Walking Stabilization of Biped with Pneumatic Actuators against Terrain Changes

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***Abstract*— Humans are supposed to utilize its joint elasticity to realize smooth and adaptive walking. Although such human-like biped walking is strongly affected by the terrain dynamics, it was not taken into account in robotic bipedalism since it is very difficult to model the dynamics formally. In this paper, instead of modeling the dynamics formally, we propose to estimate the relationship between actuation (air valve opening duration) and sensing (touch sensor information) by real walking trials, and to stabilize walking cycle by utilizing it. Since the terrain dynamics is involved in the relation, we can avoid to model it formally. We conducted walking experiments on various types of terrain to demonstrate the effectiveness of the proposed method.**

***Index Terms*— pneumatic actuator, biped walker, walking sabilization**

Antagonistic drive by pairs of muscles is supposed to play an important role in the human bipedalism. Human can easily change the joint stiffness adaptively in order to walk on various kinds of terrain. In such a case, however, the walking is strongly affected by terrain conditions such as stiffness, damping, and friction. In the existing study on robotic bipedalism, however, they did not take the dynamics into account since it is very difficult to model it formally. In the previous study on robotic biped walking, they only dealt with the static property of the terrain [1], [2], [3]. Therefore, there are few reports on antagonistic driven walking of robots although the drive is expected to be effective for adaptation.

To adopt the antagonistic drive, therefore, it is inevitable to model the terrain as well as the robot body. However, it is so difficult to model the physical interaction between the robot body and the terrain such as collision and friction formally [4]. In this paper, instead of modeling the interaction formally, we propose to estimate the relationship between actuation (air valve opening duration) and the behavior (observed by touch sensors) by real walking trials, and to stabilize walking cycle by utilizing it. Since the terrain dynamics is involved in the relation, we can avoid to model it formally.

We have designed a biped walker *Que-Kaku* driven by antagonistic pairs of pneumatic actuators trying to realize adaptability of human-like bipedalism. We adopted McKibben muscle actuators [5] to emulate human's antagonistic drive, but as a result, the robot dynamics becomes complicated because of their non-linearity and the hysteresis effects. Wisse and van Frankenhuyzen designed a similar biped mechanism and showed its walking ability by utilizing its well-designed dynamics [6]. However, they did not utilize the estimated relationship between actuation and the behavior obtained by the real walking trials, which makes building a controller easy. We also adopt the same design principle to make use of the passive dynamic walking [7], [8], [9], and apply a simple feedback control by utilizing estimated relation between actuation and behavior.

In the following sections, we first introduced the specifications of the biped walker Que-Kaku. Then, the controller is proposed by utilizing estimation between actuation and behaviors of the biped. Finally, experimental results demonstrate that Que-Kaku can walk on various types of terrain adaptively by the proposed method.

I. Biped walker with pneumatic actuators

A. specification of the robot

We have developed a biped robot driven by antagonistic pairs of pneumatic actuators shown in Fig.1. We adopted McKibben artificial muscles [5] made by HITACHI Medical Corporation [10]. Its length and radius are 0.2 [m] and 0.02 [m] (when it contracts), respectively. It generates approximately 800 [N] when the pressure in the inner tube is 0.7 [MPa]. Fig.1 shows an overview of a control system for one joint driven by an antagonistic pair of actuators. Each actuator has supply and exhaust valves that are controlled by a D/A converter through an amplifier. Joint angles are measured by potentio meters, and ON / OFF sensor on the sole detects the collision of the ground. The data are obtained through an A/D converter.

Fig.2 shows the structure of the developed planar walking robot, *Que-Kaku*. The height, width, and weight of the robot are 0.750 [m], 0.350 [m], and 5 [kg], respectively. It has four legs: two connected pairs of legs (outer and inner). Lengths of thigh and shank are 0.3 [m] and 0.35 [m], whose weights are 2.16 [kg] and 0.48 [kg], respectively. As it is designed to be self-contained, it has two CO_2 bottles on it as air sources each of which weighs 0.7 [kg] (a). The pressure of the bottle is 1.2[MPa] and it is regulated into 0.4 [MPa]. An amount of the bottle is 98 [ml] and the robot walks for 5 minutes using 2 bottles. The air is supplied into and exhausted by

