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Human Gait-Based Bipedal Walking Robot Design in Progress

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Abstract: This work presents the mechanical human gait-based 3D bipedal walking robot. The robot mimics human walking through the push-off mechanism at the ankle, the passive knee bending mechanism, and the simple lateral balance control. To generate walking, it uses simple waveforms which are derived from human gait data. The preliminary experiment demonstrates that the robot walks stably.

Keywords: Bipedal walking robot

1. INTRODUCTION

Bipedal robot locomotion has been one of daunting research topics in robotics society. As pointed in [1], the biped robot design strategy can be inclusively classified in two approaches. First approach is based on precise joint-angle control, and mainly apply the zero moment point (ZMP) principle to realize stable walking. Many bipedal walkers have been designed with the control paradigm [2][3][4]. Mostly, they tend to walk with knee bending kept to maintain stability. The pose is to minimize weight acceptance impact during the ground touch. Hip actuation is a main forward thrust source unlikely to humans, and ankle-level push-off is unused much because stability maintenance is difficult. Because they require high precision and frequent response for control, this strategy requires high energy consumption. The other approach is based on passive-dynamic principle [5]. A robot in this category is called passive-dynamic walker (PDW). PDWs rule out precise joint angle control with large energy demands, and pursue a design powered by human-like efficient energy use. This approach may be comparable to humans in terms of gait appearance, energy use and control strategy. However, their mechanism and control strategy may hinder robust behavior implementations.

This work reports the first stage result to develop a simple bipedal walking robot. Our mechanical design of the robot is proposed to evaluate three interesting points:

1. Human gait-based control input trajectory
2. Forward thrust at ankle region by potential energy
3. Passive knee bending mechanism
4. Simple lateral balance control

2. MECHANICAL DESIGN

Our bipedal walking robot is shown in Fig. 1. The full robot is 420mm tall and weighs 2.18kg. Two 370mm long legs, a small torso and feet are included. The robot has 5 degrees of freedom: two at hip, one at knee, and two at ankle. Each leg in 3 dimensional space is actuated by three motors (Dynamixel RX-28).

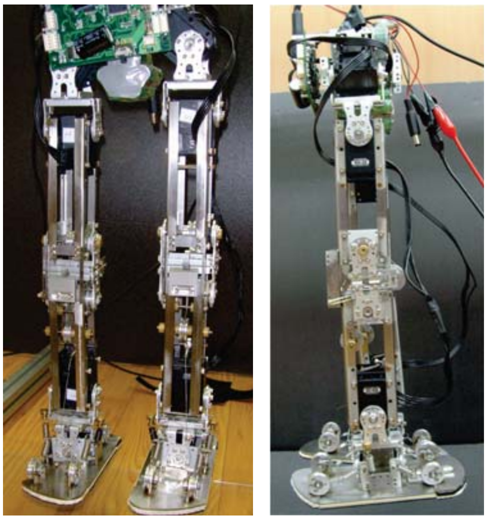

Fig. 1 Bipedal walking robot.

2.1 Foot and toe design

Foot consists of three parts, toe, middle foot body, and heel (Fig. 2(a)). Each part is 30, 100, 300 mm in length respectively. Fig. 2(b) shows each part respectively. The toe part is of a skewed curved shape similar to human toe parts outline. This makes a point contact possible when the foot pushes the ground. The point push may be beneficial to prevent thrusting the body in the wrong direction at the toe push instant.

The line outline, if any case, can push the body in the wrong direction so cause gait instability when the foot position is instantly wrong. The heel part is also of a curved shape. This realizes a point contact at the heel strike instant. The shape avoids unexpected (rotational) impact on body which may cause gait instability possibly during the heel strike. The toe part is jointly connected to the middle foot body and supported by a pair of passive springs. The heel part is connected to the middle foot body via stiff flat spring. Therefore, the heel and foot body compose almost a rigid body. However, the flat spring is still useful for impact absorption at landing

