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Oscillator-Controlled Bipedal Walk with Pneumatic Actuators

K. Tsujita*, T. Inoura, A. Morioka, K. Nakatani, K. Suzuki, T. Masuda

Osaka Institute of Technology, Osaka, Japan

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Abstract

The development of an oscillator controller for a bipedal robot with antagonistic pairs of pneumatic actuators is reported. Periodic motions of the legs switch between the swinging and supporting stages based on the phase of the oscillators. The oscillators receive touch sensor signals at the end of the legs as feedback when the leg touches the ground and compose a steady limit cycle of the total periodic dynamics of bipedal locomotion. The effectiveness and performance of the proposed controller were evaluated with numerical simulations and experiments with the hardware.

Keywords: Pneumatic acturator; Bipedal walk; Oscillator control

1. Introduction

Locomotion is an important function of mobility. Human bipedal locomotion is especially mobile and adaptable to variations in the environment.

There has been a lot of research on bipedal robots driven by DC rotary actuators with local position feedback controls. However, most of them consume a lot of energy and their knees are always bent because they are based on high-gain position control of the joints with inverse kinematics for given trajectories of the legs. This type of robot cannot utilize its own dynamics for good energy efficiency or adaptive adjustment of physical properties of the body mechanism during locomotion. Furthermore, DC rotary actuators have serious difficulties in maintaining their power-weight ratios, which limits the functions of the robots' mobility.

Leg motions in bipedal locomotion have two essential stages. One is the swinging stage and the other is the supporting stage. In the swinging stage, the actuator forces are relaxed; the joints become less stiff and more passive. In the supporting stage, stiffness of the joints increases due to forces generated by the antagonistic pair of actuators. By controlling and tuning the stiffness of the joints through the balanced adjustment of the generated force of such a pair of actuators, the robot is expected to become more adaptive to variations in the environment and in the surface of the ground.

Hosoda et al. built a 3D bipedal robot driven by antagonistic pairs of McKibben actuators. This robot has a well-balanced design and body mechanism with a simple timing controller for switching between the leg motion stages and was able to walk stably and steadily. But the control parameters, such as the time period for each stage, are determined based on trial and error.

This article reports the development of an oscillator controller for bipedal robots with antagonistic pairs of pneumatic actuators. In the proposed controller, non-linear oscillators are assigned to each joint. Periodic motions of the legs are switched between the swinging and supporting stages based on the phase of the oscillators. Oscillators contain network architecture, interact mutually with each other, and receive touch sensor signals as feedback signals at the end of the

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*Corresponding author. Tel.: +81 6 6954 8585, Fax.: +81 6 6954 8585
E-mail address: tsujita@ee.oit.ac.jp

legs when the leg touches the ground. At the moment the leg makes contact, the oscillator phase is reset, and the swinging stage is forced to change to the supporting stage. These dynamic interactions make possible mutual entrainments between oscillators and create a steady limit cycle of the total periodic dynamics of bipedal locomotion.

The effectiveness and performance of the proposed controller for the bipedal robot were investigated through numerical simulations and experiments with the hardware.

2. Model

Figure 1 is a schematic model of a planar bipedal robot. The robot has two legs, composed of two links, and a main body. The contact model at the end of the leg assumes one point of support. The motion of the robot is restricted to the sagittal plane, i.e. it is assumed to be in 2D motion. The supporting and swinging legs are numbered 1 and 2, respectively. The position vector from the origin of the inertial coordinate to the center of mass (C.M.) of the main body is defined as $r_0 = (r_{0x}, r_{0y})^T$.

The rotational angle of the main body and each link of the legs are defined as shown in Fig. 1.

