Gravity Compensation on Humanoid Robot Control with Robust Joint Servo and Non-integrated Rate-gyroscope

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***Abstract*— While gravity plays a significant role in legged motion controls, it also affects robot's each joint and prevents the decoupling of the upper layer controller of macro states such as COG from the lower layer joint controllers. This paper proposes two techniques to compensate for the effect of gravity in the joint controllers. Firstly, a robust joint servo system with two-degree-of-freedom control cascaded to PD control is presented. It robustly compensates stationary error which is mainly due to gravity. The minor loop featuring strongly stable PD feedback is regarded as a new plant of the major two-degree-of-freedom control loop and facilitates the nominal model identification. Secondly, the transient response of the trunk attitude is improved by a non-integrated type of feedback of rate-gyroscope outputs. Since it feeds back the output signal without estimating the trunk attitude explicitly, it doesn't suffer from amplified error due to drift and noise in the course of numerical integration of signals. Both are even applicable to systems with less adjustable control parameters, such as embedded PD controllers.**

***Index Terms*— humanoid robot, gravity compensation, two-degree-of-freedom control, trunk attitude stabilization, rate-gyroscope sensor**

I. Introduction

The existence of gravity is the essence of the dynamics of legged systems. By being pressed onto the ground by gravity and actuated by the reaction force, legged motions are generated. Particularly, the dynamical property that the center of gravity (COG), where the gravity force acts, is above the zero-moment point (ZMP)[1], where the reaction force acts, is often modeled as the inverted pendulum. It has been widely utilized for motion planning [2] [3] [4] [5] and control [6] [7] [8] [9] [10] [11] to represent macro dynamics of the system.

On the other side, the control architecture of humanoid robots necessarily forms a hierarchical style which allocates the controller of macro states such as COG in the upper layer and that of each actuator in the lower layer, since they are kinetically highly complex systems. It is desired that gravity is handled in the upper layer and that the lower layer deals only with joint dynamics decoupled. The gravity, however, affects each robot articulo, and is a hurdle for a clearly hierarchized system design. The computed torque method proposed by Lue et al. [12] strictly deals with dynamical properties of robots and compensates nonlinear bias forces, and its use on a humanoid controller was discussed[10]. However, it relies on dynamical parameters of robots identified in advance and is sensitive to the effect of model errors and external forces, so that it has less efficacy when compared against its computational cost. The aim of this paper is to propose two techniques to compensate the effect of gravity at the level of joint controls. Both concern a simple modification of the referential joint angles to PD controllers, so that they are even applicable to systems with less adjustable control parameters with embedded PD controllers.

Firstly, a robust joint servo system with cascaded two-degree-of-freedom control and PD control is presented. Some joint control methods applying two-degree-of-freedom control, sliding-mode control and so forth [13][14][15] have been proposed and implemented robust systems with less computational cost. Since it is not trivial to synthesize nominal models of joints in cases of complicated dynamical systems such as humanoids, the minor loop featuring a strongly stable PD feedback is regarded as a new plant of the major two-degree-of-freedom control loop and facilitates the nominal model identification.

Secondly, a transient response of trunk attitude is improved by a non-integrated type of feedback of rate-gyroscope signals. Since humanoid robots are not fixed in the inertia frame, not only the measurement of internal coordinates such as joint angles but also that of states with respect to the inertia frame is crucial. Gyroscope sensors are frequently used for trunk attitude stabilization. Many conventional approaches assume that the absolute attitude angles can be obtained [16][17][18]. An attitude angle estimation from rate-gyroscope signals [19] [20], however, commonly suffers from estimation errors due to drift and noise amplified in the course of numerical integration, and causes serious problems, particularly in humanoid motions in which motion velocity varies in a short term. To set the robot attitude accurately upright for the initial calibration is also difficult. The method proposed in this paper does not explicitly estimate the trunk attitude angles by numerical integration but directly utilizes rate-gyroscope sensations in order to improve the transient response, so that it avoids the above problems.