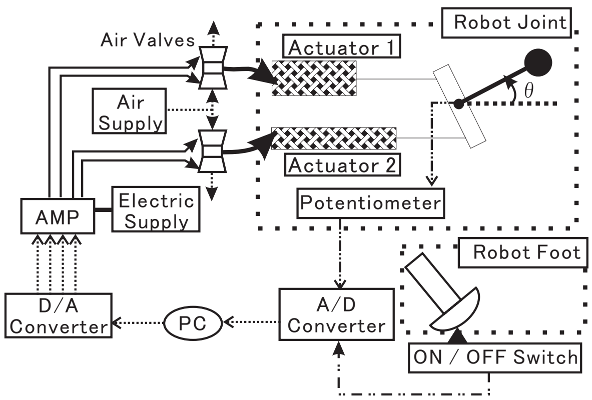


Fig. 1. Overview of the system

electromagnetic valves (b). The supply and exhaust valves can be close together. Therefore various length of the actuator can be set by an amount of supplied air, and it leads that various angle of the joint can be set by the duration to open valves. The electric cell to operate valves are set on the top of the robot (c). A capacity of the cell is much enough compared with the air bottles. The robot has a microcomputer made by iXs research [11] (d). It has round-shape soles whose radius and length are 0.125 [m] and 0.16 [m], respectively, determined by trial and error (e). The sole has an ON/OFF switch that detects collision with the ground.

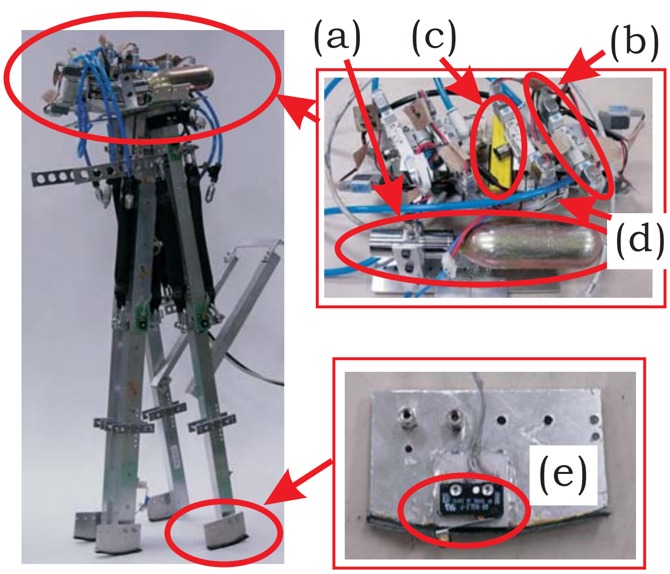


Fig. 2. Real biped walker with McKibben muscle actuators, Que-Kaku. (a) CO_2 bottles, (b) electromagnetic valves, (c) electric cell, (d) micro computer with amplifier, and (e) round foot and touch sensor

B. Strategy for walking

It is difficult for the robot we developed to follow the planned trajectory because the actuator has nonlinearity. One effective approach is, as Wisse et al. did [6], to generate the walking by operating the air valves. We operate the valves to generate a walking pattern shown in fig. 3 as mentioned below :

(i) at the k-th step, all valves are not operated for T_0 so that the robot can keep its posture,

(ii) after T_0, the valves are operated to rotate the hip joint for $S(k)$, and the knee is bent and extended within $S(k)$, and

(iii) all valves are not operated so that the robot keeps the posture until the foot of the swing leg touches the ground. After the heel strike, the swinging leg changes to be the support one, and return to the operation (i).

