

Landing Force Controller for a Humanoid Robot: Time-Domain Passivity Approach

Yong-Duk Kim, Bum-Joo Lee, Jeong-Ki Yoo, Jong-Hwan Kim, and Jee-Hwan Ryu

Abstract—For the purpose of a humanoid robot's stable walking or running, it is important to absorb landing force or ground reaction force which is generated when the robot's foot lands on the ground surface. The force can make the robot unstable, and the problem becomes serious if the robot runs. This paper proposes a control system, which can absorb the landing force of a humanoid robot. Time-domain passivity control approach is applied for this purpose. Ground and the robot's foot are modeled as two one-port network systems, which are connected and exchange energy with each other. The time-domain passivity controller has the landing force as input and controls the foot's position to reduce the force. The proposed controller can guarantee the stability of the robot system without need of any dynamic model information or control parameters. Using small sized humanoid robot, dynamic walking experiments are performed to verify the proposed scheme, and its efficiency is shown from the comparison with the other scheme.

I. INTRODUCTION

Many research groups in the world are currently working on humanoid robots and there are many successful projects [1], [2], [3], [4]. Current research, being conducted in collaborating operations with human beings [5],[6], has progressed far beyond studies in walking trajectory generation [7],[8] and online (real-time) balance control [9],[10] during walking. But the basic and most important function of the humanoid robot is the ability to walk safely in the real environment. For a stable walking, it is important to absorb either landing force or ground reaction force, which is produced when the robot's foot lands on the ground surface. The force can make the robot unstable during walking, and if the robot runs, it becomes a serious impediment for maintaining stability.

In a typical human locomotion, leg muscles are repeatedly hardened and relaxed depending on the walking pattern phase [11]. Once the muscles that move the leg hit the ground, they tend to be softer for a while to reduce the forces. In order to maintain support, they get harder again and this process is repeated in over and over again. For a walking or running robot, several approaches have been studied to reduce contact force. Some heuristic approaches have been used to shift the foot position once it reaches the surface [12], [13], [14]. However, there are problems in changing the foot position and PID controller coefficients voluntarily.

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Several researchers have studied the hybrid impedance and computed torque control, and the hybrid position and force control for the impedance adjustment of the leg [15],[16]. In this situation, however, the complex dynamics of the robot must be known, apart from it being difficult to find control parameters. In addition to these, there is a study which tries to decrease the landing force using a special foot structure [17].

This paper proposes a novel controller to compensate the landing force of a humanoid robot. Time-domain passivity approach [18],[19] is implemented for this purpose. The robot's foot is modeled as a one-port network system, which has the landing force as an input, and foot's position as an output. By calculating the energy input into the one-port network based on the landing force and the foot position, the robot's foot is controlled to absorb the landing force. The proposed control method can guarantee the stable dynamic walking without any model information and control parameters, which must be determined by calculation or trials and errors. Moreover it requires very little additional computation. The validity of the proposed control method is confirmed through dynamic walking experiments using the small-sized humanoid robot, HanSaRam-VI. The efficiency is also shown from the comparison between the proposed scheme and the other one.

The remainder of this paper is organized as follows. In Section II, the small-sized humanoid robot, HanSaRam-VI, is described. Section III presents the modeling of robot's foot system which consists of robot's foot and ground surface, and the time-domain passivity control is proposed to compensate the landing force. Section V presents the experimental results of the proposed method. Finally, conclusion follows in Section VI.

II. HUMANOID ROBOT HANSARAM-VI

TABLE I
SPECIFICATIONS OF HANSARAM-VI

Link	Length	Joint	DOF
Length between hip joints	60 [mm]	Hip	3 (×2)
Length of thigh	100 [mm]	Knee	1 (×2)
Length of shank	100 [mm]	Ankle	2 (×2)
Length between ankle and sole	40 [mm]	Waist	1
Length between toe and heel	100 [mm]	Shoulder	3 (×2)
Width of foot	60 [mm]	Elbow	1 (×2)
Length of lower trunk	100 [mm]	Wrist	2 (×2)
Length of upper trunk	100 [mm]	Total	25
Length between shoulder joints	160 [mm]		
Length of upper arm	97 [mm]		
Length of lower arm	86 [mm]		

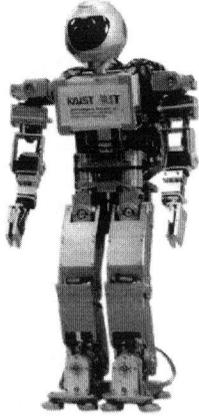


Fig. 1. HanSaRam-VI.