II. Robust Joint Servo System with Cascaded 2DOF Control/PD Control

A. Controller design

In this section, a cascade controller design method of a robust joint servo system with a minor loop consisting of a

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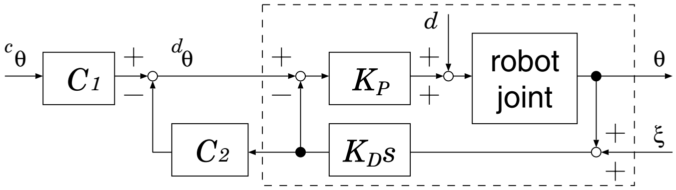


Fig. 1. Robust joint servo system proposed

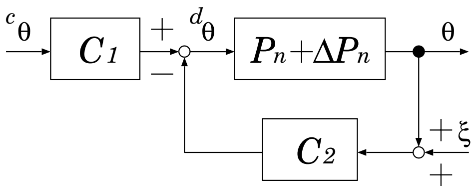


Fig. 2. Equivalent two-degree-of-freedom control system

PD controller and a major loop consisting of a two-degree-of-freedom controller is presented. It easily suppresses low-frequency disturbances including coulomb friction and model error along with gravity, which is a requirement for an improvement of the accuracy of dynamic manipulator control.

Fig.1 is a block diagram of the proposed joint control system. In the picture, the minor PD control loop is surrounded by dotted lines. The PD compensator outputs a joint torque τ in accordance with the following rule:

$$\tau = K_P({}^d\theta - \theta) - K_D\dot{\theta} \tag{1}$$

where K_P is the proportional gain, K_D is the differential gain, θ is the current joint angle, ${}^c\theta$ is the commanded joint angle, ${}^d\theta$ is the direct referential joint angle to the PD controller, d is the disturbance and ξ is the observation noise. Although a robot in general consists of a number of joints and its dynamics as the whole becomes complicated, the following second-order lag system gives a fair approximation of the dynamics of the minor loop thanks to strongly stable PD controllers assigned at each joint.

$$P_n = \frac{1}{T_P^2 s^2 + 2\zeta T_P s + 1} \tag{2}$$

where T_P is the time constant of the system, and ζ is the damping ratio. Regarding it as a new plant of the major loop, one can consider a system represented by a block diagram **Fig.2** which is equivalent to **Fig.1** where ΔP_n is the deviation of the plant including both model error and low-frequency disturbances. Input-output relationship is represented as follows.

$$\theta = G{}^c\theta + H\xi \tag{3}$$

where

$$G \equiv \frac{P_n C_1}{1 + P_n C_2} \qquad \text{(response to reference)} \tag{4}$$

$$H \equiv -\frac{P_n C_2}{1 + P_n C_2} \qquad \text{(response to noise)} \tag{5}$$

And, the sensitivity function against the plant deviation is:

$$S \equiv \frac{\partial G}{\partial P_n} \Big/ \frac{G}{P_n} = \frac{1}{1 + P_n C_2}. \tag{6}$$

Using P_n, G and S, C_1 and C_2 are represented as follows.

$$C_1 = \frac{1}{S} \cdot \frac{G}{P_n} \tag{7}$$

$$C_2 = \frac{1 - S}{S} \cdot \frac{1}{P_n} \tag{8}$$

The necessary conditions for the system being robust and stable are that G is stable, S has high-pass characteristics, SP_n has low-pass characteristics, and both C_1 and C_2 are proper. Here, we adopt the following transfer function as S which satisfies all of the above conditions.

$$S = 1 - \frac{1}{(T_L s + 1)^2} \tag{9}$$

where T_L is the time constant. Let the purpose of control be to realize the response of sufficiently stable P_n, namely, $G = P_n$, and to compensate the stationary error due to disturbances. C_1 and C_2 are obtained as follows.