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phase. The whole foot bottom is covered by moderate sponge and rubber, which are used on table tennis rackets. They provide the damping effect like the foot skin. Especially the heel part has a ticker rubber layer for stable landing. A pair of passive springs between the heel and the foot body has also a role of damping the body in landing (heel-strike). A pair of passive springs between the toe and the foot body is critical in this robot walking. During stance-to-swing transition, the foot body is off the ground, but the toe part remains contacted on the ground. The lift of foot body pulls the springs, therefore, the springs earn the potential energy, which is released to thrust the upper body forward by pushing the ground at the moment of push-off. In terms of its role, the spring is similar to the archilles tendon in human body. This mimics energetically effective human walking mechanism to use powerful impulses at push-off [6]. Passive-dynamics-based walking robots use the similar strategies to minimize motor power requirements for push-off performance [7][8][9]. The robots usually equip the push-off springs around ankle joint to achieve ankle-extension. However, in our robot, the push-off springs operates via joint between the toe and the foot body. This design is due to clear reasons. Other robots generally have solid feet so there is no other choice but ankle joint to rotate feet. With solid feet, ankle extension in stance leg tends to require large potential energy in spring to lift the upper body, but it produces large forward thrust once the foot is off the ground. Therefore, it is difficult to maintain gait stability. To moderate the issue, robots usually have curved foot bottoms. However, they may still be able to produce high forward thrust and require careful control to achieve stable swing leg motions during swing phase and stable ground touch at swing-to-stance transition. For example, push-off process is mechanically constrained just after heel strike in [10]. In our robot, a proper amount of potential energy in spring is required for joint extension between the toe and the foot body, which is powerful enough to perform push-off. The flat feet in our robot guarantees more robust posture than curved feet against external pushes.

2.2 Ankle design

The shank and foot are jointed via ankle joint with a motor. The motor body is rigidly attached to the end of shank and its shaft rotates the foot in the sagittal plane. From the heel strike to toe-ff, the motor helps upper body moves around the ankle joint of stance leg as if inverted pendulum does. It is important to note that the motor is not a major forward thrust generator for forward thrust but the springs on the foot (details in previous section) is. However, ankle rotation can affect the push-off performance critically because push-off thrust is effectively obtained when foot rotation and body position are well timely synchronized. Therefore, the motor is a key operator for gait efficiency and stability.

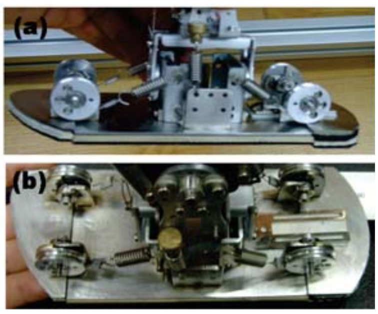


Fig. 2 Foot design.

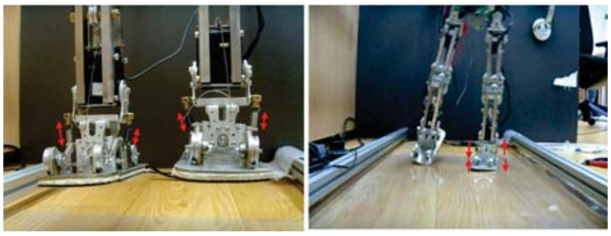


Fig. 3 Ankle design.

The ankle motion is also influential on knee bending mechanism, which will be discussed in next section. A passive spring is located on each side of the ankle to buttress the shank laterally as well as damp the contact impact in the coronal plane. Space between legs is a little wider at foot than at hip. The posture is beneficial to keep lateral stability. Therefore, the foot is designed to be inwardly a little tilt by locating a stiffer spring inside than outside. During push-off, the inside spring helps pull a stance leg in order to keep lateral stability from outward sway. The springs stiffness is decided experimentally.

2.3 Knee design

Locking mechanism is designed at knee to prevent hyperextension. Knee joint is locked after mid-swing up to the end of stance phase and unlocked during the remainder phase. As in Fig. 4, the locking mechanism is basically a type of latch. The latch arm is attached to the shank via hinge with a torsion spring. The latch body is rigidly attached to the thigh At the timing of push-off, ankle angle reaches a threshold value, then, a latch arm with a hook is pulled by a string which is connected from the foot via two pulleys, and detached from the latch body. The pulleys allow the foot rotation (push-off) to generate linear pulling force which is transferred through the string. The detachment allows the knee bending. After unlocking, knee flexes. The tip of latch body is connected to the top of shank through a spring. While knee bends, the spring gains energy, which is used to hold the shank at a certain degree. Then, inertial force drives the shank back to the extended position during forward swing phase. While extending the shank via knee joint, the ankle angle remains less than the threshold value, and string does not pull the latch arm. The torsion spring clicks the hook on the top of the latch arm into the slit of the latch surface to engage locking, Then, leg is robustly extended. Both the hook and latch surfaces are of curvature. The hook moves along the latch surface with a line contact to minimize friction. The string includes two springs serially and intermediately. The springs strain the string minimally even with no ankle-driven pulling force. Therefore, they prevent the string from leaving out of pulleys. This mechanically passive mechanism requires no extra electric power for operation.