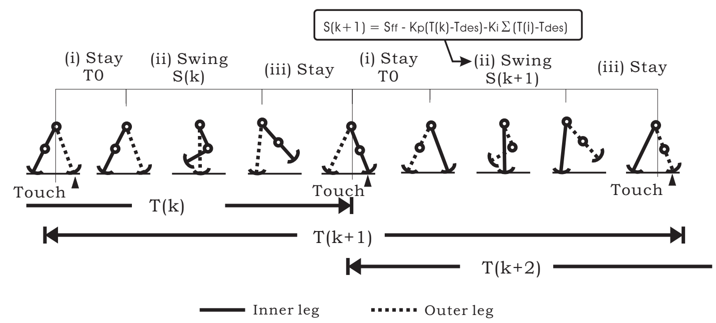


Fig. 3. Walking pattern and basic idea of a controller

In the operations (i) and (iii), the collision of the ground is detected by the switch on the sole shown in Fig. 2 (d). Operations (i)-(iii) correspond to periods (i)-(iii) in Fig. 3, respectively. Let $T(k)$ be a walking cycle from the heel strike to the next heel strike of the same leg. In the walking pattern, there are two walking parameters, T_0 and $S(k)$, which can be operated directly. The robot could walk over 30 steps (over 6 [m]) when T_0=23 [ms] and $S(k)$=240 [ms]. As a result, the robot could walk on a flat plane without controlling the position of the joint but adjusting the duration to open / close valves. However, the walking parameters are fixed and the robot cannot change a motion to stabilize walking against disturbance.

II. STABILIZATION OF WALKING CYCLE AGAINST TERRAIN CHANGES

A. design of feedback controller for pneumatic muscle walker

In order to stabilize walking against terrain changes, we deal not only the robot but terrain dynamics as controlled object (see fig. 4), and we design a feedback controller from causal relation between robot actuation and consequent sensory data. Utilizing such an approach, we need not derive the models not only of terrain but the robot with pneumatic actuators. We focus on walking cycle $T(k)$ shown in Fig.3 which are influenced by robot and terrain dynamics, and we observe the relation between open / close valve duration as the actuation and walking cycle as the causal sensory data.

We observed the relation between an opening valve duration to let a leg swing ahead (swing duration $S(k)$ in

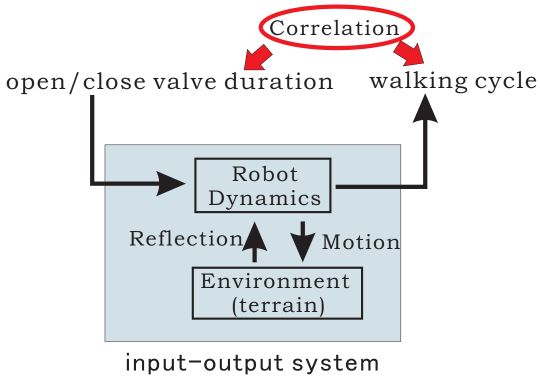


Fig. 4. One input / output system includes robot and environment dynamics. A sensory data, walking cycle, reflects both robot and terrain dynamics.

Fig.3) and walking cycle $T(k)$. As a result, we found positive correlation between them [12]. The positive correlation means that the walking cycle becomes longer when the swing duration is longer, and vice versa. Fig. 5 shows the relation between $S(k)$ and $T(k)$ when the robot walks with S(k)=180, 200, 220, 240, 260, 280, and 300 [ms] at each walking trial on a carpet. In the figure, $T(k)$ at each swing duration $S(k)$ is a mean of cycles of approximately 150 steps.

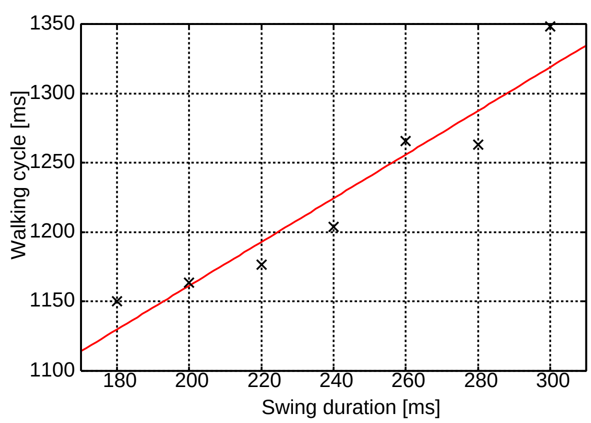


Fig. 5. A relation between swing duration $S(k)$ and walking cycle $T(k)$ on a carpet

We usage this correlation to propose such a PI controller for stabilizing walking cycle that is :

$$S(k) = S_{ff} - K_p(T(k) - T_{des}) - K_i \sum_{i}^{k}(T(i) - T_{des}), \quad (1)$$

where S_{ff} is a constant value, T_{des} is a desired walking cycle, and K_p, K_i are positive constant values.