$$C_1 = \frac{(T_L s + 1)^2}{T_L^2 s^2 + 2T_L s} \tag{10}$$

$$C_2 = \frac{T_P^2 s^2 + 2\zeta T_P s + 1}{T_L^2 s^2 + 2T_L s} \tag{11}$$

Quantizing the above with zero-order hold and the sampling time Δt, we get the following recurrence representation of an infinite impulse filter.

$$\begin{aligned} {}^d\theta[k] &= {}^c\theta[k] + 2\lambda({}^d\theta[k-1] - {}^c\theta[k-1]) \\ &\quad + (2\tau_L - 1){}^d\theta[k-2] + \lambda^{2c}\theta[k-2] \\ &\quad - \tau_P^2\theta[k] + 2\tau_P(\tau_P - \zeta\tau_L)\theta[k-1] \\ &\quad - (\tau_P^2 - 2\zeta\tau_P\tau_L + \tau_L^2)\theta[k-2] \end{aligned} \tag{12}$$

where

$$\tau_L \equiv \frac{\Delta t}{T_L}, \quad \lambda \equiv 1 - \tau_L, \quad \tau_P \equiv \frac{T_P}{T_L}$$

Note that this is only a simple modification of the referential value to the minor loop, so that it is applicable to systems with embedded PD controllers where only gains are adjustable.

B. Nominal model identification

The strongly stable minor loop, which is regarded as a plant of the major loop, facilitates nominal model identification. This section shows how to identify model parameters in Eq.(2) from the logged data of step responses of the actual robot joints, applying only a PD controller. If $\zeta < 1.0$, the ideal curve of response is represented from the initial value θ_0, the terminal value θ_∞, the peak value θ_P and the time to peak T by the following function.

$$\begin{aligned} &\theta(t) = \theta_0 + (\theta_\infty - \theta_0) \\ &\left\{ 1 - \frac{e^{-\zeta\frac{t}{T}}}{\sqrt{1-\zeta^2}} \cos\left(\frac{\sqrt{1-\zeta^2}t}{T} - \tan^{-1}\frac{\zeta}{\sqrt{1-\zeta^2}} \right) \right\} \end{aligned} \tag{13}$$

From measured values of the above parameters, ${}^m\theta_0$, ${}^m\theta_\infty$, ${}^m\theta_P$ and ${}^mT$, the initial approximation values of ζ and T_p are obtained as follows.

$$\zeta \simeq \frac{\gamma^2}{\gamma^2 + \pi^2} \tag{14}$$

$$T_p \simeq \frac{\sqrt{1-\zeta^2}\,{}^mT}{\pi} \tag{15}$$

where

$$\gamma \equiv \ln\left(\frac{{}^m\theta_P - {}^m\theta_\infty}{{}^m\theta_\infty - {}^m\theta_0}\right) \tag{16}$$

Using this initialization and the logged data, nominal models of joints are identified by a nonlinear least-square method. If the system has no peak, i.e. $\zeta > 1.0$, only T is identified with the following approximation function.

$$\theta(t) = \theta_0 + (\theta_\infty - \theta_0)(1 - e^{-\frac{t}{T}} - \frac{t}{T}e^{-\frac{t}{T}}) \tag{17}$$

C. Simulations and experiments

The performance of the proposed method was examined through simulations and an experiment on a humanoid robot UT-μ2 [21]. The body specification of the robot is shown in **Fig.11**.

Firstly, nominal models of all the joints of UT-μ2 were identified. Step responses with a 5° command angle for each joint were sampled with the other joints servo-controlled in an upright posture. We applied the simplex method for the nonlinear least square problem. **Fig.3**(a) shows all the sampled values of step response of the left shoulder abduction-adduction joint, and the initial and the optimized approximating curve, where all the values are normalized by the initial value and the terminal value. **Fig.3**(b) the result for the left knee rotation joint, plotting all sampled values normalized by the initial value and the terminal value, the initial and the optimized approximating curve. In this case, Eq.(17) was adopted as the ideal curve function.

