Acquiring Passive Dynamic Walking Based on Ballistic Walking

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ABSTRACT

In this paper, we propose the layered controller which enables the biped robot adaptively to walk in minimal energy or passive dynamic walk, if possible. This controller consists of two layers; the lower layer stabilizes the walking, while the upper layer tries to realize the minimal energy walking. The torque is applied to the robot in short time after the the free leg leaves the ground, and so the walking is ballistic. Simulation results show that the proposed controller can realize passive dynamic walking successively from ballistic walking in the simple robot model.

1 INTRODUCTION

From the observation of human walking, Mochon and McMahon proposed a ballistic walking model in which the muscles of the swing leg are activated only at the beginning and the end of the swing phase [5]. In the middle of the swing phase, the swing leg moves in a ballistic manner, which utilizes the inertial and gravitational force. This seems to be the reason why the human walking looks quite "natural" whereas the biped robot walking realized in current robotics looks unnatural.

Passive Dynamic Walking (PDW) can be considered as an extreme case of such ballistic walking since the legs are completely free from activation[4]. In this sense, starting from PDW and adding simple actuators is thought to be one plausible solution to realize natural walking, and several results are reported based on such an idea [1, 6]. But in these studies, control algorithms are fixed and so cannot adapt to the environment in which walking robot is put. For example, the robots of these studies cannot realize PDW even if it is possible. Osuka et al.[7] succeeds to realize PDW from actuated walking by changing the feedback gain of control. But their method needs the desired trajectory of PDW a priori and without information of it, their algorithm cannot be utilized.

In this paper, to let the biped learn walking with minimum energy, a layered controller is proposed that consists of two layers: the lower layer for ballistic walking and the upper layer for minimizing the energy by changing the parameter of the lower layer. At the beginning of walking, the controller can realize the stable ballistic walk thanks to the lower layer, and after a while, the upper layer searches appropriate parameters for the lower one. As a result, passive dynamic walking can be realized when the physical parameters of the robot are appropriate.

2 LAYERED CONTROLLER FOR BALLISTIC WALKING

Taking the Poincaré section at heel contact in phase space of walking motion, the change of the walking in each step is described as the transposition of the point on the Poincaré section.

In passive dynamic walking in which no external force is applied to robot, the state of (n+1)-th step depends only the state of n-th step;

$$s_{n+1} = f(s_n) \tag{1}$$

Many studies on ballistic walking have derived the conditions for walking stability from the condition that $s = f(s)$ on Poincaé section. This condition is quantified by the multi-dimensional partial derivative (or Jacobian) $\bigtriangledown f$. If all eigenvalues of $\bigtriangledown f$ lie within the unit circle, walking is stabilized[8][3].

In ballistic walking, the condition for stable walking is analyzed in the same way. Suppose the torque, τ_w, is applied in short time after the free leg leaves the ground in the following way,

$$\tau_w = \begin{cases} A_n & (0 < t < t_0) \\ 0 & (t_0 < t < T) \end{cases} \tag{2}$$

Here, t is the time after the free leg leaves the ground, t_0 is very short time as compared with walking cycle T. A_n is constant value.

In this case, the displacement equation on Poincaré section becomes

$$s_{n+1} = f(s_n, A) \tag{3}$$

In this ballistic walking in which torque is applied in short time, contrary to passive dynamic walking, the walking stability is controlled to some extent because the next state, s_{n+1} can be changed by A_n. Formal'sky derived the stable walking condition by formulating 3 as a boundary-value problem like $s = f(s, A)$ when t_0 is infinitesimal (the torque A is applied like δ-functions.)[2]. Linde has found the condition for stable walking using the Jacobian of f [8].

The method mentioned above is effective when all parameters of the robot model are known a priori. But if the parameters are unknown, how robot can attain the minimal energy gait adaptively using its own sensor inputs?

