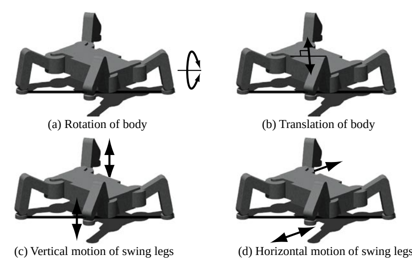



Figure 3: Four attitude control methods

## 3.1 Attitude control methods and computer simulation

To produce the required moment for attitude recovery in the two-leg supporting phase, the method using rotation of the body along the diagonal line between the support legs as shown in **Fig.3**(a) has been proposed [16]. The required moment for attitude recovery, however, can be produced by the translation of body position as shown in **Fig.3**(b). Furthermore, though the recovery motion of swing legs has been considered as disturbance that induces the oscillation of body [4], by controlling the recovery path appropriately, swing legs can be used for the damping control of body attitude.

From the above discussion, four attitude control methods as shown in **Fig.3** are considered in this paper.

(a) Rotation of body along the diagonal line between the support legs.

(b) Translation of body along the direction perpendicular to the diagonal line between the support legs.

(c) Vertical motion of swing legs during recovery.

(d) Horizontal motion of swing legs during recovery.

First, each method is simplified as a three-link model corresponding to a support leg, a body, and a swing leg as shown in **Fig.4**, and motion equations of each model and optimum linear regulators are designed to repress the oscillation of the body. **Fig.5** shows ex-

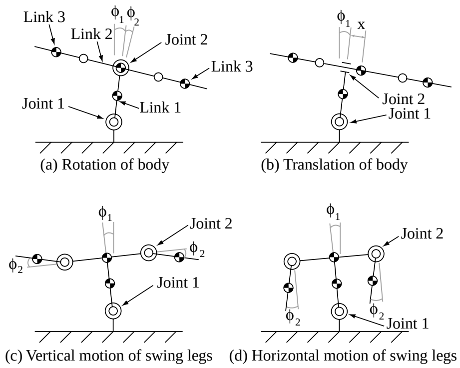



Figure 4: Analysis models

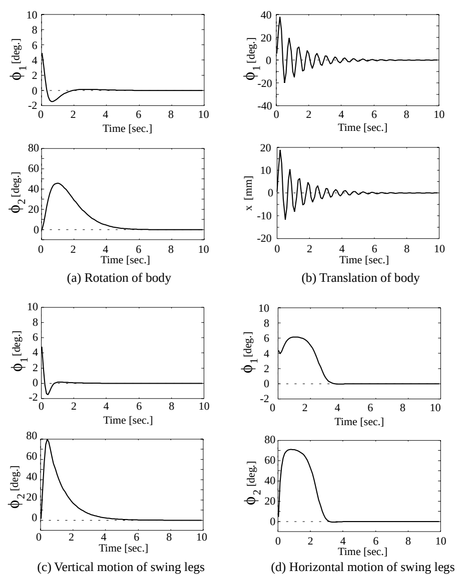



Figure 5: Simulation results

amples of computer simulation of the designed optimum linear regulators when the initial conditions are $\phi_1 = 5[deg.]$,$\phi_2 = 0[deg.]$, and $x = 0[deg.]$

From **Fig.5(a)** using the rotation of body, the body has to be inclined up to 40 [deg.] toward the inclination direction to recover the inclination of the support leg. **Fig.5(b)** using the translation of body shows that maximum body movement to recover the inclination of the support leg is 0.2 [m] Though this body motion can be executed by TITAN-VIII, the inclination of the support leg becomes vibrational. Next, in **Fig.5(c)** and **(d)**, the maximum angles of the swing legs become 80 [deg.] and 70 [deg.], respectively. Thus, it is difficult to stabilize the body attitude using the effect of vertical and horizontal motion of the swing legs only because of the limitation of the actual movable joint angles.