Next, the proposed controllers were implemented in accordance with the identified joint models, and their response were examined through simulations. **Fig.4** is the result on the left shoulder abduction-adduction joint, where sampling time is 0.003[s], $T_p \simeq 0.03$, $\zeta \simeq 0.8$ and $T_L = 0.05$. In these simulations, random values within -0.01∼0.01 were added to the output to emulate observation noise. The following was also added as a model of disturbance:

$$d = -0.1 - 0.01\mathrm{sgn}(\dot{\theta}) - 0.2\theta \tag{18}$$

where the first, second and third terms correspond with a constant external force, kinematic coulomb friction force and gravity force, respectively. Those coefficients are larger than are estimated in the usual case. As the figure shows, the above quasi disturbance caused almost 30% stationary error without the proposed method, and was robustly compensated with the proposed method.

Fig.5 is the result of a step response to a 5° command angle on the left shoulder abduction-adduction joint which the proposed controller was applied to. One can see that the stationary error about 0.5° was compensated as well in the simulation. However, a large overshoot, which did not appear in the simulation, and delayed convergence deriving from the side-effect of the overshoot arose. They are thought to be due to wind-up phenomenon since the proposed compensator equivalently contains an integrator. In order to improve them, an anti-reset wind-up compensator should be implemented.

III. Trunk Attitude Stabilization with Feedback of Non-integrated Rate-Gyro Sensor Signal

A. Controller design

This section describes a non-integrated type of feedback control of rate-gyroscope sensor signals, which improves the transient response of trunk attitude. For simplicity, let us consider the motion of a humanoid robot particularly in the sagittal plane. Suppose the robot is standing on its supporting foot with its sole contacting the ground as in **Fig.6**(a). ϕ in the figure is the reclining angle of the upper body with respect to the vertical axis, which equals the sum of joint angles of the supporting leg.

$$\phi = \sum_{i\in\mathcal{L}} \theta_i \tag{19}$$

where $\mathcal{L}$ is the set of joint indices of the supporting leg. Here, the positive directions of ϕ and θ_i are assumed to be the same. θ_0 is the hip joint angle of the supporting leg. Approximating by a simple model where one rigid body rotates about the hip joint of the supporting leg as **Fig.6**(b) illustrates, the equation of motion of the upper body is represented as follows.

$$J\ddot{\phi} = mgr\phi + \tau_0 \tag{20}$$

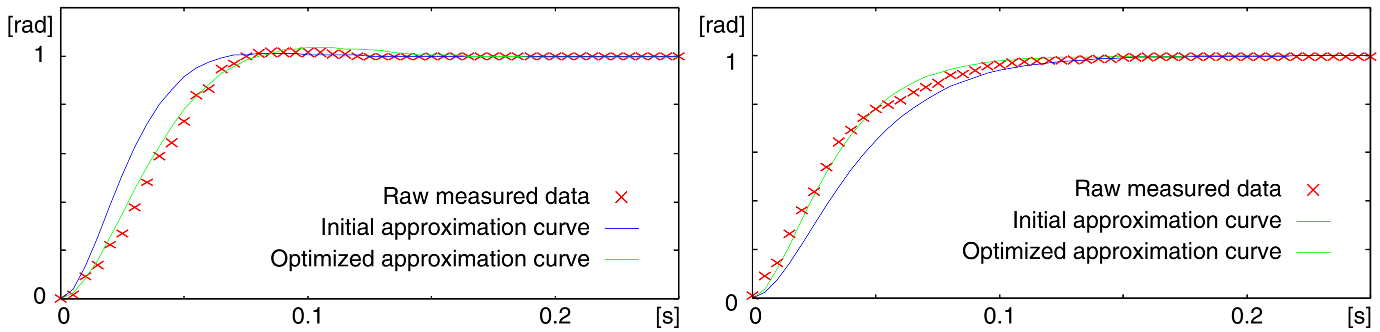
where m is the mass of the upper body, J is the inertia moment of the upper body around the hip joint, r is the distance between the center of rotation of the hip joint and the center of mass of the upper body, τ_0 is the hip joint torque and g is the acceleration of gravity. Suppose τ_0 is decided in accordance with the following PD compensator for a referential hip joint angle ${}^d\theta_0$ as well as Eq.(1).