To assure the walking stability, it is necessary to give the appropriate torque to the robot according to the current state s_n, so that the s_n is a cyclic solution. For that, the inverse relation of equation 3 is useful.

$$A_n = g(s_n, s_{n+1}) \tag{4}$$

If this function is available, the controller to realize the desired state can be built.

$$A_n = g(s_n, s_d) \tag{5}$$

Under this control, the desired state to realize the gait with minimum energy can be searched safely by the following equation.

$$A_{min} = \min_{s_d} g(s_d, s_d) \tag{6}$$

We propose the controller which implements equation 5 as the lower layer and equation 6 as the upper layer as shown in Fig 1. The lower layer of the controller regulates the torque so as to keep the intersectional point on the Poincare plane, s_n, coincident to the desired state, s_d. The upper layer of the controller receives the information of current magnitude of the torque applied to the waist, τ_w, from the lower layer and gives the new desired state to be realized in the lower layer.

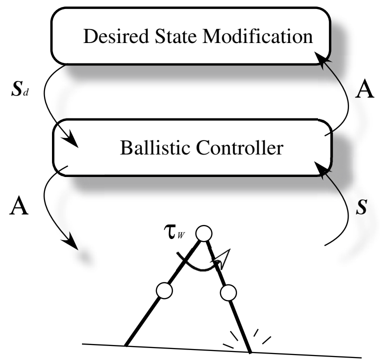


Figure 1: Proposing layered controller for biped walking

In the lower layer, the controller should implements equation 5. But it is impossible to know the function f without knowing the physical parameters of the robot. If the model of the robot is simple, it is possible to prepare the simple feedback controller that works as well as the function f by getting the relationship of torque, A_n, and the resultant state, s_{n+1} from observing several trial walks. An example of this implementation will be shown in section 3.1. For the more complicated robot model, it is difficult to obtain the relationship from observations of trial walks. So, we introduce the neural network that maps the causality of the torque and the resultant state. This neural network implements the equation 4 from learning the several trials in learning phase. The simulation relult of this implementation will be shown in section 3.2.

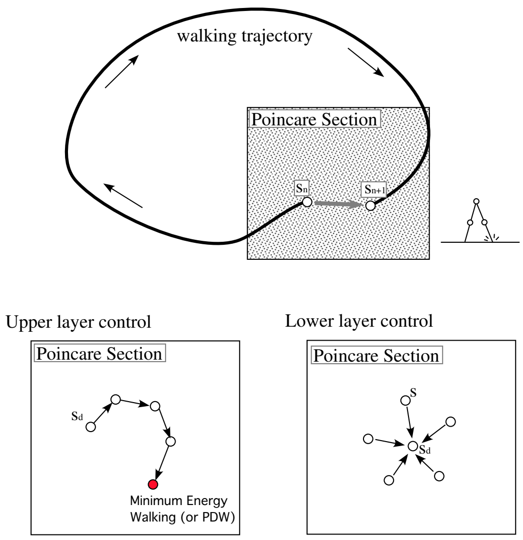


Figure 2: Poincaré section is taken at heel strike. On this plane, the lower layer of the controller tries to keep the state at heel contact in the same area as the desired one which is given by the upper layer. The upper layer of the controller tries to search the desired state which realize walking mode with minimum energy.

In the upper layer, to implement the equation 6, the desired state, s_d, that enables the robot to walk with minimum energy is searched by stochastic hill-climbing method, as follows.

$$
\begin{array}{l}
if(|s - s_d| < \delta) \\
\quad\quad if(A_{min} > A) \\
\quad\quad\quad\quad A_{min} = A \\
\quad\quad\quad\quad s_{d0} = s_d \\
\quad\quad s_d = s_{d0} + random\ perturbation
\end{array}
$$

The upper layer of the controller modifies the desired state s_d. While ballistic torque produced by the controller varies from time to time, the upper layer does not change the desired state. When the torque is settled, which is observed by the error $|s - s_d| < \delta$, the layer will modify the desired value in a random manner, and find the gradient to reduce the ballistic torque. In this way, the layered controller makes the biped learn the passive dynamic walking by itself, if possible.

