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Ballistic Control for Biped Walking with Pneumatic Actuators

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Abstract—Walking is a complex behavior that emerges from interaction between the agent body and the terrain. To realize adaptive dynamic walking by an artificial agent, therefore, not only its body and control dynamics but also the dynamics of the terrain should be taken into account. This paper describes a biped walker with pneumatic actuators and a ballistic controller that only applies driving force in a limited period of time to utilize the dynamic property of the robot body. Feedback is designed based on the ballistic control, which is derived by estimation by experimental trials.

1. Introduction

The parameters of existing biped robots concerning to statics and kinematics such as link length, range of joint movement, required static torque are determined based on the kinematic and static balance analyses. The other parameters concerning to dynamics are design arbitrarily, such as link mass, center of gravity, inertia. A standard way to control such a biped robot is (1) to design desired motion of each leg assuming that the terrain is known, (2) to derive desired motion of joints based on the inverse kinematics, and (3) to apply position based control to track the desired joint trajectory. Since the analyses are only based on the kinematics, the trajectory of each leg is designed independently to the dynamics of the terrain. Therefore, the robot will be unstable when the kinematic model of the terrain is incorrect or the impact between the leg and the terrain is more than quasi-static. This may be one of reasons why most of the existing biped walkers are brittle against to the terrain disturbance.

There are several studies trying to realize efficient walking by designing not only the kinematics but also the dynamics of the walking robot. Passive dynamic walking [1], biped walking on an inclined slope without any actuation, is supposed to be a key to realize such energy efficient walking, and there have been several studies trying to design controllers for walking on the flat or even on climbing planes [2, 3, 4, 5].

If the robot should be controlled to track given desired trajectories that are based on the kinematics, it is convenient to use electric motors with high reduction ratio. The inertial and reaction force will disturb the tracking control if the ratio is small. This may be the reason why electric motors with high reduction ratio are mainly adopted for the existing biped robots.

On the other hand, a pneumatic actuator is also one of the promising candidates for actuating biped robots since it can provide large force with a light mechanism, and since its elasticity will play a role to preserve and release the impact energy, which can enable energy efficient walking and running [6]. However, it is difficult to control its position precisely because of its complicated dynamic characteristics, time delay and non-linearity. To realize biped walking by such actuators, Wisse and Frankenhuyzen designed the biped walker that can walk passively, and applied simple feedforward control without dealing with complicated dynamics of the actuator [5].

Such simple feedforward control is enough as far as the biped robot walks within the stability margin provided by the well-designed body. To extend the adaptability to terrain changes, we should model the dynamics of the walking in some way, and should apply feedback control based on the model. If the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and that of the pneumatic actuator are strongly coupled. Because of this coupling, it may be difficult to build a terrain model and an actuator model separately. To realize biped walking based on passive dynamic walking, therefore, we need a new modelling scheme that models terrain dynamics and actuator dynamics altogether.

In this paper, we develop a biped walker with pneumatic actuators with a feedback controller to deal with terrain changes. The feedback controller is a ballistic controller that only apply driving force in a limited period of time to utilize the dynamic property of the well-designed body. The model needed to develop the controller is estimated by trials of a real biped robot.

The remainder of this paper is organized as follows. First, we describe the design of the biped robot. Next, we investigate the input-output relation of the robot by several trials, and apply it to develop a simple feedback controller. Finally, we show experimental results that the robot can walk down over a difference in level.

2. A biped robot with pneumatic actuators

We developed a biped robot with pneumatic actuators shown in Figure 1. Its height, width, and weight are