$$\tau_0 = K_P({}^d\theta_0 - \theta_0) - K_D\dot{\theta}_0 \tag{21}$$

If ${}^d\theta_i$ is the same as the commanded value of θ_i, ${}^c\theta_i$, the transfer function from ${}^c\phi \left(= \sum_{i\in\mathcal{L}} {}^c\theta_i\right)$ to ϕ is:

$$\frac{\phi}{{}^c\phi} = \frac{K_P}{Js^2 + K_Ds + K_P - mgr} \tag{22}$$

where we assumed ${}^c\phi - \phi \simeq {}^c\theta_0 - \theta_0$ and $\dot{\phi} \simeq \dot{\theta}_0$. As is shown in the following subsection, a transient response of the system (22) induces large overshoot. In cases of humanoid robots, the restitution force to compensate attitude errors is limited depending on the supporting condition due to the lack of mechanical connectivity with the environment. Consequently, it is required both to give sufficiently quick responsiveness and to suppress overshoots, which is difficult to achieve with only a PD compensator. The proposed controller decides the



(a) left shoulder abduction-adduction ($\zeta < 1.0$) (b) left knee rotation ($\zeta = 1.0$)

Fig. 3. Nominal model identification from step response

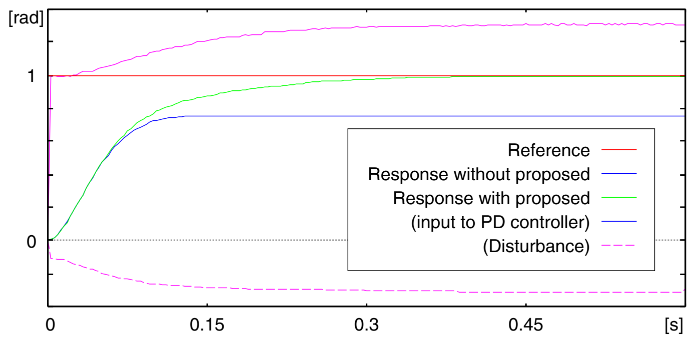


Fig. 4. Step response of proposed system in simulation

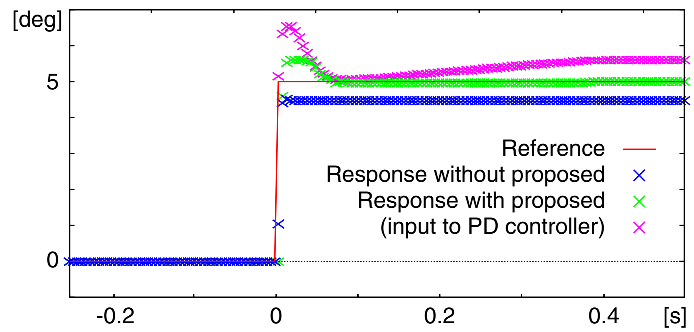


Fig. 5. Step response of proposed system on actual robot

referential hip joint angle ${}^d\theta_0$ from its commanded value ${}^c\theta_0$ and the output of rate-gyroscope sensor $\dot{\phi}$ as follows.

$$ {}^d\dot{\theta}_0 = {}^c\dot{\theta}_0 + P({}^c\theta_0 - {}^d\theta_0) - D\dot{\phi} \tag{23} $$

where P and D are constant values. For the other joint angles (typically, knee and ankle joints), the commanded ${}^c\theta_i$ are directly applied to ${}^d\theta_i$ (i.e. ${}^d\theta_i = {}^c\theta_i$). From Eq.(20)(21)(23) and their Laplace transform, we get:

$$ \frac{\phi}{{}^c\phi} = \frac{K_P(s+P)}{Js^3 + (JP + K_D)s^2 + As + (K_P - mgr)P} \tag{24} $$