Table 3: Comparison of power consumption for attitude control

| method | a | b | c | d |
|---|---|---|---|---|
| sum of power [w] | 0.74 | 12.02 | 1.22 | 1.44 |

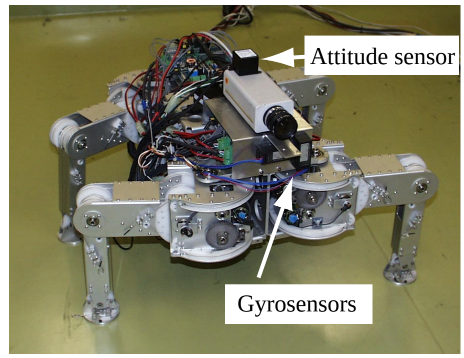



Figure 6: 4-legged walking robot, TITAN-VIII

To compare the energy efficiency for these methods, the sum of power consumption was calculated. **Table 3** shows the comparison of power consumption for each method. The method (a) was the least power consumption. On the other hand, the method (b) was the worst and it needed ten times larger power consumption than method (a).

## 3.2 Damping control experiment in two-leg supporting phase

The damping control experiment using four attitude control methods proposed in Section 3.1 was carried out with the quadruped walking robot named TITAN-VIII shown in **Fig.6**. This robot is equipped with a computer board (Pentium 200MHz, Japan Data System), AD/DA boards, Ethernet card, silicon disk, 3-axes attitude sensor, (Maxcube, Japan Aviation Electronics), and two gyrosensors (Gyrostar, Murata).

In the experiment, the body of TITAN-VIII standing with two support legs was tilted by an external force applied to the body by pushing by hand. The body's attitude return to the stable state was measured for each control method after the hand is released.

The ankle of TITAN-VIII is restricted mechanically to let the sole be parallel to the body. Thus, as shown in **Fig.7**, the body attitude returns to the stable state without an attitude control if the inclination angle is smaller than about 8 [deg.]. The moment for the recovery of body inclination is produced by the soles.

For the purpose of increasing the dynamic effect of the

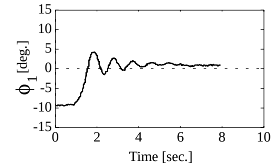



Figure 7: Experimental result (no sensor)

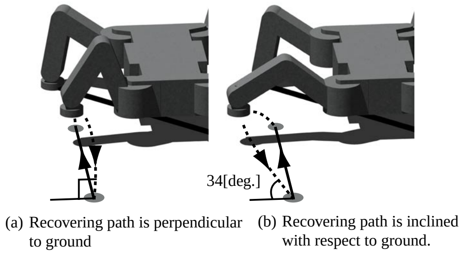



Figure 8: Recovering path of swing legs

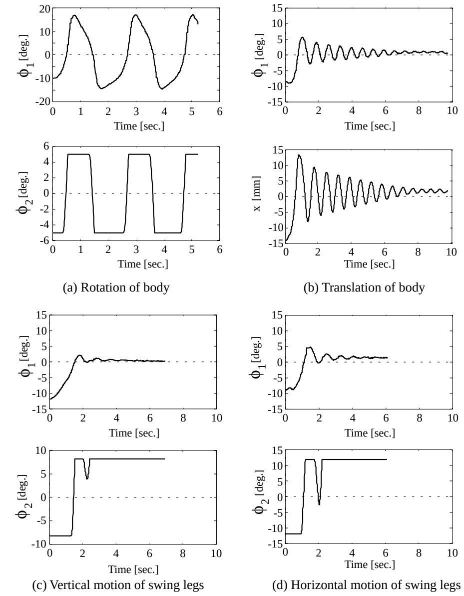



Figure 9: Experimental results of attitude control for slow trot gait

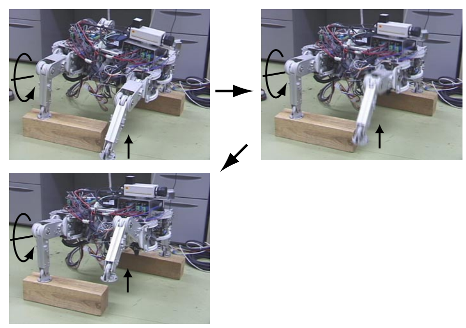


Figure 10: Experiment of attitude control using swing legs

swing legs to the body, the swing legs are stretched laterally in the middle of the return path as shown in **Fig.8(b)** and the inertia of the legs is increased.