B. walking controller against terrain changes

We utilize the controller on two types of terrain changes mentioned below. One is a terrain shape such as a difference in level and the other is a terrain condition such as a friction and stiffness. When the terrain is changed, the walking cycle is changed with same valve opening duration. It means that the terrain information can be detected by extracting difference of robot dynamics, and we use a controller expressed as eqn. (1) to set the duration $S(k)$.

1) change of terrain level: In the real world, there are many rough terrains and the locomotion is influenced by them. Here, we treat the case that the robot walks down a small difference in level. After the robot walks down, a center of mass moves ahead and the angular velocity becomes larger, therefore the walking cycle becomes shorter. The controller detects the change of the walking cycle, and set valve opening duration by letting desired walking cycle T_{des} in eqn. (1) be the cycle when the variance of the walking cycle is small.

2) change of terrain condition: The terrain condition, a friction and stiffness, influences the walking cycle. Fig.6 shows walking cycles at each step when the robot walks at $S(k)$=240 [ms] on the carpet and on the linoleum floor. This figure says that the walking cycles are different at each terrain condition. Fig.7 shows correlations between $S(k)$ and $T(k)$ at each terrain condition. In Fig.7, the swing duration should be changed to preserve same walking cycle. For example, when the robot walks on the carpet at $S(k)$ = 193 [ms], the walking cycle is 1150 [ms] (point A in Fig.7). When the terrain condition is changed to the linoleum floor, the walking cycle is changed shorter as 1050 [ms] (point A'), and the walking cycle should be changed as $S(k)$=253 [ms] to keep same walking cycle (point A").

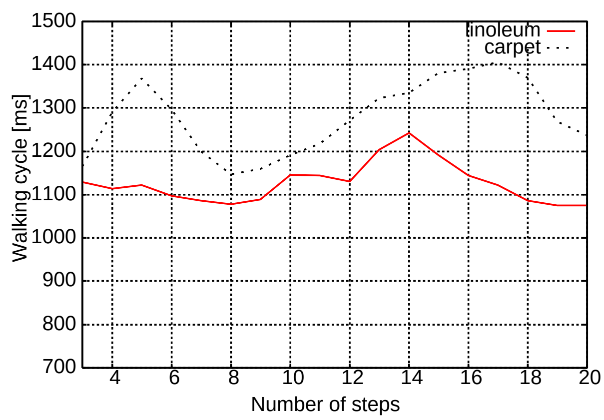


Fig. 6. The walking cycles when the robot walks on the different terrain at same swing duration $S(k)$ = 240 [ms] after 3rd step

If both one-to-one mappings between $S(k)$ and $T(k)$ are known, we can change $S(k)$ after terrain change, though we should detect the terrain condition change. However, it is impossible to measure all one-to-one mapping about all terrain condition, and it is difficult to detect the terrain condition changes. We then utilize the controller mentioned in eqn. (1). When the terrain condition changed with same swing duration, the walking cycle is changed and the controller set new swing duration according to eqn.1 by letting the desired walking cycle T_{des} be the one when the variance of the walking cycle is small.

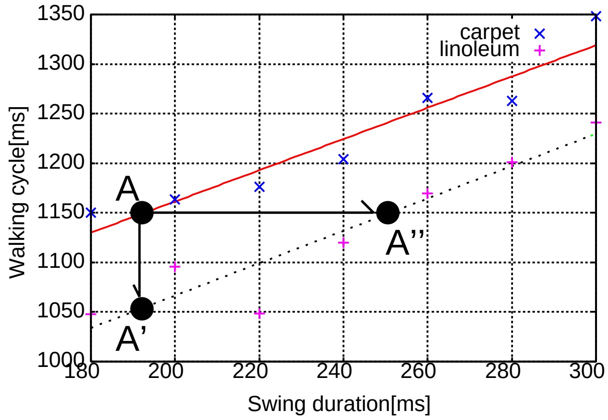


Fig. 7. A relation between swing duration and walking cycle on carpet and linoleum floor. When the robot walks at same walking duration, the walking cycle becomes shorter when the robot walks from the carpet and the linoleum (line A-A'), and $S(k)$ should be changed to walk at same walking cycle on various terrain (line A-A'')

III. Experiments

A. Experiment I : stabilization against terrain level change

First, we demonstrate a performance of the controller mentioned as eqn.1. Fig.8 shows a walking terrain. The robot starts at (A) and walks down at (B) where the terrain is changed in level as 8 [mm], and the trial is regarded as success when the robot reaches a goal (C).