Fig. 1 and Table I show a small-sized humanoid robot, HanSaRam-VI and its specification. It has 25 DOFs, and consists of 12 DC motors in lower body and 13 RC servo motors in upper body. Its height and weight are 52 cm and 4.5 kg, respectively. This biped robot's structure is mainly composed of Duralumin. Even though HanSaRam-VI is a small humanoid robot, the design of the lower body is focused on generating sufficient power and accurate control, and therefore consists of DC motors and Harmonic drives. In the design of the upper body, 13 RC servo motors are used, due to light weight and easy to control.

The on-board Pentium-III compatible PC with running RT-Linux calculates the walking pattern in real time. The walking pattern is generated on-line based on three-dimensional inverted pendulum model [20]. The stand-alone vision system using PDA is equipped to find out three colored objects in real time. To measure forces on the foot, 4 FSRs are equipped on each foot.

With the help of all the computational and power parts, HanSaRam-VI has the ability for fully independent sensing, processing, and locomotion.

III. LANDING FORCE CONTROLLER USING TIME-DOMAIN PASSIVITY APPROACH

A. The time-domain passivity

In this section, we briefly review time-domain passivity concept before it is implemented for absorbing the landing force. Recently, the sampled time passivity concept has been proposed in [21], because many of the input and output variables in control problems can be measured by computer, and the conjugate variables which define power flow in such a computer system are sampled time values. The robot control system to compensate the landing force is assumed to take a force as an input, and computes foot's position as its output. Typically, this input force is measured by force sensors and used through AD converter at each sample time. And the computed position output is applied to a motor controller so that motors can follow reference position continuously.

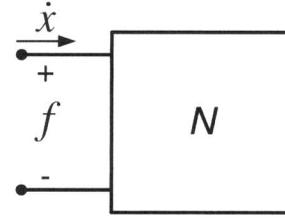


Fig. 2. One-port network model.

First, we define the sign convention for all forces and velocities so that their product is positive when power enters the system port. Also, the system is assumed to have initial stored energy at $t = 0$ of $E(0)$ (Fig. 2). Following variables for force and position are defined during one sample time $t_{k-1} \leq t < t_k$ for the sampled time system:

- 1) $f(t) = F(k)$ is the force at k , which is constant during one sample time, $t_{k-1} \leq t < t_k$.
- 2) $x(k)$ and $x(k-1)$ are the positions at k and $k-1$ sample times, respectively.

Then, the passivity of the sampled system can be defined as the following:

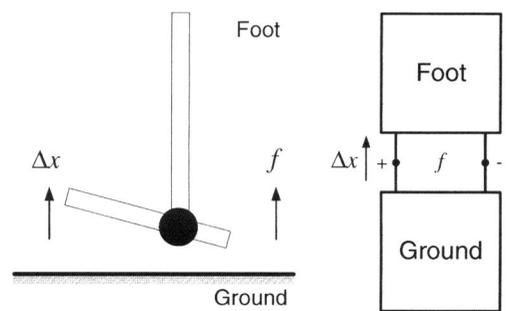
Definition 1: The one-port network N with initial energy storage $E(0)$ is sampled time passive if and only if

$$E(k) = \sum_{j=0}^k F(j)(x(j) - x(j-1)) + E(0) \geq 0 \quad (1)$$

where $j = 0, 1, 2, \dots, k = 0, 1, 2, \dots$, for sampled force $F(j)$ and position $x(j)$.

Note that if $E(k) \geq 0$ for every k , this means the system dissipates energy. If there is an instance that $E(k) < 0$, this means the system generates energy, and the amount of generated energy is $-E(k)$.