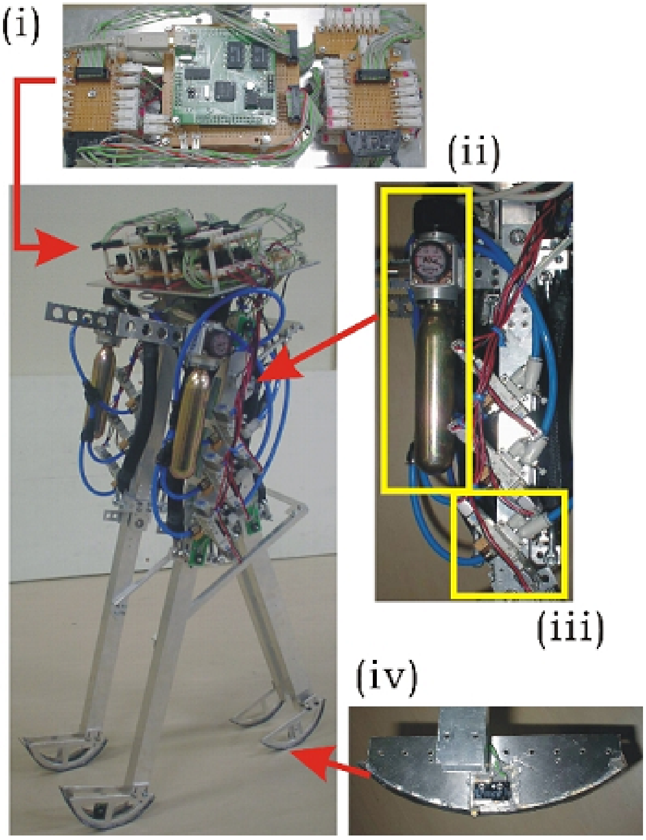

Figure 1: A biped robot with pneumatic actuators: (i) a micro computer (H8/3067) (ii) two CO_2 bottles as air supply, (iii) six ON/OFF electric valves for air supply and exhaust, and (iv) touch sensors on a feet

0.75[m], 0.35[m], and 5.0[kg], respectively. The robot has four legs two of which are connected to each other to prevent the robot from falling down sideways. Each leg has a knee. The length and weight of its thigh and those of its shank are 0.3[m], 2.1[kg], 0.35[m], and 0.5[kg], respectively. All the joints are driven by an antagonistic pair of McKibben muscle actuators [7] by Hitachi Medical Corporation [8]. The robot is equipped with (i) a micro computer (H8/3067) on the top, (ii) two CO_2 bottles as air supply, (iii) six ON/OFF electric valves for air supply and exhaust, and (iv) touch sensors on feet to sense the contact against the terrain.

In Figure 2, we show a control architecture for driving a joint. Each joint is driven by an antagonistic pair of the McKibben actuators each of which has a pressure sensor and supply and exhaust valves. Sensory data from the pressure sensors and potentiometers attached to the joints are sent to the micro computer via A/D converters. In experiments conducted in this paper, however, these data are not used on-line. The computer controls the supply and exhaust valves to rotate the joint. In the experiments, pressure of the supply air is 5[MPa] whereas that of the exhaust is atmospheric pressure.

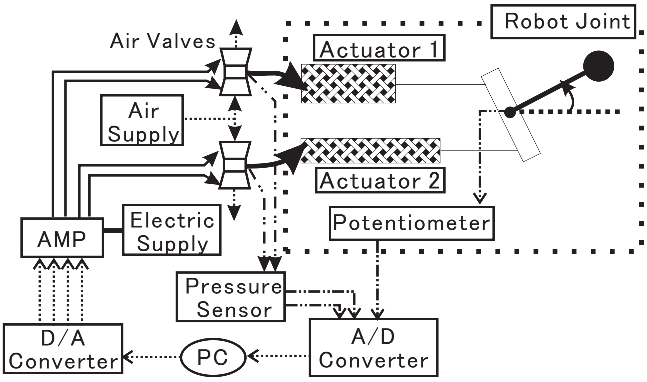

Figure 2: A control architecture for driving a joint

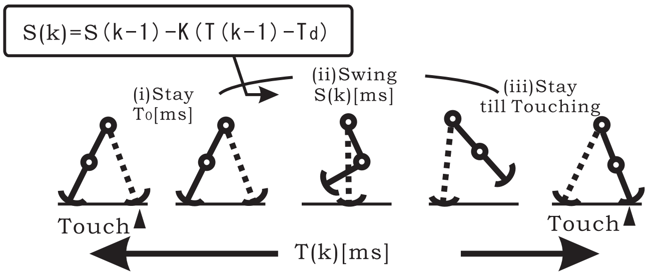

Figure 3: Ballistic control for the biped walker

3. Ballistic control for the biped walker

3.1. Ballistic control

Since the robot is designed appropriately for realizing passive dynamic walking, it can walk on a flat plane with a simple controller. To utilize the well-designed dynamics, we adopt a ballistic controller that only apply driving force in a limited period of time. Figure 3 shows the applied ballistic controller.

(1) For T_0[s] after a touch signal of a foot, all valves are closed, and the robot keeps the same posture. The robot moves ballistically according to the inertial force.

(2) After T_0 [s], the supply valve of the actuator of the hip joint that drives the swing leg is open to the supply pressure, whereas the exhaust valve of the antagonistic is open to the atmosphere for $S(k)$ [s]. The valves of the knee joint of the swing leg are opened and closed in an appropriate way so as to avoid the collision with the floor. Since the movement of the knee is small, the way does not strongly affect the behavior very much.

