Abstract

In this paper, we investigate the limit cycle of a biped walker driven by pairs of pneumatic artificial muscles. We show, experimentally, that the period of the limit cycle changes when we apply different control parameters and we estimate the relationship between the period and the parameters through trials. A step-by-step feedback controller is proposed to stabilize walking based on the estimated relation. The stability of the feedback controller is demonstrated by showing that the biped can walk down a stair.

KEY WORDS—biped walking, pneumatic actuator, artificial muscle, limit cycle

1. Introduction

Recently, a number of biped walkers have been designed and built to realize human-like walking (Hirai et al. 1998; Lim et al. 2002; Kaneko et al. 2004; Ogura et al. 2005). One can design the parameters of such a robot using both kinematics and dynamics. Most existing biped robots are, however, designed based on kinematic and static balance analyses, and their dynamic parameters, such as link mass and center of gravity, are determined arbitrarily. A standard way to control such robots is: (1) design the desired motion of each leg based on, for example, ZMP (Zero Moment Point) criteria (Vukobratovic and Stephanenko 1972) on a pre-determined terrain (Yamaguchi et al. 1998; Kajita et al. 2002); (2) derive the desired trajectories of joints based on the inverse kinematics; and (3) apply position-based control to track the trajectories. The robot is, therefore, stiff when it walks, energetically inefficient, and brittle against terrain disturbances.

There are several ongoing studies trying to realize natural and efficient walking by designing not only the kinematic parameters but also the dynamics. Passive dynamic walking (McGeer 1990; Goswami et al. 1996; Garcia et al. 1998), biped walking on an incline without any actuation, is supposed to be the key to designing such energy efficient walkers. By applying small control signals, it has been shown that biped robots designed for passive dynamic walking could walk on a flat plane (Collins et al. 2005; Wisse 2004; Asano et al. 2002; Sugimoto and Osaka 2002; Morita et al. 2004). These researchers used electrical motors to drive the walker via low-reduction gears or by direct drive motors, which made the robot very heavy.

A McKibben pneumatic artificial muscle (Chou and Hannaford 1996; van der Linde 1999; Klute and Hannaford 2000) is a promising candidate for the realization of powered passive dynamic walking. It can provide large forces with a lightweight mechanism and its elasticity preserves and releases impact energy. However, it is difficult to control the position of joints driven by such actuators precisely because of their complicated characteristics, such as time delay, hysteresis, and nonlinearity. To realize biped walking utilizing such actuators without formally dealing with their complicated dynamics, a feedforward controller was shown to be effective by making use of well-designed dynamics suitable for passive dynamic walking (Wisse and van Frankenhuyzen 2002). It was shown experimentally that the walking limit cycle was quite stable. However, there was no tunable control parameter and they could not change the limit cycle.

In this paper, we apply a limit cycle approach to analyze the effect of control parameter variation on the behavior of a biped driven by pneumatic artificial muscles. We design a real-world prototype that has tunable control parameters. We then apply a step-by-step feedback controller to stabilize walking.

The remainder of the paper is organized as follows. First, we describe the design of a 2D walker with McKibben pneumatic artificial muscles. Second, we estimate the relationship between the control parameter and the period of the limit cycle through experimental trials. Based on this relationship, we
derive a step-by-step feedback controller to stabilize walking. Finally, we demonstrate that the biped can walk down a stair with using the proposed feedback.

2. A 2D Biped Walker with Pneumatic Artificial Muscles

There have been several studies into controlled actuation to stabilize a passive dynamic walker whose motion is restricted to the 2D sagittal plane. Most of them adopted electric servomotors to drive joints (Asano et al. 2002; Sugimoto and Osuka 2002; Morita et al. 2004). The use of electric motors to drive the walker, requires the adoption of relatively low reduction gears to preserve back drivability of the hip joint to enable the leg to swing freely according to gravity, which results in large motors, e.g. direct drive motors (Sugimoto and Osuka 2002; Morita et al. 2004).

On the other hand, a McKibben pneumatic artificial muscle is a promising candidate for the realization of powered passive dynamic walking since it can provide large forces with a lightweight mechanism and its elasticity preserves and releases impact energy. In Figure 1, we show the architecture of a planar biped walker driven by antagonistic pairs of McKibben pneumatic muscles.