Inclination angle of the support leg along the diagonal line between the support legs, $\phi_1$, and control variables $\phi_2$ and $x$ for each control method are shown in **Fig.9**. Here, $\phi_2$ in **Fig.9(a)** is the body rotation angle, $x$ in **Fig.9(b)** is the body displacement, and $\phi_2$ in **Figs.9(c)** and **Fig.9(d)** is the angle of joint 2 in **Fig.4** calculated from the amount of swing motion.

**Fig.10** shows the damping control experiment using the vertical motion of the swing legs. In this experiment, the swing legs are swung up during the recovery of body attitude. From the experimental results in **Fig.9(a)** using the rotation of body, the swing leg of the leaning side contacted the ground because the body was tilted more and more, and large body vibration was generated by the reaction force. Next, for the method using the translation of the body shown in **Fig.9(b)**, though the body attitude was vibrational, it finally converged to horizontal. From the comparison of **Fig.9(c)** and **Fig.7**, which are the results for the control method using vertical motion of the swing legs and without an attitude control, performance of convergence was clearly improved by the dynamic effect of swinging. However, the swing width of the swing leg is limited in the joint movable area, and thus, recovery from a large tilt angle to horizontal is difficult using only this method. On the other hand, **Fig.9(d)** which shows using the horizontal motion of the swing legs indicates the convergence performance is hardly improved. This is because the displacement of actual links was smaller than the case using vertical motion of the swing legs, and the dynamic effect is small.

These results suggest that the attitude stabilization performance might be the highest by combining the vertical motion of the swing legs and translation of the body. **Fig.11** shows the experimental result when these two methods are simply superimposed. In comparison with **Fig.11**, **Fig.7** and **Fig.9(b)**, both convergence performance and stability are improved.

# 4 Dynamically stable walking experiment with TITAN-VIII

The dynamic trot gait control method, which employs feedforward control using the 3D sway compensation trajectory and feedback control using vertical motion

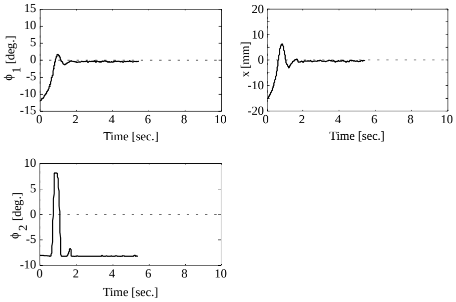
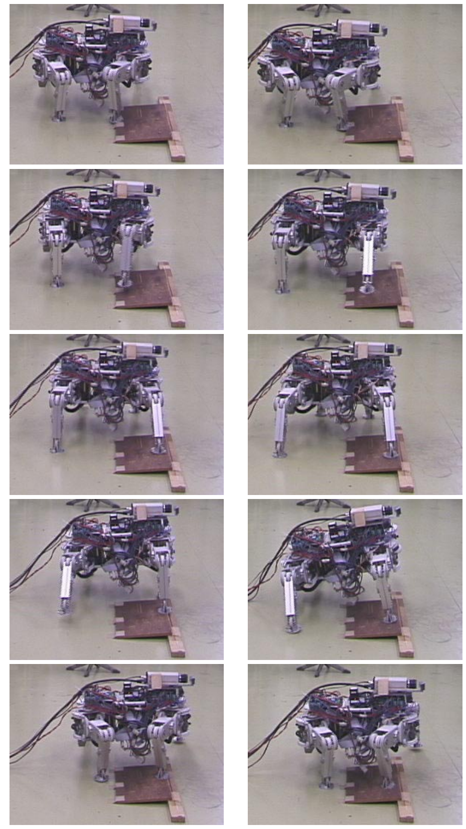



Figure 11: Experimental result (Combination of translation of body and vertical motion of swing legs)

of the swing legs and translation of body, was applied to TITAN-VIII, and the walking experiment on rough terrain was carried out.