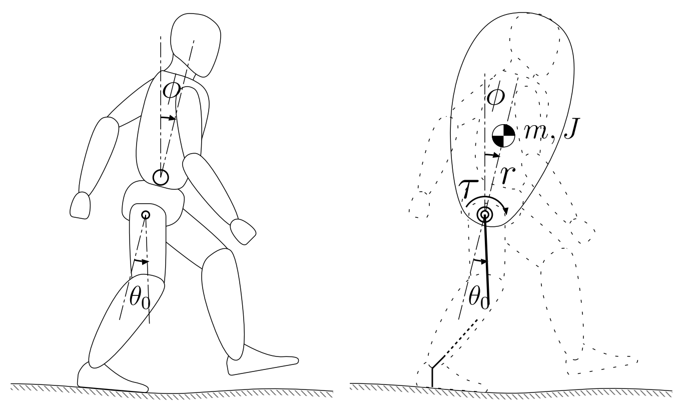
where

$$ A \equiv K_D P + K_P(D+1) - mgr. \tag{25} $$

Since it is a third-order lag system, it is potentially able to reduce the overshoot in a certain duration in the transient phase. Similar to the joint servo controller in the previous section, it is easy to apply to systems with an embedded PD controllers. In the next subsection, we verify the effect of this method through numerical simulations.

B. Numerical simulations

Here, we consider the application of the proposed method to the humanoid robot UT-μ2, and set each parameter for $m = 4.0$, $r = 0.1$, $J = 0.04$, $K_P = 70.0$, $K_D = 2.0$, $P = 0.2$ and $D = 0.1$. **Fig.7** shows bode diagrams of the transfer function (22) and (24) within 0.1∼10[rad/s], which is thought to be the actual working range in the frequency domain. One can see that the gain is reduced to less than 0[dB] almost without affecting the phase characteristics. **Fig.8** is a simulation result of a step response to ${}^c\phi = 1$, in which the overshoot is reduced almost by half and the error from the reference is almost zero until 2[s]. In turn, **Fig.9**, which is a result of the same simulation but the logged time is 20[s], shows that both methods induce the same amount of stationary error. Actually, it is proved that both converge to $K_P/(K_P - mgr)$ at $t = \infty$ from final-value theorem. Consequently, the proposed method cannot improve the steady-state characteristics but only the transient characteristics. It is necessary to combine it with a long term compensation of gravity introduced in the previous section.



(a) Humanoid model (b) Approximated model

Fig. 6. Humanoid trunk dynamics model

Fig.10 is a result of a sine wave response with ${}^c\phi = \sin 2\pi t$. Though the phase-lag is almost the same as the case without

