Semi-passive Biped Robot using Motion Control Combining Energy and PD Controls

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***Abstract*—This paper presents the method to control the motions of semi-passive walking by a biped robot. A passive walking robot can walk on the sloped ground without an actuator by using the potential energy. However, the robot without an actuator cannot walk on the horizontal ground. Therefore, two motors were installed on the hip of the passive-walking robot in order to load the torque for walking on the horizontal ground. A control law combining proportional – differential and energy ones was applied for a continuous walking motion. Computer simulations with its dynamic model were carried out to confirm the validity of the proposed control law and find out the optimal conditions for the walking motion. Based on the calculated results, the experiments have been performed to find the appropriate control gains for the continuous walking on the horizontal ground.**

***Index Terms*—Biped walking robot, Passive walking, Motion control, PD control, Energy control.**

I. INTRODUCTION

Recent biped robots have advanced performance in walking. However, their energy efficiency in walking motion are not good in comparison with human beings [1]. Therefore, the walking efficiency has been considered as an important issue for innovation of humanoid robots. Then, the passive walking robots have been investigated to solve this problem [2]-[6]. The passive walking robots can walk on the sloped ground by using the potential energy. However, they can't walk on the horizontal ground because they have no energy source to move its legs.

The present research aims to develop the passive-walking biped robot that can walk on the horizontal ground. Therefore, two motors are installed on the hip of the biped robot in order to load the control torques for walking motion. In our previous researches, the computer simulations with dynamic model were carried out to investigate the walking capability of the biped robot [7]-[8]. The experimental biped robot was developed and examined. It was confirmed that the biped robot can walk on the horizontal ground by PD (proportional- differential) control [9].

In this paper, the control law combining energy and PD ones was proposed for walking of the semi-passive walking robot. In the proposed control law, the PD control is used for holding the desired angle of the torso. The energy control is also used for swinging the leg forward. The validity of the proposed control law was investigated through computer simulations and experiments.

II. COMPUTER SIMULATION

The computer simulations with the dynamic model of the biped robot with a torso were performed [8].

A. Analysis Model

Figure 1 shows the analysis model of the walking robot. The robot consists of a torso, a hip and two legs with feet. By alternating the state of both legs between stance and swing, the robot can walk successively. For generating torque for walking motion, two motors are installed at the hip joints. Where τ_1 and τ_2 denote the control torque between the stance-leg and the torso, and the torque the swing-leg and the torso, respectively.

B. Equation of Motion

The motion equation of the robot is given by

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \left[\boldsymbol{C}_c(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \boldsymbol{C}_d\right]\dot{\boldsymbol{\theta}} + \boldsymbol{g}(\boldsymbol{\theta}) = \boldsymbol{B}\boldsymbol{\tau} \tag{1}$$

where, $\boldsymbol{\theta} = \{\theta_1 \quad \theta_2 \quad \theta_3\}^T$, $\boldsymbol{\tau} = \{\tau_1 \quad \tau_2\}$, $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{C}_c$ is a Coriolis and centrifugal force matrix, $\boldsymbol{C}_d$ is a viscosity damping matrix, $\boldsymbol{B}$ is a coefficient matrix about control torque, and $\boldsymbol{g}$ is the gravity vector, respectively.

C. Exchange between Stance Leg and Swing Leg

The condition of the touchdown of the swing-leg is given by

$$\theta_1 + \theta_2 = \pi / 2 . \tag{2}$$

The contact between the swing-leg and the ground when the swing-leg passes through the stance-leg was ignored. Then the impact at the touchdown was assumed to be inelastic. It was also assumed that the stance-leg leaves from the ground at the moment of touchdown.

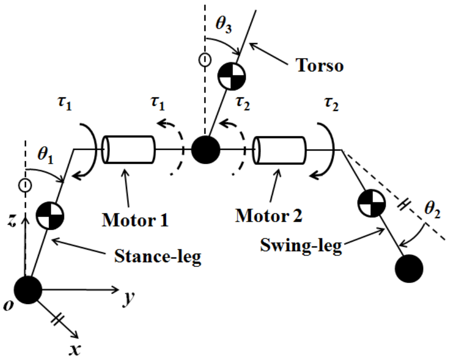

Fig.1 Analysis model of the walking robot with motors

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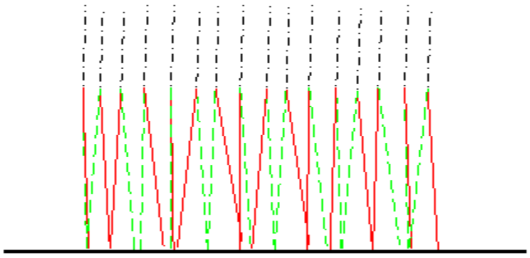