In the experiment, TITAN-VIII walked with the dynamically stable trot gait in an environment where an unknown and leaning step exists, and the attitude stabilization performance was examined. **Fig.12** is a series of photos of the experiment, and **Fig.13** shows the inclination angle of the support leg around the diagonal line between the support legs. In this experiment, the duty factor is 0.5, the walking cycle is 10[s], and the walking velocity is 0.02 [m/s]. The photos on the left in **Fig.12** show the results using the 3D sway compensation trajectory and the proposed attitude stabilization control. The photos on the right show the results using the 3D sway compensation trajectory only. **Fig.14** shows the return path of the swing legs. The horizontal axis is the walking direction, and the vertical axis is the vertical direction. By using swing leg control only in the region where the height of the swing leg from the ground is larger than a specific height (5 [cm]), the body vibration caused by the contact of the swing leg to the ground is prevented.

From **Fig.13**, dynamically stable walking with small attitude fluctuation can be performed by the 3D sway compensation trajectory on a flat surface in $0 \sim 12$[s]. In 12$\sim$25[s], one of the right legs runs on the step. For the case without attitude control, the body gradually inclined and the swing leg contacted the ground unexpectedly as shown in the fourth photo of the right column in **Fig.12**. However, for the case with the proposed attitude stabilization control, maximum inclination of the body was about 8 degrees. As shown in **Fig.11**, if the inclination of the body is smaller than about 10 degrees, the body attitude can be recovered by the proposed attitude control method. Thus, dynamically stable walking was realized even in an en-



(a) attitude control (b) no sensor

Figure 12: Dynamically stable walking experiment on rough terrain

vironment where an unknown and leaning step exists, and the effectiveness of the proposed attitude stabilization control was confirmed.

# 5 Conclusion

In this paper, the 3D sway compensation trajectory, an expansion of the conventional sway compensation trajectory toward longitudinal and vertical motion, is proposed. The 3D sway compensation trajectory enables keeping ZMP on the diagonal line of the support legs more efficiently with less energy consumption.

Next, four adaptive attitude control methods using the body position and swing leg motion control are proposed, and the damping performance of each method was compared through computer simulation and damping control experiments with TITAN-VIII.

Furthermore, the feedforward and feedback dynamic trot gait control system that combines the 3D sway compensation trajectory and the adaptive body position and swing leg motion control is developed and the walking experiment on rough terrain using TITAN-

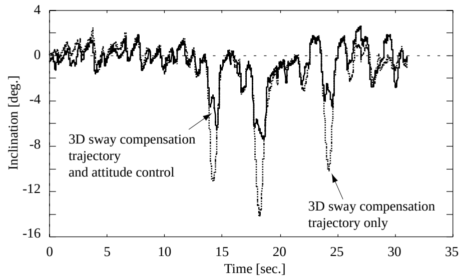



Figure 13: Body inclination of robot walking dynamically on rough terrain

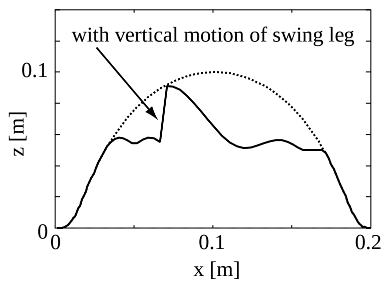



Figure 14: Recovering path of swing leg

VIII is carried out. Results of the experiment showed that this control methodology was very effective for practical use and could make dynamically stable walking of walking vehicle possible on rough terrain.

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