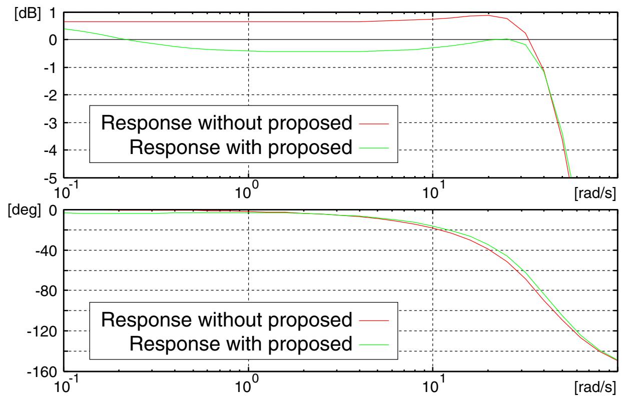


Fig. 7. Bode diagram of $\phi/{}^c\phi$

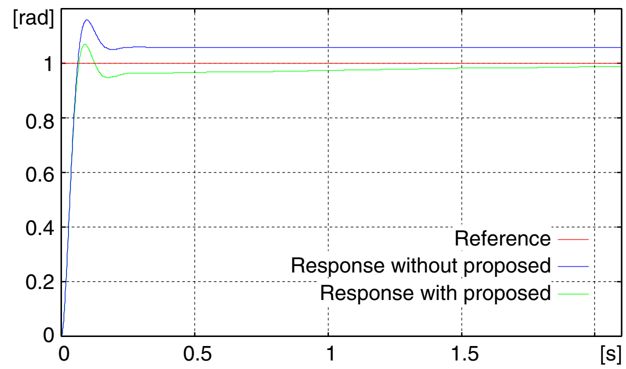


Fig. 8. Indicial response of ϕ

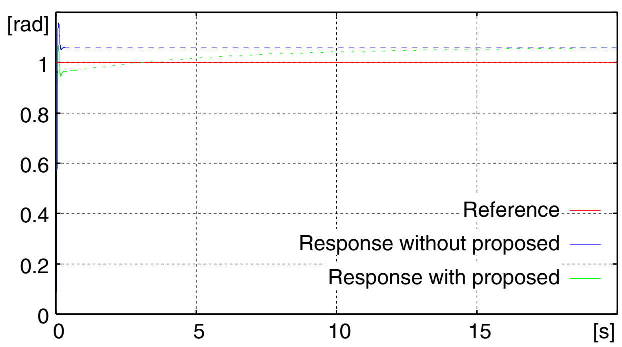


Fig. 9. Indicial response of ϕ (in longer scope)

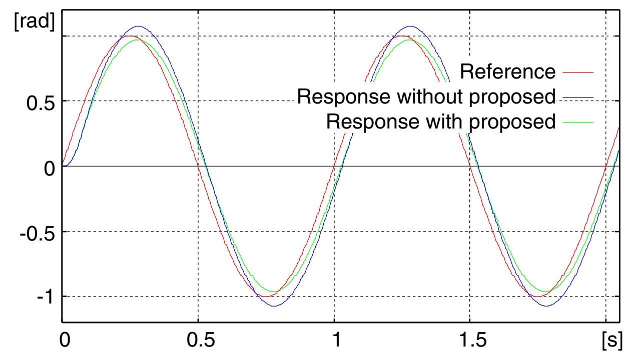
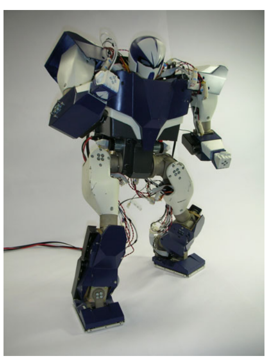


Fig. 10. Sine wave response of ϕ



Name:	UT-μ2
Number of joints:	20
	8 for arms,
	12 for legs
height:	580 [mm]
weight:	7.5 [kg]

Fig. 11. Outer view of UT-μ2 and its body specifications

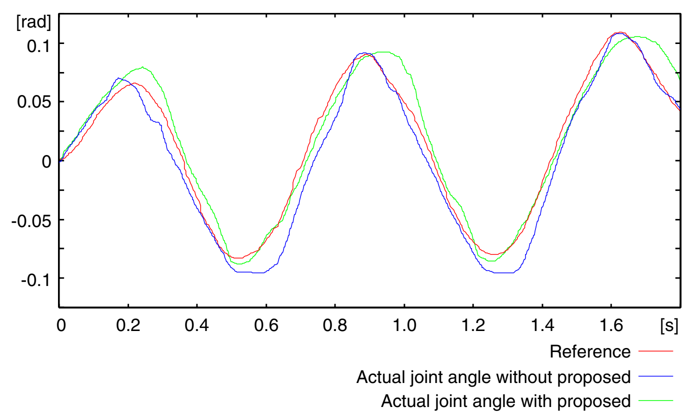


Fig. 14. Left hip abduction-adduction joint angle loci of the walk

gyroscope feedback, it sufficiently suppresses the overshoot and does not induce large swaying movement.