(3) $T_0 + S(k)$[s] after the impact, all the valves are closed

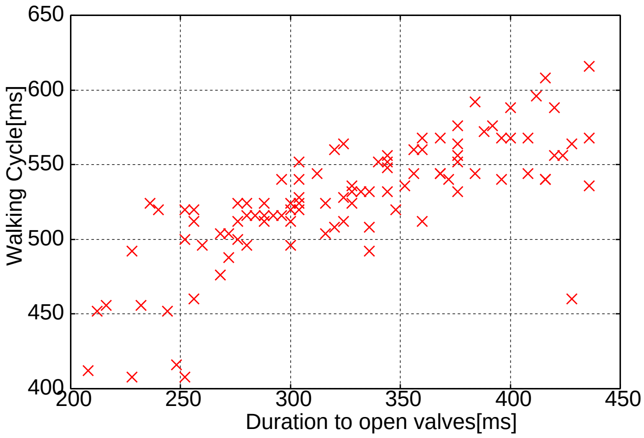

Figure 4: The relation between the opening valve time $S(k)$ and walking cycle time $T(k)$

again, and the robot waits for the next impact. In this phase, the robot moves ballistically according to the inertial force. When the impact is sensed, go back to the procedure (1).

3.2. Identification of input-output relation

By the ballistic controller described in the previous subsection, the biped robot can walk on a flat plane. Although the walking is robust within the stability margin provided by the well-designed body, it is still week against disturbance and modelling error. We should model the dynamics of the walking in some ways, and should apply feedback control based on the model to deal with them. Note that the model consists not only of the robot body but also of the terrain. If the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and that of the pneumatic actuator are strongly coupled. Because of this coupling, it may be difficult to build a terrain model and a robot model separately. To realize biped walking based on passive dynamic walking, therefore, we need a new modelling scheme that models terrain dynamics and actuator dynamics altogether.

In this paper, we propose to investigate the input-output relation of the real robot by several trials. Thanks to the good dynamic property, the robot has a certain stable basin that we can change the walking parameters in a certain range. Therefore, we can acquire the relation between walking parameters and emerged walking behavior from walking trials.

During walking by the ballistic controller, we change the valve opening time $S(k)$ from 200[ms] to 450[ms]. Figure 4 shows a clear relation, a positive linear relation between the valve opening time $S(k)$ and the walking cycle time $T(k)$. By utilizing the relation, we can apply feedback control.

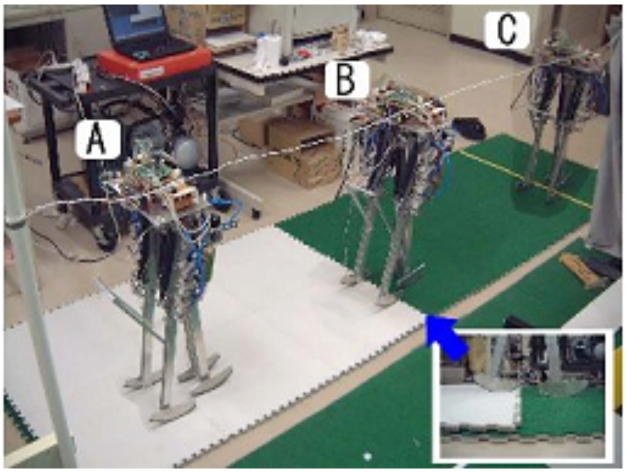

Figure 5: The robot walks down over a difference 4[mm] in level on an urethane foam floor.

3.3. Feedback control of cycle time

We apply feedback control to make the walking cycle time $T(k)$ converge to a desired one T_d by changing the valve opening time $S(k)$ in every step:

$$S(k) = S(k-1) + K(T(k-1) - T_d), \qquad (1)$$

were K is a feedback gain constant. In this paper we chose $T_d = 560$[ms] according to the result shown in Figure 4. The feedback gain is selected empirically, $K = 0.3$.

We show experimental results that the robot can walk down over a difference in level (Figure 5). The floor is made from urethane foam, and the difference is 4[mm]. The walking trajectory of each trial differs from those of others since the initial position and posture cannot be reproduced identically. Therefore, we run 100 trials, to validate the effectiveness of the proposed scheme in a probabilistic way. As a result, the robot can walk over the difference 82/100 times with the proposed feedback controller, whereas 10/100 times without it. This result tells that the proposed controller can deal with the disturbance provided by walking over the difference. In Figures 6 and 7, we show changes of the walking cycle without and with the controller. At the position of the difference, the walking cycle largely decreases, and the controller can deal with it to recover the walking cycle.