$k_3^p = 0.337[\mathrm{N \cdot m/rad}]$, $k_3^d = 4.911[\mathrm{N \cdot m \cdot s/rad}]$,
$\theta_{3d} = 5[\mathrm{deg}]$, $k^e = 7.658[\mathrm{N \cdot m \cdot s/(rad \cdot J)}]$, $E_0 = 1.44[\mathrm{J}]$

Fig.2 Example when the robot could continuously walk by the proposed control method

The angular velocity of the joints after touchdown is computed as follows. The angular momentum is conserved before and after touchdown for the whole robot about the leading contact point, the trailing leg about the hip and the torso about the hip. Equation (3) is given by these conservation laws of angular momentum:

$$\boldsymbol{Q}^+(\boldsymbol{\theta}^+)\dot{\boldsymbol{\theta}}^+ = \boldsymbol{Q}^-(\boldsymbol{\theta}^-)\dot{\boldsymbol{\theta}}^- . \tag{3}$$

The superscripts “-” and “+” denote the state before and after touchdown, respectively. The relation of the angles before and after touchdown is given by

$$\boldsymbol{\theta}^+ = \boldsymbol{R}\boldsymbol{\theta}^- + \boldsymbol{\theta}_0 , \quad \text{a} \tag{4}$$

where

$$\boldsymbol{R} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{5}$$

$$\boldsymbol{\theta}_0 = \{-\pi/2 \quad \pi/2 \quad 0\}^T , \tag{6}$$

Resultantly, the angular velocity of all joints after touchdown is calculated by

$$\dot{\boldsymbol{\theta}}^+ = \boldsymbol{Q}^+(\boldsymbol{\theta}^+)^{-1}\boldsymbol{Q}^-(\boldsymbol{\theta}^-)\dot{\boldsymbol{\theta}}^- . \tag{7}$$

D. Motion Control

The control law combining PD (proportional– differential) and energy ones has been employed for the walking motion. The PD control is used for holding the desired angle of the torso. The energy control is also used for swinging the leg forward. In the case of this control law, the control torques τ_1 and τ_2 are given by Eq. (8) and (9).

$$-\tau_1 - \tau_2 = -k_3^p(\theta_3 - \theta_{3d}) - k_3^d\dot{\theta}_3 \tag{8}$$

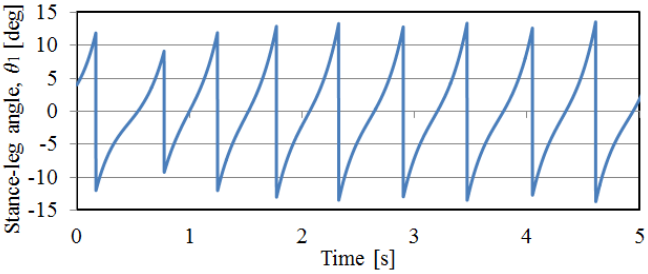
$$\tau_2 = -k^e(\dot{\theta}_2 - \dot{\theta}_1)(E - E_0) \tag{9}$$

The k_3^p, k_3^d, and k^e denote the proportional, differential, and energy control gains, respectively. The E denotes the sum of kinematic and potential energies of the analysis model. The E_0 denotes the desired energy. The control torque τ_1 is given by

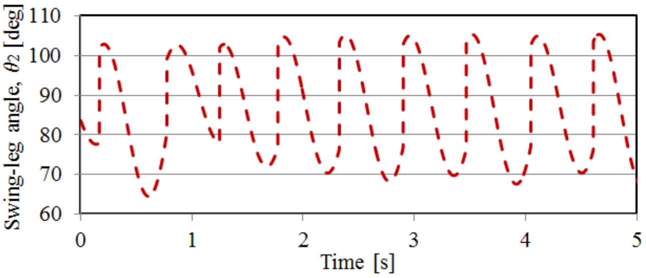
$$\tau_1 = k_3^p(\theta_3 - \theta_{3d}) + k_3^d\dot{\theta}_3 + k^e(\dot{\theta}_2 - \dot{\theta}_1)(E - E_0) \tag{10}$$