C. Walking experiment on UT-μ2

The efficacy of the proposed method was verified through experiments using UT-μ2. An outer view and body specifications of the robot is shown in **Fig.11**. The robot is equipped with three rate-gyroscopic sensors CRS03 (Silicon Sensing Systems Japan Ltd.). We examined 8×0.35[cm·s/step]$\times6$ steps of walking motion by the robot. **Fig.12** displays snapshots of a walking motion without the proposed controls. In this experiment, the robot was unable to keep walking more than three steps, failing to compensate disturbances. **Fig.13** shows the result with the proposed method, in which the robot succeeded to complete the walk. **Fig.14** presents left hip abduction-adduction joint angle loci in the experiments. Positive side of the vertical axis means the leftward inclination. By comparing the referential trajectory and the result locus without the rate-gyroscope feedback, one can estimate the robot was inclining rightward probably because of the initial configuration error from overall drift of the locus and the overshoots particularly around 0.5$\sim$0.6[s] and 1.2$\sim$1.4[s]. On the other hand, the locus with the feedback shows better tracking capability.

IV. Conclusion

Two techniques to absorb the effect of gravity at the level of the joint controller, namely, a robust joint servo system

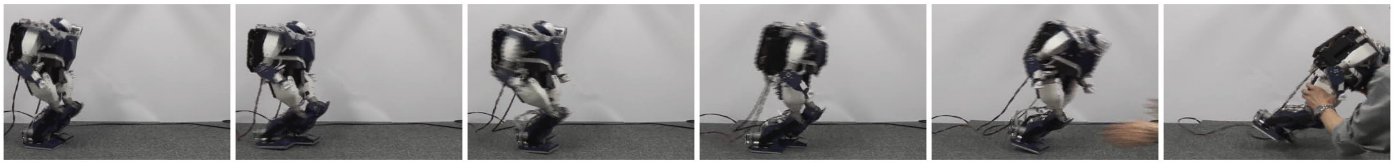


Fig. 12. failure of 0.35[s/step] walk by UT-μ without the proposed feedback control

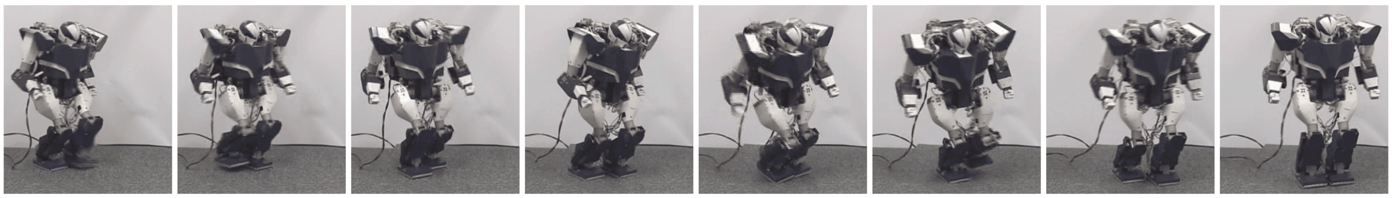


Fig. 13. success of 0.35[s/step] walk by UT-μ with the proposed feedback control

with two-degree-of-freedom control cascaded to PD control, and a non-integrated type of feedback of rate-gyroscope outputs, were presented. The former facilitates nominal model identification on dynamically complicated systems such as humanoid robots, and robustly compensates the stationary error due to low-frequency disturbances. The latter improves the transient response characteristics of the trunk attitude without amplifying the error since it doesn't estimate the trunk attitude angles explicitly. Both can be used on systems with embedded PD controllers, requiring only modifications of referential joint angles to PD controllers.

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