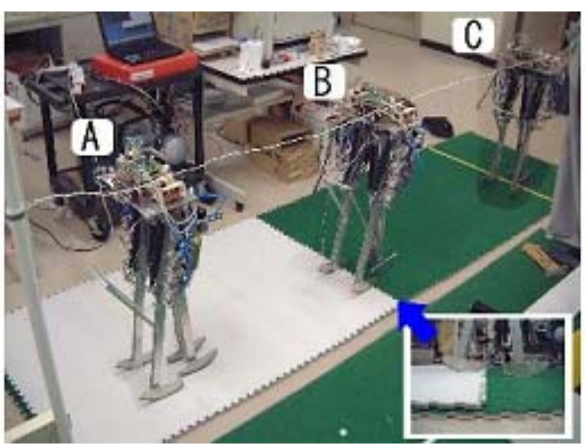
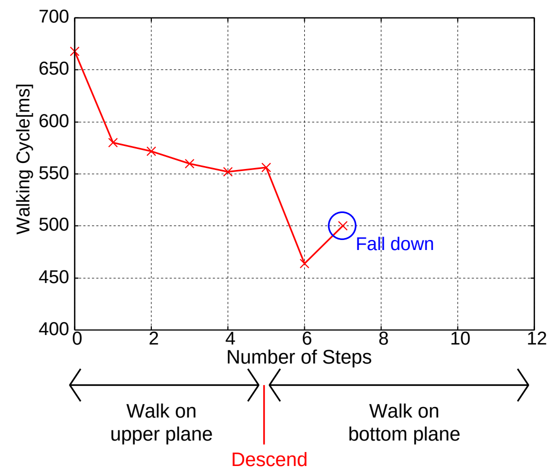
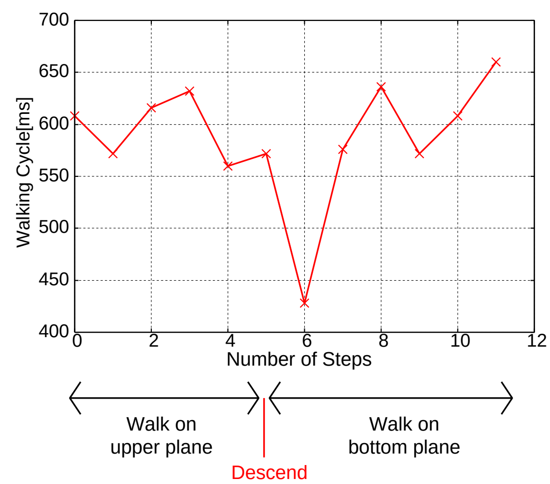


Fig. 8. Terrain with a small difference in level at (B).

In the experiment, the walking cycle was different in each trial because it depends on initial velocity and terrain condition, therefore we took statistical evaluation that measures a success rate of several trials. As a result, the robot with the controller could walk down 87 times per 100 trials while the robot without proposed controller could walk down only 10 times per 100 trials. At this experiment, the gains of the controller were Kp = 0.3 and Ki = 0.3. The walking cycles are shown in Fig.9. Note that the walking cycle in this experiment is measured from a moment when outer leg as support leg touches the ground to a moment when the inner leg as swing leg touches the ground. In the figure, the walking cycle becomes shorter as about 450 [ms] when the robot walks down the difference. The controller changes the duration $S(k)$ longer to let the walking cycle become longer. In the case of the robot with the controller, the walking cycle recovered as 600 [ms] meanwhile the robot without the controller fell down.



(a) Without walking cycle control. After 5th step, the walking cycle becomes shorter and robot is fallen down at 7th step.