B. Modeling robot's foot system



(a) Robot's foot and ground surface. (b) One-port network models of the robot's foot and ground surface.

Fig. 3. Robot's foot system modeling.

To implement the time-domain passivity approach, the robot's foot and the ground are modeled as a network system. Both systems can be modeled as one-port network systems, which are connected each other. Fig. 3 shows the real and the

modeled network system, respectively. The sign convention for force and velocity is defined so that the energy is positive when the power enters the system port of the robot's foot. In Fig. 3(b), the force and the velocity are positive in the upper direction.

Since the ground can be considered as an intrinsically passive system, the connected system (the robot's foot and the ground) can be passive if the robot's foot, the one port network, is passive. This is a situation where the foot is physically absorbing the contact force. Once we prove the passivity, stability of the robot system can be also guaranteed because passivity is a sufficient condition of stability.

On the other hand, when the robot's foot, one port network, is active (while the input energy is negative), the robot might be unstable. This is the case when the robot's foot kicks the surface, which causes a big landing force between the foot and the ground. This force is the main reason for the unstable walking. Therefore, a control algorithm is required for alleviating the landing force.

C. Landing force controller

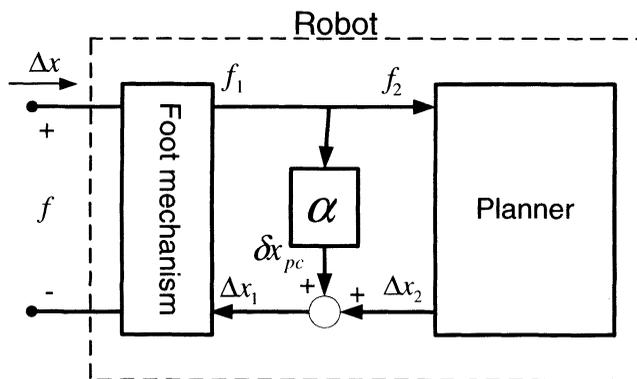


Fig. 4. One-port network with PO/PC.

We can divide the one-port network of the robot's foot system into two parts: mechanism part with low-level position controller and planner part with high-level controller. Fig. 4 shows the separated network system of robot's foot. $f (= f_1 = f_2)$ is the landing force, which can be measured by the FSR sensors on the robot's foot. x is the actual height position of the robot's foot, and Δx is the difference between two consecutive sampled data of x . The modified position (x_1) is obtained from the originally planned walking pattern (x_2) and the output of the passivity controller (δx_{pc}). x_2 is a planned height position of walking pattern from the walking pattern planner, which did not consider the landing force from the ground. If we use the planned walking pattern, the robot's foot might get a big landing force from the ground in a very short time, and it makes the one-port of the robot's foot active. In order to reduce the landing force, the passivity controller is attached to modify the planned walking pattern (x_2) to x_1 by adding δx_{pc} . Therefore, the robot takes the ground reaction force into account and it can make a contact to the ground more securely.

The proposed time-domain passivity control system consists of a passivity controller (PC) and passivity observer (PO), which controls and monitors the input/output energy flow between the robot's foot and the ground. Passivity observer computes the energy flow using the landing force and the foot position as follows:

$$W(k) = W(k-1) + f_1(k)(x_1(k) - x_1(k-1)) \quad (2)$$

$$W_o(k+1) = W(k) + f_1(k)(x_2(k+1) - x_1(k)) \quad (3)$$

where $W(k)$ is the total energy output from 0 to k , and $W_o(k+1)$ is the prediction of the one-step-ahead energy output. The last term of Eq. (3) is the estimation of the one-step-ahead energy output, which is the output energy from k to $k+1$. Note that we know the planned position $x_2(k+1)$ at step k . If the PO can predict whether the system at the next step will be passive or not at the current step k , the PC can modify the desired position at the next step ($k+1$) to make the system passive. The PC absorbs exactly the net energy output (if any) measured by the passivity observer at each time sample.