4. Discussion

Since walking is locomotion, the foot positions always change, and characteristics of the floor also changes at every foot step. Also, the characteristics is affected by the dynamics of the walking robot. So far, such interaction between the walking robot and the floor is totally ignored by just kinematically modelling them. In real situations, however, such variation cannot be ignored. Moreover, if the

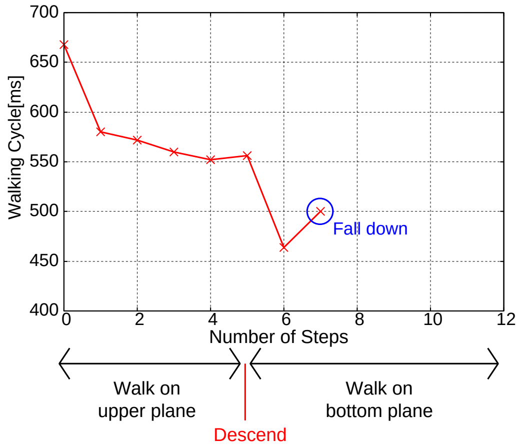

Figure 6: Change of the walking cycle without the proposed feedback control: Because of the difference, large cycle change occured at the 5th step, and the robot fell down at 7th step.

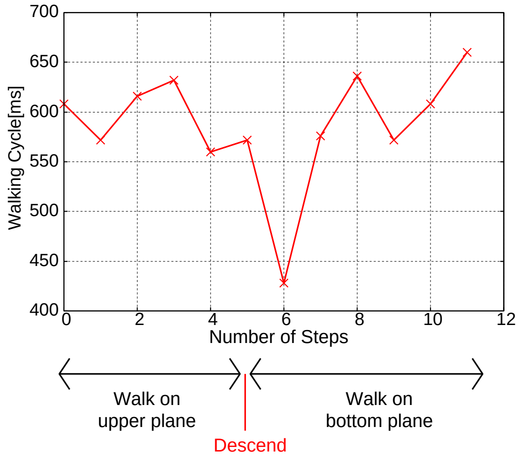

Figure 7: Change of the walking cycle with the proposed control: Because of the difference, large cycle change occured at the 5th step, but the robot could recover from it.

robot is designed for passive walking, the joints are backdrivable, and therefore, the dynamics of the terrain and that of the robot are strongly coupled. From these reasons, it is not supposed to be appropriate to model the floor by a deterministic model like a spring/damper model that is often adopted in the simulator. We proposed a simple way to identify the relation between the valve opening time (the driving input) and the walking cycle (the output), and to apply feedback control by utilizing the relation. Since the interaction between the robot and its environment is not negligible to build an adaptive robot [9], we believe that the proposed scheme will open a new horizon to control walking robots.

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References

[1] Tad McGeer. Passive dynamic walking. *The International Journal of Robotics Research*, 9(2):62–82, 1990.

[2] K. Ono, R. Takahashi, T. Shimada, and A. Imadu. Self-excited walking of a biped mechanism. In *Proceedings of the International Symposium on Adaptive Motion of Animals and Machines*, 10 2000.

[3] Fumihiko Asano, Masaki Yamakita, and Katsuhisa Furuta. Passive dynamic walking and energy-based control laws. In *Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems*, pages 1149–1154, 2000.

[4] Y. Sugimoto and K. Osuka. Walking control of quansi-passive-dynamics-walking robot “quartet iii” based on delayed feedback control. In *Proceedings of 5th International Conference on Climbing and Walking Robots (CLAWAR 2002)*, pages 123–130, 2002.

[5] M. Wisse and J. van Frankenhuyzen. Design and construction of mike: 2d autonomous biped based on passive dynamic walking. In *Proceedings of the International Symposium on Adaptive Motion of Animals and Machines*, 3 2003.

[6] Marc H. Raibert. *Legged Robots That Balance*. The MIT Press, 1986.

[7] Richard Q. van der Linde. Design, analysis, and control of a low power joint for walking robots, by phasic activation of mckibben muscles. *IEEE Trans. on Robotics and Automation*, 15(4):599–604, 1999.

[8] Hitachi Medical Corporation web page. http://www.hitachi-medical.co.jp/english/index.htm.

[9] Rolf Pfeifer and Christian Scheier. *Understanding Intelligence*. The MIT Press, 1999.