(b) With cycle control. After descending, the walking cycle becomes longer within a few steps

Fig. 9. The result of walking cycle when the inner leg swings without / with the control.

Fig.10 shows a sequential picture when the robot with the controller walked down two differences in level. The robot without the controller could not walk down the steps in many trials. Through these two experiments, we could evaluate the effect of the controller to stabilize walking cycle against disturbance.

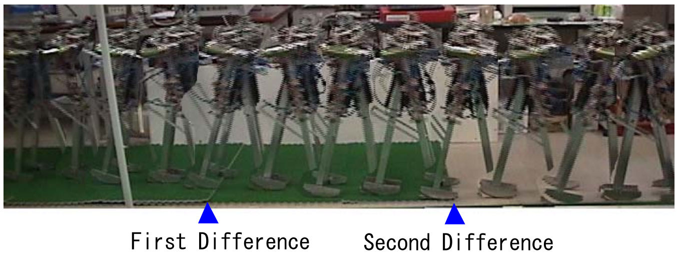


Fig. 10. The result of walking with proposed controller when the robot walks over two differences in level

B. Experiment II : stabilization against terrain surface material change

In the experiment, a desired walking cycle T_{des} was set as 1150 [ms], and robot walked from the carpet floor to the linoleum floor. When the robot walks on the carpet, swing duration is 193 [ms] in order that the walking cycle is 1150 [ms]. S_{ff} in eqn.(1) is then set as S_{ff}=193 [ms]. It is difficult to let two terrain surface levels be same, we then let the robot walk only on the linoleum and supposed that the terrain had already changed and the walking cycle had been changed at around 1050 [ms] at the beginning of the walking in the experiment. Fig.11 shows the result that the robot walks from the carpet to the linoleum floor. The walking cycles and swing durations at each step are the means of 10 walking trials. In Fig.11 (a), the walking cycle is adjusted as 1150 [ms], and in (b), the swing duration is converged into near $S(k)$ = 253 [ms] at which the robot walks at $T(k)$ = 1150 [ms] on the linoleum floor in Fig.7. In these figures, Kp = 0.5 and Ki = 0.5.

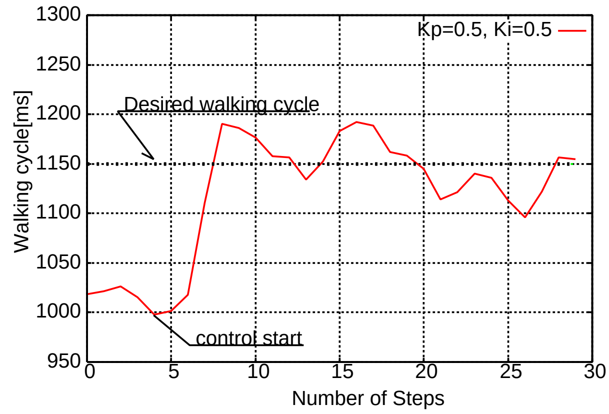
Fig.12 (a) shows the walking cycle and Fig.11 (b) shows the swing duration when Kp = 1.5 and Ki = 0.5. These figures show that the walking cycle and swing duration oscillate more widely than the case of Kp=0.5 and Ki=0.5. Though the walking cycle is converged into desired one, the robot in some trials fell down because the swing duration oscillated too widely. Through some trials with various gains Kp and Ki, we found that the walking cycle can converge into the desired one and the swing duration converges into the corresponding one on the linoleum floor by choosing appropriate gains. In conclusion, we could adapt the robot against the terrain changes by the controller. Notable feature of the controller is that the controller is not derived from explicit terrain and robot models and it only uses simple and cheap ON / OFF switches on the soles.