The state variable is defined as follows:

$$z = [r_{0x}, r_{0y}, \theta_0, \theta_1^{(1)}, \theta_2^{(1)}, \theta_1^{(2)}, \theta_2^{(2)}]^T \quad (1)$$

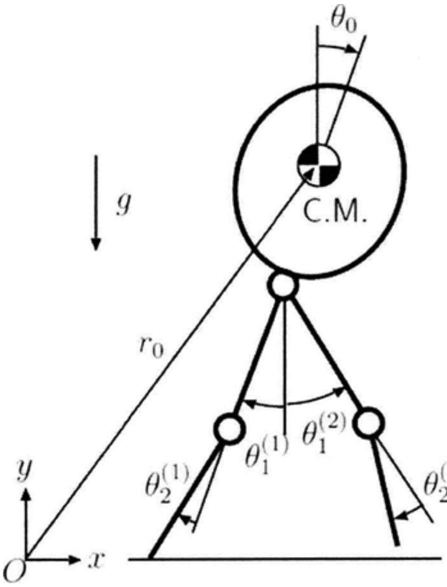

Fig. 1. Schematic model of a bipedal robot.

Equations of motion for state variable z are derived as:

$$M\,d^2z/dt^2 + H = G + T + E\,\lambda \quad (2)$$

where M, H, G, and E are inertia matrix, nonlinear term, gravity term, and Jacobian matrix, respectively. λ is the reaction force at the contact point of the supporting leg. Vector T is composed of the input torques at the rotational joints of the legs $T_j^{(i)}$, $i=1,2, j=1,2$, which are generated by the antagonistic pairs of pneumatic actuators.

$$T = [0 \quad 0 \quad 0 \quad T_1^{(1)}\, T_2^{(1)}\, T_1^{(2)}\, T_2^{(2)}]^T \quad (3)$$

3. Control scheme

Figure 2 shows the control scheme of the proposed system. The controller has a nonlinear oscillator network with individual oscillators assigned to joints. The antagonistic pairs of pneumatic actuators are driven by timing signals as functions of the oscillator phases. The contact sensor signals are feedback for the oscillator network. These dynamic interactions cause the entrainment and generate a stable limit cycle for locomotion. With the oscillator phase defined as $\varphi_m^{(k)}$ $(k,m=1,2)$, the oscillator network can be expressed in the following equations;

$$z_m^{(k)} = exp(j\,\varphi_m^{(k)}) \qquad j\text{: Imaginary unit} \quad (4)$$

$$d\varphi_m^{(k)}/dt = \omega + K(\varphi_m^{(l)} - \varphi_m^{(k)} - \gamma_{lk}) + \delta\,(\varphi_{Ak} - \varphi_m^{(k)}) \quad (5)$$

$$\gamma_{12} = -\gamma_{21} = \pi \quad (6)$$

$$T_{mn}^{(k)} = F(\varphi_m^{(k)}) \quad (7)$$

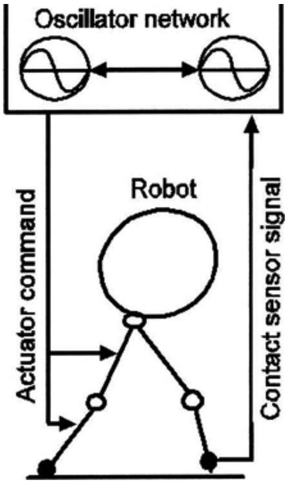

Fig. 2. System architecture.

where $z_m^{(k)}$ is the state of oscillator m of leg k, ω and K are constant numbers, and φ_{Ak} is the nominal value of oscillator m's phase at the moment of leg k's contact with the ground. δ is the impulsive function. γ_{lk} is the nominal phase difference between oscillators l and k. In bipedal locomotion, this value is given as π . $T_{mn}^{(k)}$ is the On/Off timing of the air valve of actuator n (n = extensor or flexor) of joint m of leg k and is given as a function of the oscillator phase.

4. Numerical simulations

Table 1 shows the physical parameters of the robot. Figure 3 shows the results of the numerical simulation and indicates walking cycle time. We found that the system reached a stable limit cycle and achieved steady locomotion with the proposed control system. Figure 4 is the time history of the vertical reaction force at the end of the leg. As can be seen in this figure, the system maintains steady locomotion, and the time history of the reaction force has a well-known double maximum profile. It also should be noted that the proposed system effectively utilizes body dynamics (i.e. the legs' ballistic trajectories and the inverted pendulum mode) and obtains dynamic stability.