E. Result of Computer Simulation

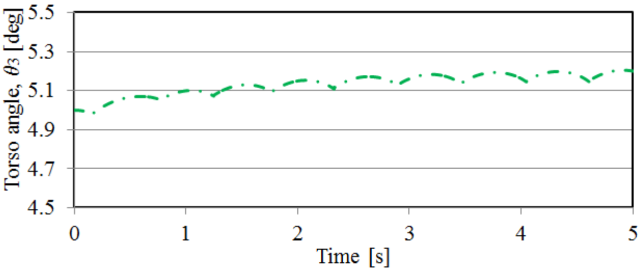
The robot could continuously walk holding the desired angle of the torso by the proposed control law. The appropriate control gains were found out through trial and error. An example of the calculated results is shown in Fig. 2. The time histories of the stance-leg angle θ_1, the swing-leg angle θ_2, and the torso angle θ_3 are shown in Fig.3.



(a) Stance-leg angle θ_1



(b) Swing-leg angle θ_2



(c) Torso angle θ_3

$k_3^p = 0.337[\mathrm{N \cdot m/rad}]$, $k_3^d = 4.911[\mathrm{N \cdot m \cdot s/rad}]$,
$\theta_{3d} = 5[\mathrm{deg}]$, $k^e = 7.658[\mathrm{N \cdot m \cdot s/(rad \cdot J)}]$, $E_0 = 1.44[\mathrm{J}]$

Fig.3 Time histories of the angles when the robot could continuously walk

F. Composition of the Experimental Robot

Figure 4 shows the developed experimental robot system. The lengths of legs and torso are 310 [mm] and 140 [mm], respectively. The each leg consists of two parallel links in order to constrain the walking motion in the x-z plane. Therefore, the inside leg is connected with an additional frame. The outside leg is also connected with an additional one. The total mass of whole system is 0.743 [kg]. The control torques are generated by the motors installed at the portions of inside and outside hip joints. The encoders are attached at the axes of motors to measure the angles of both inside and outside hip joints.

Figure 5 shows the photographs of controllers, attitude sensor, and wireless signal-communication module. Two micro controllers are installed for motion control and computation of sensors’ data. The attitude sensor (HiBot Co.) is attached on the torso to measure the attitude angle of torso. The wireless signal-communication module, namely ZigBee module (Maxstream Co.) is also attached on the torso to communicate with the personal computer outside the robot system.

Figure 6 shows the touch sensor attached on the foot. Touch sensors are attached on both inside and outside feet to detect the contact between the foot and the ground. Then, the battery is equipped in the space of the torso to supply electric power for the main controller and the two motors.

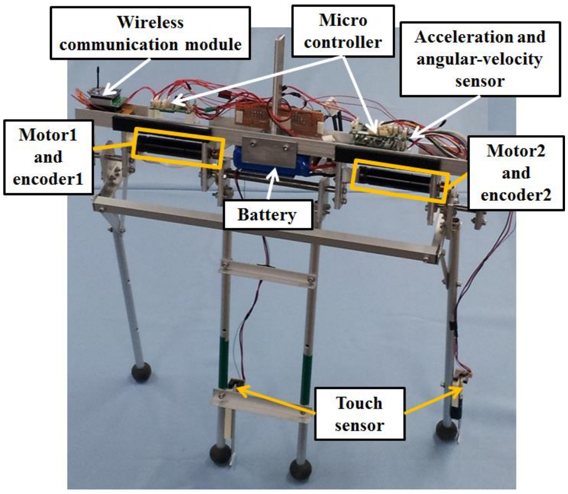
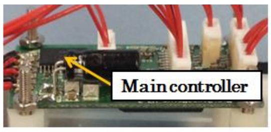
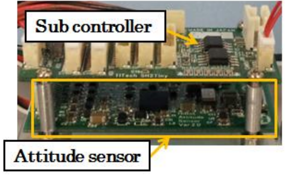