Each actuator is driven by a 3-position solenoid valve with closed center position that can take three positions: supplying the air from the source, expelling air to the atmosphere, and closed. This is the technical difference from (Wisse and van Frankenhuyzen 2002), who adopt a 2-position valve that does not have the closed center position. The robot can realize a spring-like joint by just closing the valves of the antagonistic muscles. It can even regulate the stiffness by changing the amount of air inside. This allows the robot to have a tunable control parameter.

The robot has a touch sensor on each foot. The on/off information is fed to a single chip microcomputer H8 (Renesas Technology Co.). According to the information received, the computer outputs open/close commands to the solenoid valves. It has two 1.2 MPa CO₂ bottles as air sources each of which weighs 0.7 kg and a battery that weighs 0.1 kg. The supplied pressure is regulated at 0.7 MPa by pressure regulators.

We developed a real-world prototype, shown in Figure 2. All the joints are driven by McKibben pneumatic artificial muscles by HITACHI Medical Corporation (Hitachi) (Figure 3). The length and radius of the actuator are 0.2 m and 0.020 m (when it contracts), respectively. It generates approximately 800 N when the pressure in the inner tube is 0.7 MPa. The height, width, and weight of the walker are 0.75 m, 0.35 m, and 5 kg, respectively. It has four legs to avoid sideways swinging, two of which are connected to each other. The length and weight of its thigh are 0.3 m and 2.16 kg and those of the shank are 0.35 m and 0.48 kg, respectively.

Fig. 1. Architecture of a planar biped walker driven by antagonistic pairs of McKibben pneumatic muscles. The main feature of the walker is the 3-position solenoid valves with closed center position that enables the robot to control joint elasticity.

The robot is self-contained and has two air bottles with regulators, all control valves, a microcomputer board, and an electrical battery. It has six sets of 3-position solenoid valves that weigh 0.6 kg. It has round soles whose curvature and length are 0.125 m and 0.08 m, respectively. It has ON/OFF switches that detect collisions with the ground.

3. Effect of Control Parameter on Limit Cycle Period

3.1. A Feedforward Controller for Limit Cycles

Since the robot is designed appropriately, it can walk on a flat plane using a simple feedforward controller. Figure 4 shows schematic explanation of the controller.

(i) For \( T_0 \) after a foot touch signal, all valves are closed, and the robot retains the same muscle tension. The robot moves ballistically according to the inertial force.

(ii) After \( T_0 \), the hip actuator that drives the swing leg is supplied with pressurized air, while air is expelled from the antagonistic hip actuator driving the stance leg, for
Fig. 2. A 2D biped walker with McKibben artificial muscles. The robot is self-contained and has two air bottles with regulators, all control valves, a microcomputer board, and an electrical battery.

Fig. 3. The McKibben artificial muscle adopted for the biped robot. It is contracted when air is supplied (upper), and is relaxed when air is expelled (bottom).

\( S(k) \). The flexor and extensor muscles of the knee joint are operated in an appropriate way so as to avoid collision with the floor. Since the movement of the knee is small, it does not strongly affect the behavior.

(iii) \( T_0 + S(k) \) after the impact, all valves are closed 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, procedure (i) starts again.

Using this feedforward controller, the robot can walk stably on a flat urethane floor. In Figure 5, we show the cyclic motion of the hip joint when the robot walks, the control parameters being \( T_0 = 32 \text{ ms} \) and \( S(k) = 320 \text{ ms} \). From the figure, we can see that the robot falls into a cyclic motion after several steps.

3.2. Relation between Valve Opening Duration and Walking Period

The important feature of the controller is that it can change the valve opening duration \( S(k) \) because we adopt 3-position valves. From preliminary experiments, we found that the time to fill the McKibben air muscle was approximately 0.5 s no matter how large the supply pressure. Therefore, we can change the propulsion force by changing \( S(k) \) up to 0.5 s.

Although we can expect that walking behavior will change when we change \( S(k) \), the relation between the parameter and the walking behavior is not clear because of the nonlinear dynamics of the actuator and of the unknown dynamics of the terrain. Therefore, we estimate the relationship between the parameter and the behavior through experimental trials.