IV. Conclusion

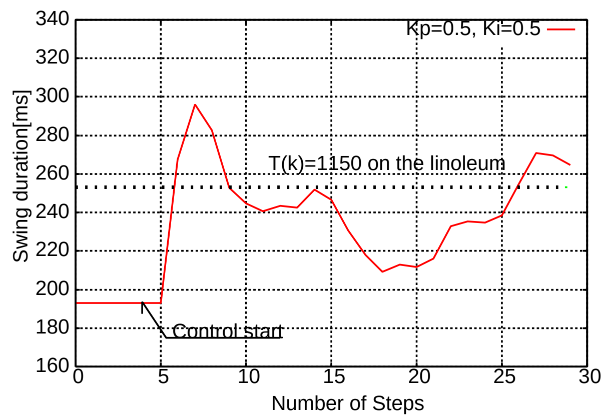
It is difficult to model the interaction between the robot and terrain dynamics although the terrain parameters are important factors for walking. It is also difficult to derive the model of our robot which has McKibben pneumatic actuators although the robot is thought to be suitable to generate dynamic motions such as running and hopping. In this paper, we focus on the walking cycle which depends not only on the robot motion but on the interaction between robot and terrain. We propose a controller to stabilize from the observation of the relation between actuation and consequent sensory information, that is, the valve opening duration to swing a leg and the walking cycle. This approach to design a feedback controller is useful in the case that the explicit model of the robot is difficult to be derived.

We utilized the controller for two types of the terrain changes. One is terrain shape such as a difference in level, and the other is terrain materials such as a friction and stiffness. The terrain changes influence the walking cycle, and the controller can detect the transition of walking cycle with same valve opening duration. The controller also change the swing duration to converge into desired walking cycle.

In the experiments, we confirmed the effect of the controller. The robot with the controller could walk over the difference in level as 8[mm]. The walking cycle became shorter when the robot walks down the difference, but the

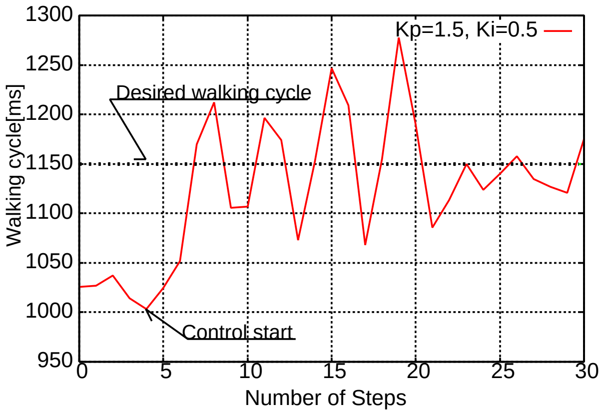


(a) walking cycle $T(k)$

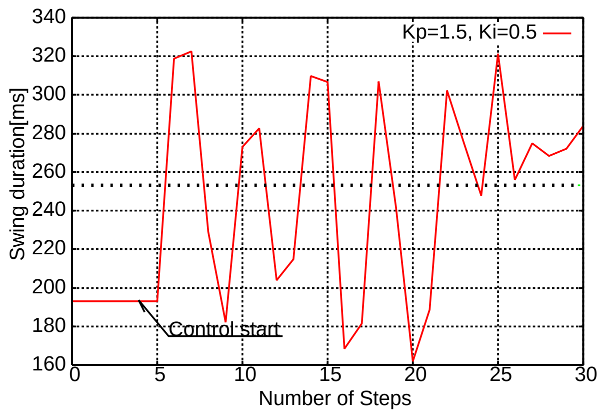


(b) Swing duration $S(k)$

Fig. 11. Walking cycle and swing duration when the robot walks from carpet to linoleum floor. The controller works after 4th step, and $Kp = 0.5$ and $Ki = 0.5$.



(a) walking cycle $T(k)$



(b) Swing duration $S(k)$

Fig. 12. Walking cycle and swing duration when the robot walks from carpet to linoleum floor. The controller works after 4th step, and $Kp = 1.5$ and $Ki = 0.5$.

controller recovered the walking cycle. We also confirmed the effect of the controller against terrain condition change through walking. The walking cycle was shifted when the terrain condition was changed and the controller set the swing duration to converge into the same cycle as the one before the terrain condition is changed.

The McKibben pneumatic actuator has springy nature. We will utilize such a feature to stabilize walking and to generate dynamic motions. We have built 3D biped walker that has two legs while Que-kaku has four legs. The 3D walker also has ankle joints, and it is expected that the walking cycle can be controlled by the stiffness of the ankle while swing duration keeps same period. We also expect that the ankle joint and knee joint can absorb an impulsive force on landing the ground and utilize the force to leave the ground. These are future issues.

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