3 SIMULATION RESULTS

Several simulations are performed to show the effectiveness of the proposed layered controller. The first experiement shows that the proposing controller can realize passive dynamic walking stably on a simple robot without knees. In the second experiment, it is shown that introducing a neural network in the lower layer controller can successfully suppress the limping gait of a biped robot with knees and then a gait with minimal energy can be realized.

In the following simulations, each leg of a biped without knees is 1.5 [kg] and 0.6 [m]. For a biped model with knees, the mass of thigh and shank is 1.0 [kg] and 0.5 [kg], respectively, and the length of them is 0.3 [m]. The floor is described by spring-dumper model. The coefficients of spring and dumper of the floor model is 20000.0 [N/m] and 100.0 [N sec/m], respectively. The iteration time is 0.2 [msec].

3.1 Result on a biped without knees

In this experiment, to stabilize the ballistic walking constant torque is applied to the hip joint during 0.1 [sec] after the free leg leaves the ground. As the first trial to implement "ballistic controller", we adopted the simple feedback algorithm,

$$A_{n+1} = A_n - \alpha|s - s_d|, \tag{7}$$

and as the representational variables of walking state, we adopt the angular velocity of waist joint, $\dot{\theta}_w$, so above equation becomes

$$A_{n+1} = A_n - \alpha(\dot{\theta}_w - \dot{\theta}_{wd}), \tag{8}$$

where $\dot{\theta}_{wd}$, and α denote the desired value of $\dot{\theta}_w$ provided from the upper layer, and feedback gain, respectively.

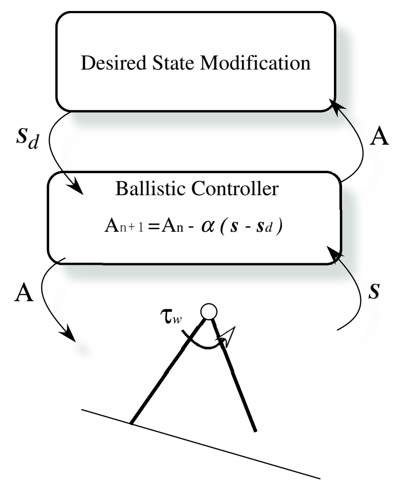
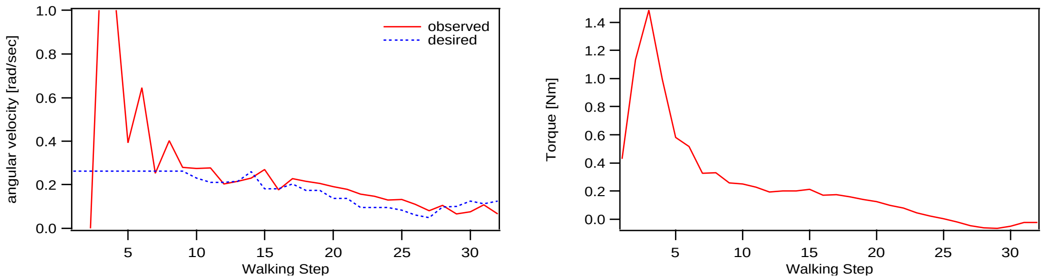


Figure 3: Layered controller with simple feedback controller

A simulation result with a biped without knees is shown in Fig. 4 . Fig. 4(a) and (b) show the angular velocity of the waist joint at the impact of each step, and the torque magnitude applied to the waist joint, respectively. At the beginning, the torque is not settled, therefore the desired waist velocity is not changed. Nevertheless, the biped continued to walk thanks to the ballistic controller. After 10 steps, the torque is settled, and the upper layer begins to search for a better desired value that makes the torque smaller. Afterward, the torque is continuously decreased and passive dynamic walking is realized within 30 steps.