Table 1. Physical parameters of robot.

Length of body	0.20 [m]	Mass of body	1.32 [kg]
Length of thigh	0.25 [m]	Mass of thigh	0.59 [kg]
Length of shank	0.25 [m]	Mass of shank	0.47 [kg]
Total height	0.70 [m]	Total mass	3.44 [kg]

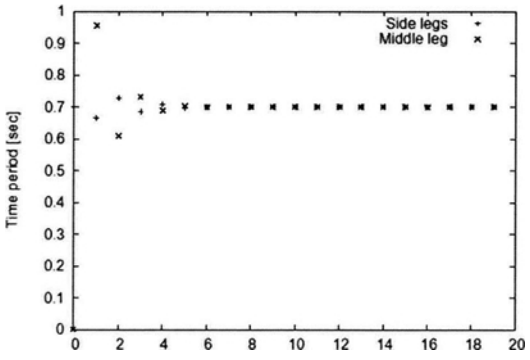

Fig. 3. Walking cycle time.

Figure 5 shows the actual cycle times when the nominal time periods for the oscillators are changed during locomotion. The x and y axes are the nominal and actual time periods of the walking cycle, respectively. These results show that the system can continue stable locomotion over various lengths of time. This means the system has a considerably wide basin of attraction for limit cycle.

5. Hardware experiments

We did a walking experiment using the robot shown in Fig. 6. The model robot has three legs, two side legs and one middle leg. The two side legs are connected to each other with a connection rod, and the motion of each side leg is the same. This mechanism ensures that the motion of the robot is restricted to the sagittal plane.

Figure 7 illustrates the architecture of the experimental setup. The host computer controls the electric valves. The contact signal from the touch sensor is input to the host computer through an A/D converter. The air pressure is adjusted to 0.5 [MPa].

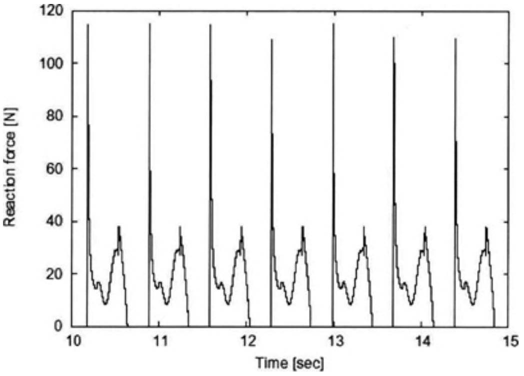

Fig. 4. Reaction force.

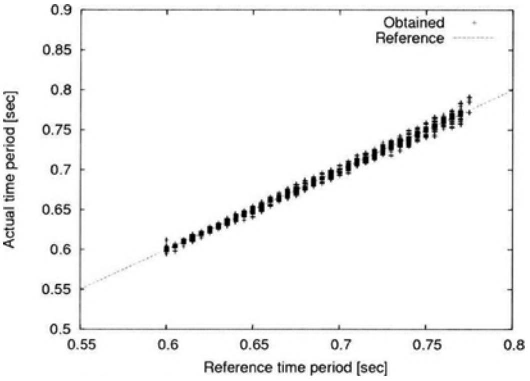

Fig. 5. Walking cycle time at variable reference.

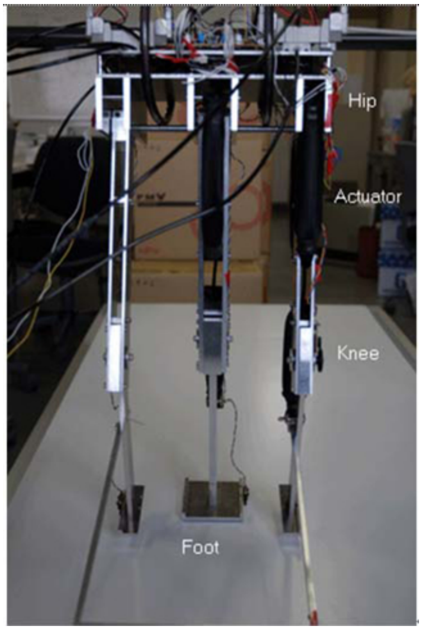

Fig. 6. Robot hardware.