Based on the PO (steps 4 and 5 below), the PC algorithm (steps 6 and 7 below) for the one-port robot's foot is developed as follows:

- 1) $f_1(k) = f_2(k)$ is the input;
- 2) $\Delta x_1(k) = x_1(k) - x_1(k-1)$
 $\Delta x_2(k+1) = x_2(k+1) - x_1(k)$;
- 3) $\Delta x_2(k)$ is the output of the one-port network;
- 4) $W(k) = W(k-1) + f_1(k)\Delta x_1(k)$ is the energy output at step k
- 5) $W_o(k+1) = W(k) + f_1(k)\Delta x_2(k+1)$ is the prediction of the energy level at step $k+1$
- 6) The PC output for making the system passive is calculated as follows:

$$\delta x_{pc} = \begin{cases} \frac{-W_o(k+1)}{f_1(k)}, & \text{if } W_o(k+1) < 0 \\ 0, & \text{if } W_o(k+1) \geq 0 \end{cases}$$

- 7) The modified desired height position can be calculated from $\Delta x_1(k+1) = \Delta x_2(k+1) + \delta x_{pc}(k)$.

It should be noted that the PO/PC is for achieving the stable landing of humanoid robot. Once the stable landing is achieved (maintaining N steps with positive energy, where N is constant.), the robot's walking path should be modified to follow the initially planned walking path. The walking pattern, changed by the passivity controller, is interpolated to the initially planned walking pattern by using the polynomial method. In this stage, passivity observer is also reset to prepare the next observation.

IV. EXPERIMENTS

Dynamic walking experiments were performed to verify the proposed time-domain passivity control approach. The results are compared with those using no landing force control and the heuristic control to absorb the force. In the experiments, the biped robot walked with a speed of 4 cm/s

and a step length of 3 cm. Double and single support phases of a step were 0.15 s and 0.6 s, respectively. All experimental results are plotted after the initial 2 seconds of operation and then for 5 seconds thereafter.

A. Walking experiments without landing force control

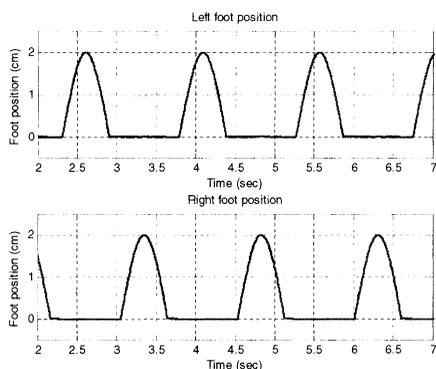


Fig. 5. Foot's height position without landing force control.

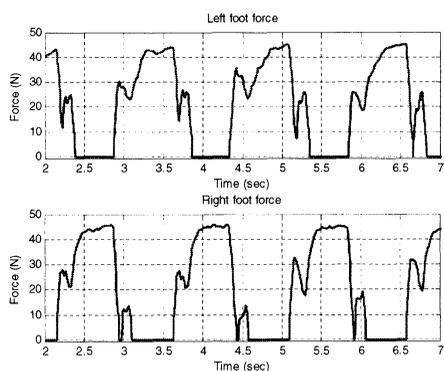


Fig. 6. Force without landing force control.

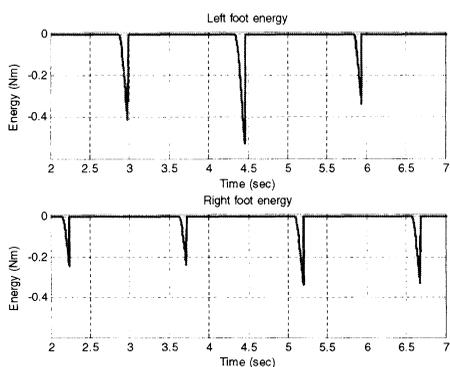


Fig. 7. Energy without landing force control.