In this paper, we investigate the relation between the valve opening duration \( S(k) \) and the walking period \( T(k) \). The other control parameter \( T_0 \) is fixed throughout the experiments. As mentioned above, \( S(k) \) influences the propulsion force of the walker; we can expect a longer walking period \( T(k) \) when \( S(k) \) increases.

We conducted experimental trials as follows: first, \( S(k) \) is 320 ms for 5 steps to stabilize walking. Then, suddenly \( S(k) \) is changed to a random value between 200 ms and 450 ms and we observe the walking period \( T(k) \). On the urethane floor, the robot can keep walking even if the control parameter is changed suddenly. In Figure 6, we plot \( S(k) \) versus the walking period \( T(k) \). We set control parameter \( T_0 \) to be 32 ms throughout the trials. Although the relation between \( T(k) \) and \( S(k) \) is a little blurred because the dynamic of the terrain is not deterministic, \( T(k) \) appears to be proportional to \( S(k) \).


The relationship obtained can be utilized to derive step-by-step feedback control to stabilize walking.
Fig. 4. Feedforward controller: schematic explanation of when to actuate the muscles and when to relax them.

Fig. 5. An example of the cyclic motion of the hip joint when we apply feedforward control to the prototype. The control parameters are $T_0 = 32$ ms and $S(k) = 320$ ms.

4.1. Designing a Feedback Controller to Regulate the Walking Period

We found that $T(k)$ was almost proportional to $S(k)$ (Figure 6). Based on this, we can derive a step-by-step feedback controller to regulate the walking period:

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

where $K$ is a positive constant. This controller increases the valve opening duration $S(k)$ when the walking period is less than the desired period. Although we could add proportional feedback terms to eq.(1), we did not include them in the experiments since it was too sensitive. The stability of the controller will be discussed in more detail in the future.

4.2. Experiment: Walking over a Stair

In order to evaluate the proposed feedback controller, we conducted experiments with the biped robot walking over one 9 mm stair. Figure 7 shows the experimental setup. The floor is made of the same material used to obtain the relationship between the walking parameter and the walking period. The robot starts from position (A), walks over a stair at (B), and we regard the trial as successful when it reaches position (C).
Fig. 7. Setup for the experiment. The robot starts from (A), walks over the disturbance at (B), and reaches (C).

Fig. 8. Walking cycle of the robot with (a) / without (b) the proposed controller when walking over the difference in level.

The walking trajectory of each trial differs from any other since the initial position and posture cannot be reproduced identically. Therefore, we conducted 100 trials, to validate the effectiveness of the proposed scheme in a probabilistic way. The robot walked successfully over the stair 82/100 times with the proposed feedback controller, and 10/100 times without it. This result strongly suggests that the proposed controller can deal with the disturbance provided by walking over the stair. In Figure 8, we show changes of the walking cycle with and without the controller. At the position of the disturbance, the walking cycle generally decreases, and the controller can deal with it to recover the walking cycle.

5. Conclusion and Discussion

We have investigated the characteristics of the limit cycle of a biped driven by pneumatic artificial muscles. We designed a prototype walking robot that has 3-position solenoid valves so that we can tune control parameters to change the walking behavior. It has been shown that the limit cycle period can be changed by applying different control parameters. We estimated the relationship between the control parameter and the period through experimental trials. Finally, we designed a step-by-step feedback controller to stabilize walking based on the estimated relation.

The contribution of this paper is:
1. design of hardware that has tunable control parameters;
2. showing that the limit cycle behavior changes when a different control parameter is applied, and obtaining the relationship between the behavior and the parameter;
3. identifying the relation through experimental trials since the dynamics of the pneumatic muscles and the terrain cannot be modelled formally; and
4. designing a step-by-step feedback controller to stabilize walking based on the estimated relation, and showing experimentally its effectiveness.

Since walking is locomotion, foot positions always change, and the characteristics of the floor also change at every step. Also, the characteristics are affected by the dynamics of the walking robot. These interactions between the walking robot and the floor are totally ignored in kinematic models. In real situations, however, such variation cannot be ignored. Moreover, if the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and of the robot are strongly coupled. For these reasons, it is not appropriate to model the floor by a deterministic model like a spring/damper model, as is often adopted in simulations. 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, we believe that the proposed scheme will be of benefit in the control of walking robots.

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References