$$LockingMechanism(\theta_a) = \begin{cases} locked & \text{if } \theta_a < c \\ unlocked & \text{otherwise} \end{cases}$$

where θ_a is the ankle angle. A threshold value c is 20 degrees.

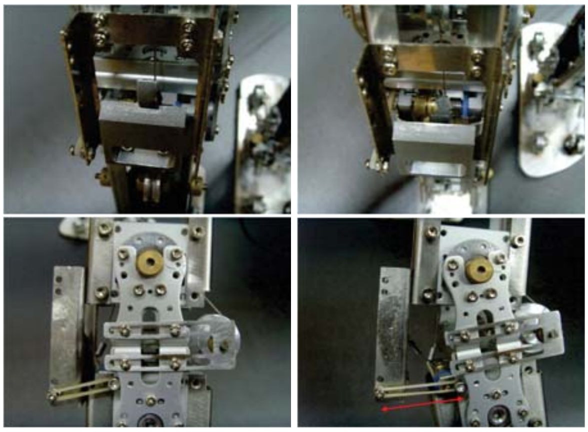


Fig. 4 Knee design.

2.4 Hip design

The hip design is presented in Fig. 5. A small torso and both legs are joined around hip. A drive motor is located on each hip. A motor attached to the thigh drives anterior-posterior swing relative to torso. The motor is rotated 10 degree outward, therefore, legs trajectory is drawn outward during forward swing from the top view. The location mimics human leg posture and is very helpful to maintain lateral stability as well as forward balancing. Therefore, the leg is laterally mobile. A group of springs hold the leg laterally as in Fig. 5. The springs help improve lateral balancing during the ground contact. At swing phase, the springs pull the swing leg to help lifting. The lateral sway is used to achieve clear swings and improve lateral balancing. In torso, electronics and batteries are equipped. Dynamixel motors used in this robot are easily controllable by using a compatible controller board (CM-2+, Robotis, inc.). The controller relays control input signals from a PC to motors.

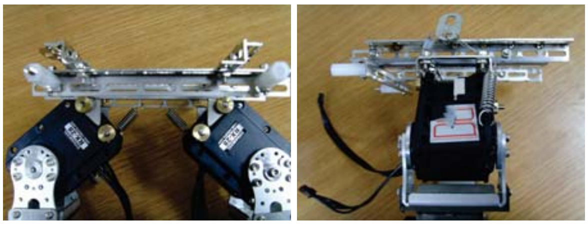
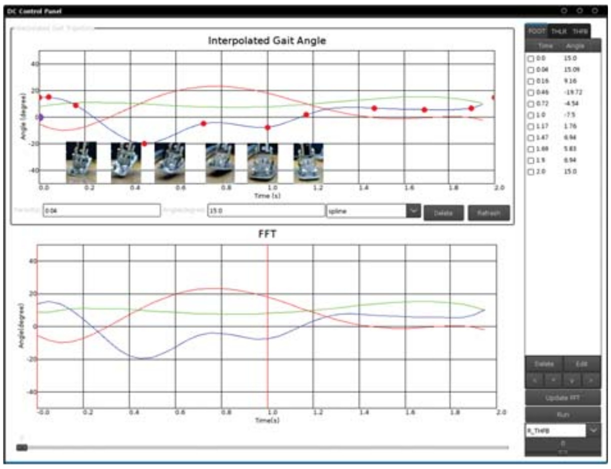


Fig. 5 Hip design.

3. CONTROL INPUT SIGNALS

Fig. 6 shows the program to feed the control input trajectory to motors. The red line depicts the control input trajectory to perform hip swing motion. The blue line is the control input trajectory at the ankle motor, the green line represents the control input trajectory for lateral balance control. The control input signals are produced by applying the Fast Fourier transform to human gait data.