First, the experiments were performed without landing force control. Fig. 5 shows the walking trajectory without considering landing force. When robot's foot was landing, there was a big landing force as shown in Fig. 6. This force caused 'double contacts' of the foot. Even after the robot's

foot landed on the ground, it was bounced back from the ground instantaneously due to the big landing force such that it disturbed stable dynamic walking. During the support phase, there were two large peaks at the start and end of supporting time. The first peak was caused by the foot's landing at the beginning of the double support phase and the second peak came from the another foot's landing at the start of the next double supporting phase. It should be noted that two force plots are different because the mass distribution was asymmetric in the real robot. Fig. 7 shows the input energy from the one-port robot's foot. When the foot kicks the surface, the energy becomes negative and the robot's foot is no longer passive. It means that the robot might be unstable due to this active energy output from the foot.

B. Walking experiments with the heuristic method

In the second experiments, the controller made the robot shorten the legs when the huge force was detected as follows [14]:

$$\Delta \dot{x} = \sigma(f)v + (1 - \sigma(f))(-\omega \Delta x) \quad (4)$$

where Δx is the modification of the foot height and f is the force. The control mode is switched by the function of $\sigma(f)$ (Fig. 8). In the experiments, v and ω were selected as 12 and 30, respectively.

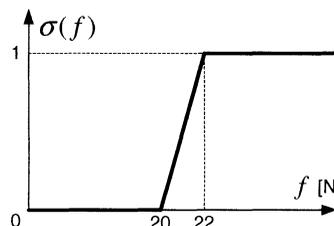


Fig. 8. Switching function for the heuristic method.

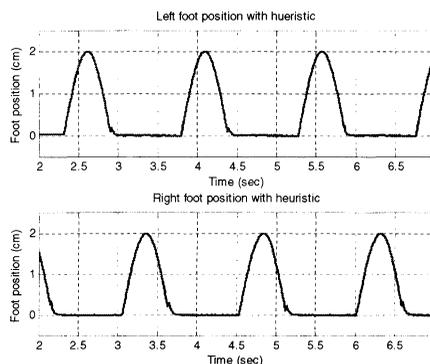


Fig. 9. Foot's height position with the heuristic method.

Fig. 9 shows the foot was moved upward a little to absorb the landing force. The amount of displacement is plotted in Fig. 10 and Fig. 11 indicates the force was reduced relatively in comparison with the previous result. But, from the energy

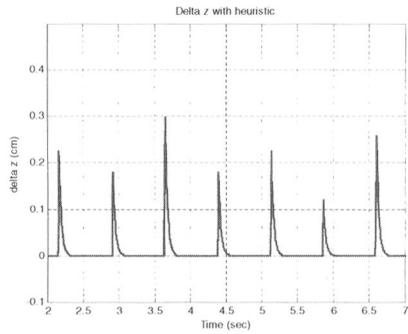


Fig. 10. Δx with the heuristic method.

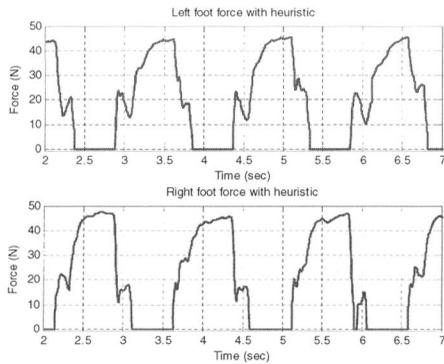


Fig. 11. Force with the heuristic method.

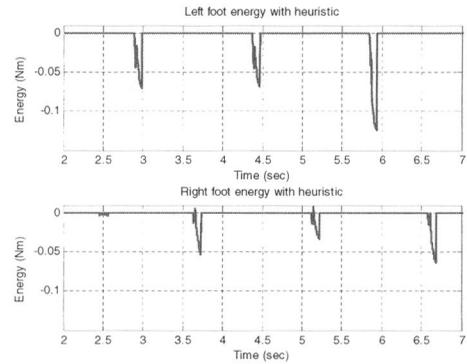


Fig. 12. Energy with the heuristic method.