Fig.4 Experimental robot system



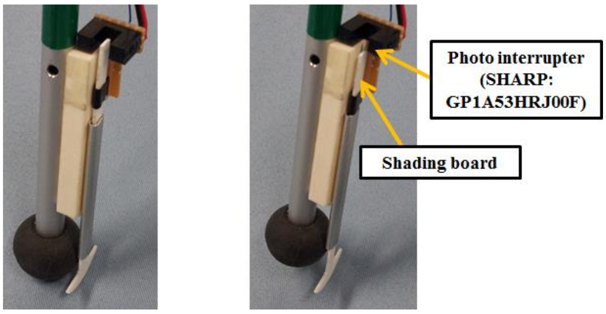
(a) Main controller



(b) Sub controller and attitude sensor

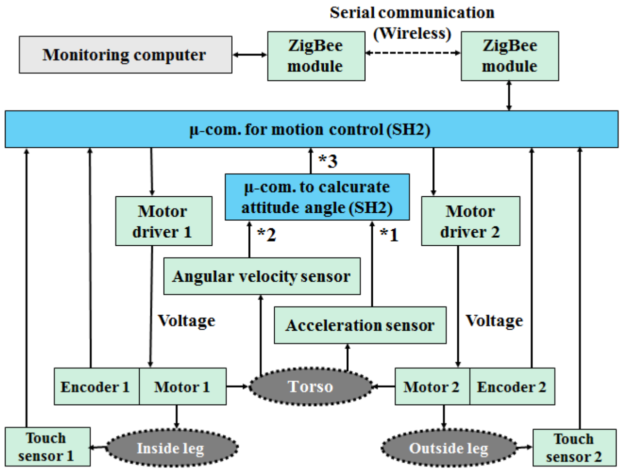
(c) Wireless signal-communication module

Fig.5 Compositions of the controllers, attitude sensor, and wireless signal-communication module



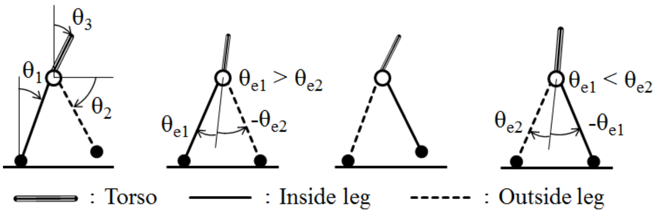
(a) The foot touches the ground (b) The foot leaves from the ground

Fig.6 Touch sensor attached on the foot



***1 : Accelerations (*x*'-, *y*'- and *z*'-directions)**
***2 : Angular velocities (about *x*'- and *y*'-axes)**
***3 : Attitude angle θ_3 of torso (CAN comunication)**

Fig.7 System configuration of the experimental robot



(1) Inside leg is stance-leg (2) Both legs are stance-leg (3) Outside leg is stance-leg (4) Both legs are stance-leg

Fig.8 States of the experimental robot

G. *System Configuration*

Figure 7 shows the configuration of the experimental robot system. The robot has two embedded controllers. The main controller is for the motor control and others. Then, the sub controller is for the attitude sensor. The two controllers are connected by the CAN communication channel with each other. Besides, the data of leg angles, torso angle and touch sensors are transferred from the main controller to the personal computer outside the robot system through the serial communication channel.

States of the robot are recognized by two touch sensors. The angle of the torso θ_3 is determined by computing with data of the attitude sensor to measure the acceleration and angular velocity [10]. The data of torso angle θ_3 is sent to the main controller and used for the motion control. The relative angles between torso and each leg are measured by encoders in the motors. The absolute angles θ_1 and θ_2 of legs are computed with the torso angle θ_3 and the rotational angles measured by two encoders, which are used in the feedback control for walking. The sampling time of the motor controls are set to 1 [ms]. The data of legs and torso angles as well as touch sensors are preserved in the main controller while the robot walks. Then, the data are transferred from the main controller to the personal computer outside the robot system after the robot finishes walking.

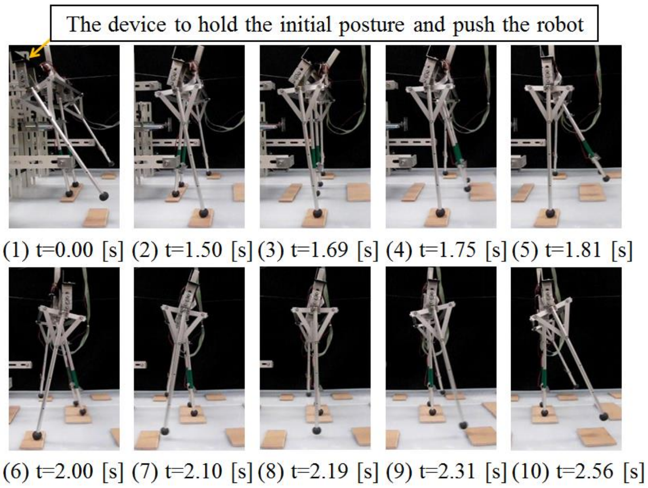
III. WALKING EXPERIMENT

The developed robot system with the proposed method has been confirmed through experiments of walking on the horizontal ground.