Time	Angle
☐ 0.0	15.0
☐ 0.04	15.09
☐ 0.16	9.16
☐ 0.46	-19.72
☐ 0.72	-4.54
☐ 1.0	-7.5
☐ 1.17	1.76
☐ 1.47	6.94
☐ 1.69	5.83
☐ 1.9	6.94
☐ 2.0	15.0

Fig. 6 Control input program.

A gait cycle takes 1.5 seconds. The gait cycles are continuously repeated to generate walking.

A gait motion of the bipedal robot can be divided into four phases :

- 0.0 - 0.5 sec : Ankle push-off
- 0.5 - 0.8 sec : Knee bending
- 0.8 - 1.0 sec : Ground touch
- 1.0 - 2.0 sec : Weight support

4. EXPERIMENT

Fig. 7 shows time-series snapshots of a robot gait taken from the front(Fig. 7(a)) and the side(Fig. 7(b)) views. The robot walked 20 steps during 15 seconds. Its total walking distance was 100cm. Therefore, the robot walked at 6.67 cm/s with an average stride of 5cm.

5. CONCLUSION AND FUTURE WORK

This work illustrated a bipedal robotic walker design in progress. Further investigation is still required to improve the robot. For example, its walking speed is better to be higher. However, test results in this work support the feasibility of the design approach. In the future, walking speed and dynamic stability will be improved. Its design should be upgraded to attenuate impact during the ground touch. In addition, the effectiveness of the proposed design will be evaluated in terms of energy efficiency.

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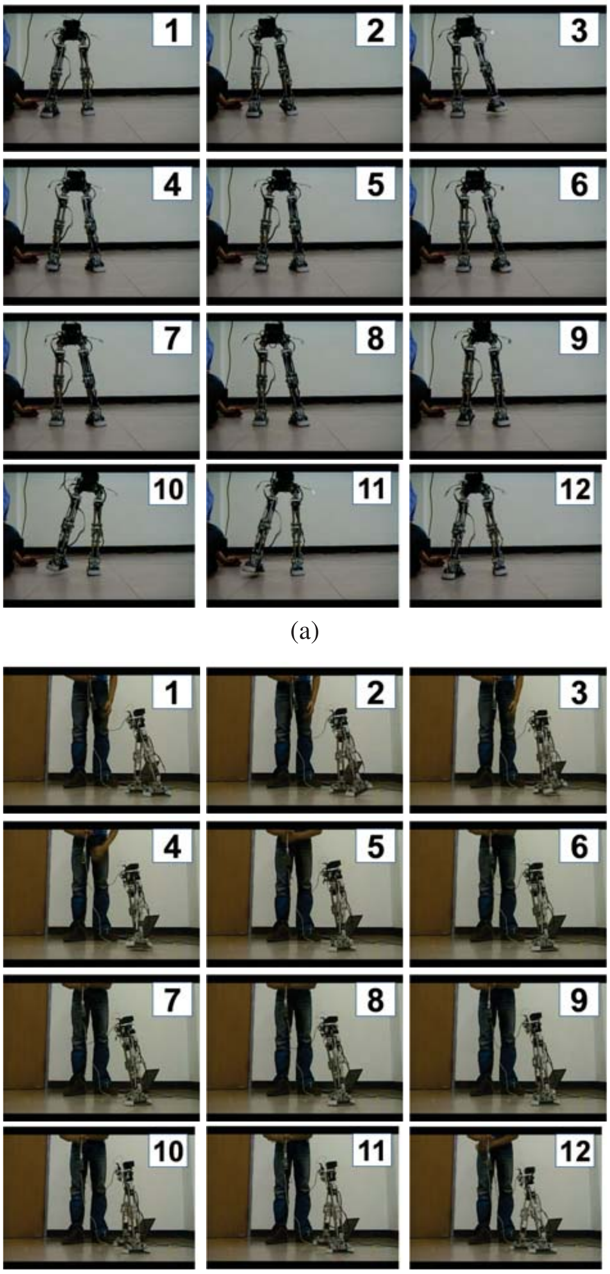

(a)

(b)

Fig. 7 (a) Snapshots of robot walking from front view, and (b) from side view.

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