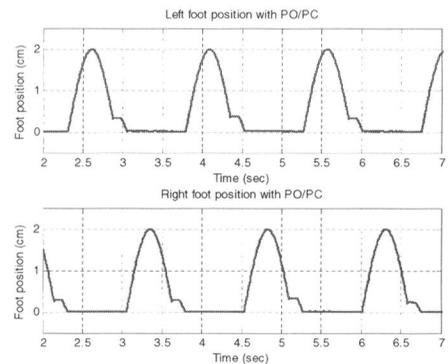


Fig. 13. Foot's height position with PO/PC.

view point, it is not enough to meet the passive condition, as shown in Fig. 12. The energy was still active. Though the heuristic method could reduce the force somewhat, it was too difficult to obtain a reasonable control parameters (v , ω , and $\sigma(f)$) for the experiments. It needed many trials and errors experiments.

C. Walking experiments with the PO/PC

Fig. 13 - Fig. 16 show the results when the proposed time-domain passivity controller was implemented. The modified walking pattern is plotted in Fig. 13. Foot is slightly moved upward on each landing time, since the passivity controller modified the planned walking pattern to satisfy the passivity condition. After 10 steps in which the energy stays positive, it was shifted to its original planned position by cubic spline interpolation. As shown in Fig. 14, the force was remarkably reduced because the passivity controller immediately reduced the force. There was no presence of 'double contact' any more. Fig. 16 shows the robot system's energy. Due to the bigger force than the value which PO initially estimated, the system could not be passive. But the result indicates the scale of negative energy decreased by 1,000 times, and the system was controlled to satisfy the passivity condition by 5 steps (0.025ms).

The results of the overall experiments indicate that the proposed passivity controller absorbs the impulsive landing force at the ground surface effectively and makes stable foot landings possible. It is important to note that system dynamic

equations are not used any more in the proposed method. Moreover, control parameters are not required.

V. CONCLUSION

For a stable dynamic walking or running of humanoid robot, the control of the landing force is indispensable. This paper proposed the novel controller to compensate for the landing force. For the use of the time-domain passivity approach, the ground and the robot's foot were modeled as two one-port network systems, which are connected and exchanging energy each other. The time-domain passivity controller, which has the force as an input and controls the foot's position to reduce the force, was implemented. The proposed scheme was verified with the developed small-sized humanoid robot, HanSaRam-VI. The efficiency of the proposed scheme was shown in the comparison with the experimental results of the scheme without landing force control and of the heuristic scheme. The proposed method could stabilize the landing motion of the biped robot. Besides, it could guarantee the stable dynamic walking without any system model information or control parameters at all.

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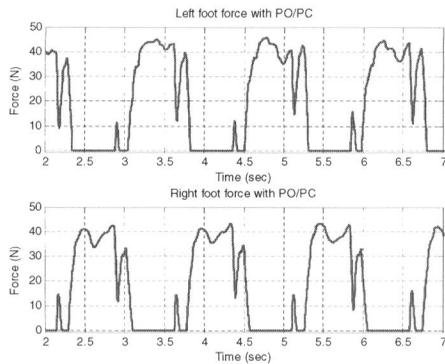


Fig. 14. Force with PO/PC.

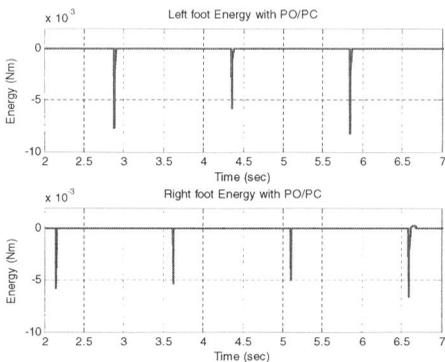


Fig. 15. Energy with PO/PC.

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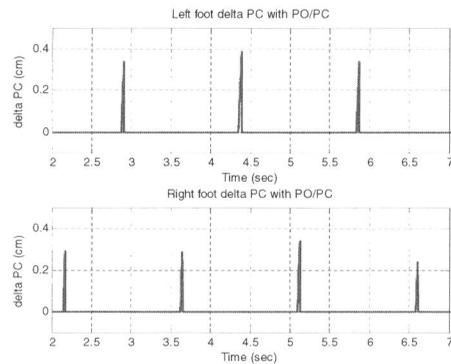


Fig. 16. δx with PO/PC.

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