A. *Motion control for Walking experiment*

In simulation, the stance-leg was assumed to leave from the ground at the moment of the touchdown. However, in the actual walking motion, there exists the period that both legs are in stance state. Therefore, motion control method for the real robot needs to be modified as follows. Walking motion of the real robot is divided into four states according to the values of the touch sensors and the angle of the legs as shown in Fig. 8. The states are as follows.

(1) The inside leg is stance leg.
(2) The outside leg is stance leg.
(3) The both legs are stance legs and θ_1 is positive.
(4) The both legs are stance legs and θ_1 is negative.



(1) t=0.00 [s] (2) t=1.50 [s] (3) t=1.69 [s] (4) t=1.75 [s] (5) t=1.81 [s]

(6) t=2.00 [s] (7) t=2.10 [s] (8) t=2.19 [s] (9) t=2.31 [s] (10) t=2.56 [s]

Fig. 9 Walking motion of experiment by PD controls

Therefore, different control methods are applied according to the states as follows.

In the state (1) or (3), the control torques τ_1 and τ_2 are given as follows

$$\tau_1 = k_3^p(\theta_3 - \theta_{3d}) + k_3^d\dot{\theta}_3 + k^e(\dot{\theta}_2 - \dot{\theta}_1)(E - E_0), \tag{11}$$

$$\tau_2 = -k_e(\dot{\theta}_2 - \dot{\theta}_1)(E - E_0). \tag{12}$$

Where The k_3^p, k_3^d, and k^e denote the proportional, differential, and energy control gains, respectively. The E denotes the sum of kinematic and potential energies of the analysis model. Then, the E_0 denotes the desired energy. The θ_{3d} denotes the desired angles.

In the state (2) or (4), the control torques τ_1 and τ_2 are given as follows

$$\tau_1 = -k^e(\dot{\theta}_1 - \dot{\theta}_2)(E - E_0), \tag{13}$$

$$\tau_2 = k_3^p(\theta_3 - \theta_{3d}) + k_3^d\dot{\theta}_3 + k^e(\dot{\theta}_1 - \dot{\theta}_2)(E - E_0). \tag{14}$$

The control torques are generated at the motors by the PWM (Pulse Width Modulation) signals from the main controller.

B. Experimental Conditions

The initial posture and velocity must be given to the robot when it starts walking. The device to hold the initial posture of the robot and push it was developed in order to perform the experiment under the same condition. Then, the condition that the robot has the same length's legs causes a contact between the swing-leg and the ground at the moment when the swing-leg passes through the stance-leg. To solve this problem, the plates for putting feet are set on the ground as shown in Fig. 9.

C. Experimental Result

Based on the calculated results, the experiments have been performed to find the appropriate gain for walking. The result of walking by PD control [9] is shown as follows. The continuous scenes of the walking motion are shown in Fig. 9. They were captured with the high speed camera (CASIO: EX-FH25). The changes of the angles θ_1, θ_2, θ_3 and the values of data by touch sensors are given in Fig. 10.

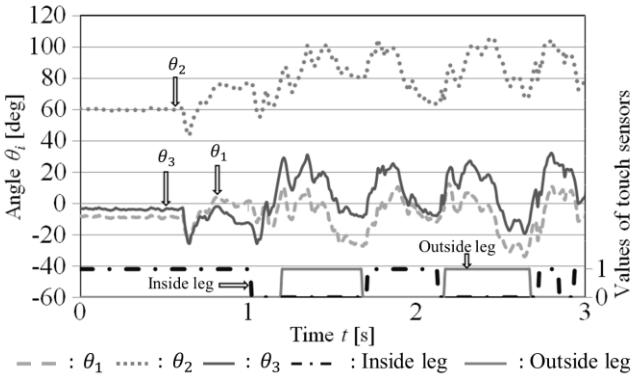


Fig.10 Changes of the joint angles and the data by touch sensors

IV. CONCLUSION

The method to control the motions of semi-passive walking by a biped robot had been investigated for a continuous walking on the horizontal ground. In this paper, the control law combining proportional - differential and energy ones was applied for a continuous walking. In the numerical simulations, the robot could continuously walk holding the torso by the proposed control law. Based on the calculated results, the experimental robot system was developed.

The experiments have been performed with the developed robot system and the proposed control method. Efficiency of the proposed control law has been examining.

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