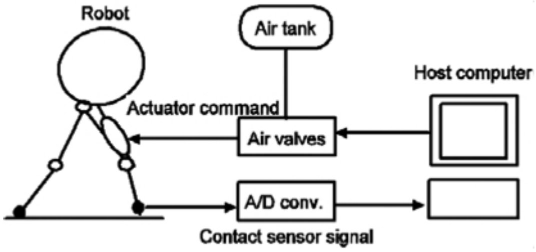

Fig. 7. Architecture of hardware setup.

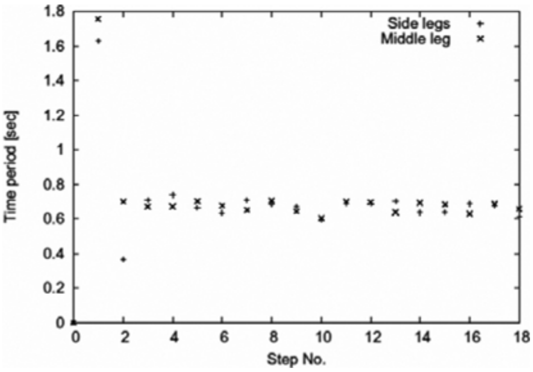

Fig. 8. Walking cycle time for each leg.

Figure 8 shows the walking cycle time for each leg. We can find that cycle time converges to a fixed time period (0.7 [sec]) with only slight deviations. These deviations are caused by fluctuations in the surface of the ground. The results indicate the efficiency of the developed system.

6. Conclusions

We developed a bipedal robot with antagonistic pairs of pneumatic actuators controlled by a nonlinear oscillator network. Periodic motions of the legs are switched between the swinging and supporting stages based on the phase of the oscillators. The oscillators receive touch sensor signals at the end of the legs as feedback when the leg touches the ground and compose a steady limit cycle of the total periodic dynamics of bipedal locomotion. The effectiveness and performance of the proposed controller for the bipedal robot were evaluated with numerical simulations and experiments with the hardware.

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References

McGeer, T., 1990, “Passive Dynamic Walking,” *International Journal of Robotics Research*, Vol.9, No.2, pp.62~82.

Wisse, M. and Frankenhuyzen J., 2005, “Design and Construction of MIKE; a 2-D Autonomous Biped Based on Passive Dynamic Walking,” *Adaptive Motion of Animals and Machines*, pp.143~154.

Linde, R. Q., 1999, “Design, Analysis and Control of a Low Power Joint for Walking Robots, by Phasic Activation of Mckibben Muscles,” *IEEE Trans. Robotics and Automation*, Vol.15, No.4, pp.599~604.

Ono, K. and Yao, X., 2005, “Simulation Study of Self-Excited Walking of a Biped Mechanism with Bent Knee,” *Adaptive Motion of Animals and Machines*, pp.131~142.

Taga, G., 1995, “A Model of the Neuro-musculo-skeletal System for Human Locomotion: I. Emergence of Basic Gait,” Biological Cybernetics, No.73, pp.97~111.

Sugimoto, Y. and Osuka, K., 2002, “Walking Control of Quasi-passive-dynamic-walking Robot 'Quartet III' Based on Delayed Feedback Control,” *proceedings of 5th CLAWAR*, pp.123~130.

Hosoda, K., 2005, “Design and Control of a 3D

Biped Robot Actuated by Antagonistic Pairs of Pneumatic Muscles," *in 3rd International Conference of Adaptive Motion of Animals and Machines*.

Collins, S., Ruina, A., Tedrake, R. and Wisse, M., 2005, "Efficient Bipedal Robots Based on Passive-Dynamic Walkers," *SCIENCE*, Vol.307, pp.1082~1085.

Verrelst, B. et al., 2005, "The Pneumatic Biped "Lucy" Actuated with Pleated Pneumatic Artificial Muscles," *Autonomous Robots*, Vol.18, No.2, pp.201~213.