(a) the angular velocity of hip joint at the moment of heel strike in each step

(b) the magnitude of output torque at each step

Figure 4: Walking mode converges to PDW under the proposing controller when the slope is inclined 1 [deg]

3.2 Results on a biped with knees

When the feedback control proposed above is applied to a robot with knees, ballistic learner cannot make the walking mode approach to the desired one because the walking mode is easily fell into the 2-cycled mode. To let walking mode converge to 1-cycled mode, the ballistic learner is enhanced with neural network as shown in Fig. 5.

This neural network calculates the magnitude of the torque when the state at heel contact and the difference between the current state and the desired one are given. Because the appropriate torque value to realize the desired state is unknown a priori, the function g of equation 6 is realized by neural network. In training phase during which random torques are given to biped robot, the neural network is trained by means of backpropagation algorithm so that the A_n at n-th step can be obtained when the state at n-th step and one at (n+1)-th step are given. The algorithm of the upper layer is the same as that described in the previous section.

Fig. 6 shows simulation results. In this experiment, the time from the moment the knee of free leg is straight to the heel contact, is adopted as the representational variable of walking state. Until the 30th step, random torque is given for training the neural network of ballistic learner. When the ballistic learner works after 30th step, the walking mode is stabilized by ballistic learner and converges to one cycled walking within 10 steps. And after about 50th step, the upper layer controller is activated and begins to search better desired value of the state.

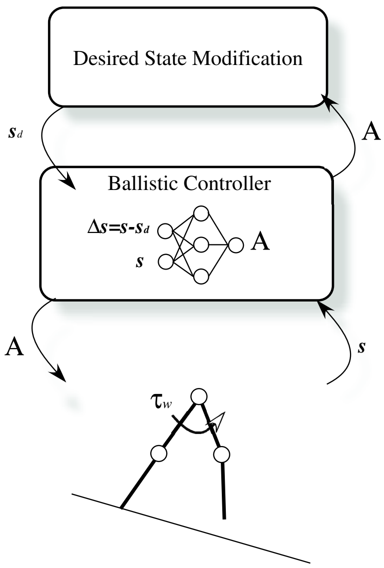
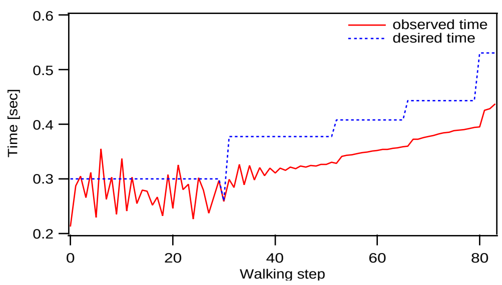
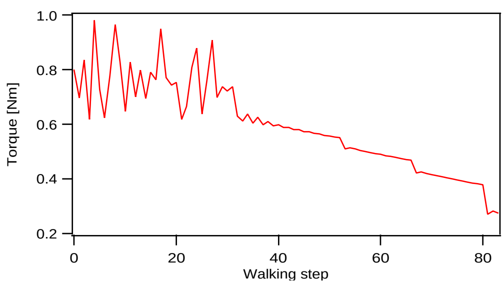


Figure 5: Layered controller with neural network



(a) the time during which the knee of free leg is straight



(b) the magnitude of output torque at each step

Figure 6: Applying layered controller to robot with knees

4 DISCUSSION AND FUTURE WORKS

Here, we disscuss about two problems of the method presented in this paper.

The first problem is about the representative variables of state. In this paper, as the representative variables of the state, we adopted the angular velocity of hip joint for the biped model without knees and the time during which the knee of free leg is straight, for the biped model with knees. But currently we don't know what variables to be chosen to certain biped model. Other variables or some combinations of them might be plausible. How to choise the appropriate variables is the next challenge.

The second one is about the estimation of falling down. The upper layer tries to search the desired state which enables the robot to walk with minimum energy, without knowing the safety zone of states on Poincaré section. So, if the robot cannot realize passive dynamic walking, the robot inevitably falls down in the final stage of searhing. We are now trying to add another module which evaluates the stability of walking.

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