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Biped Locomotion by Reduced Ankle Power

Keon Young Yi* and Yuan F. Zheng
Dept. of Electrical Engineering
The Ohio State University
Columbus, OH 43210

Abstract—
Power reduction in the ankle joints of a biped robot is considered in this paper. The ankle of human being has small torque and is very flexible within a certain range (very stiff near and beyond this range). This characteristic makes foot landing soft and gives a good contact between its sole and the ground. This feature can be implemented in a biped robot by using a small actuator for the ankle joints. A small actuator consumes less energy and makes the robot leg light. With less power in the ankle joints, walking becomes more difficult to control for the robot. This problem can be solved by providing the feedback control presented in this paper.

We demonstrate two locomotion examples, standing and walking respectively, to show the validity of the proposed control scheme. In standing, the control input is the displacement of the ankle joint of the supporting leg. The control mechanism decides the bending angle of the body and the position of the swinging leg. For walking, only the bending angle of the body is used to avoid the discontinuity of the control input. Experimental results are presented to show the effectiveness of the new mechanism.

I. Introduction

Mobile robots have been developed for many years. They have been designed with wheels, tracks and legs. The goal of many of these research and development efforts has been aimed to a robot that can replace human beings in industrial sites, especially in hazardous areas such as nuclear power plants and ocean floors. Most of these robots, however, cannot be easily adapted to environments designed for humans. If such devices are to be used at an industrial site, they will require special arrangements such as ramps to allow them to move around. Since these places are originally designed for humans, it is desirable to have robots of human build instead of modifying an industrial site for robots. Legged robots have better mobility in rough terrain since they can use isolated foothold that optimizes support and traction, whereas a wheel requires a continuous path of support. Moreover, the payload can be traveled smoothly despite pronounced variations in the terrain using an active suspension that decouples the path of the body from the paths of the feet. In the biped robot case, robot can move along narrow paths where a broad base of support is impossible.

To realize these advantages a great deal of research has been done in this field [1], [2], [3], [4], [5]. However, research on biped robot has been making slow progress because of the difficulty to maintain stable locomotion while the robot is walking on different floor conditions.

Recently, many researchers studied biped robots walking on different terrains [6], [7], [8] and with consideration of biped dynamics [9], [10], [11], [12], [13]. Analyses on walking/standing of human being also have been conducted [14], [15], [16], which reveal that the ankle of human being has small torque and is very flexible within a certain range (very stiff near and beyond this range). However, no one has addressed the same problem of a biped robot.

Walking method of a biped can be classified as two categories, dynamic walking and static walking. In static walking gait postures at every instance should be stable, while the gait postures of a dynamic walking are not stable in static but stable in dynamic because the torques from the dynamic energy changes are involved in every joints. In our previous work [6], the same type of motor was used for every joint. This is because in static walking, the ankle joints need a large torque. The flexibility of the ankle joint of human being makes foot easily compliant and gives a good and firm contact between its sole and the ground. This feature can be implemented in a biped robot by using a small DC motor for the ankle joint. A small motor consumes less energy than a large motor, and more importantly, it can make the leg light. Light legs can reduce the power consumption of other joints even further and enable the robot to walk faster. However, a less powerful ankle joint will make biped walking and even standing more difficult because static gaits can no longer be used in which the ankle joints needs large power to support the body of the robot. For small ankle power, the robot has to use the body and leg motions to dynamically balance itself.

In this paper, we present a biped robot with reduced ankle power and a controller which controls its motion. The flexibility of the biped ankle joint is implemented by limiting the maximum power of the ankle motor instead of replacing it with a small motor because the power of small motor needed can be obtained by experiment. The displacement of the ankle joint is used as the input to the controller, and a dynamic feedback mechanism is implemented for the controller. Biped locomotion of standing and walking will be implemented using the proposed con-

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*Dr. Yi is a visiting scholar from Hanyang University, Seoul, Korea.

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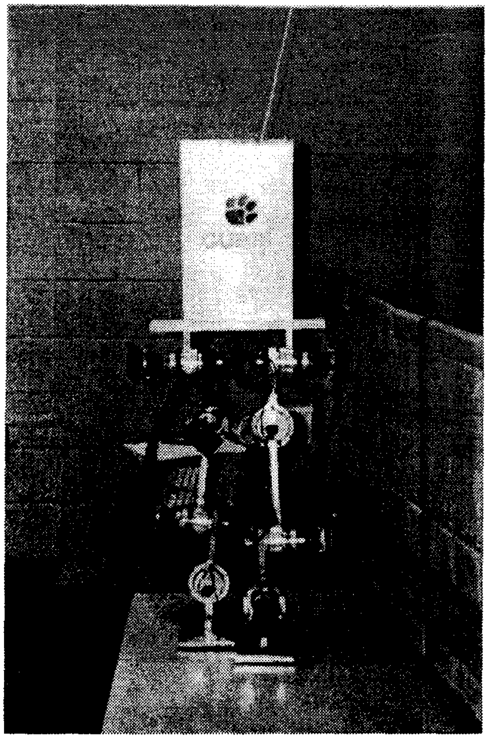

Fig. 1. The SD-2 Robot.

trol mechanism. In the standing case, the displacement of the ankle joint decides the bending angle of the body and the position of the swinging leg. In walking, only the bending angle of the body is used for balancing the robot because the leg motion is programmed for walking. Experimental results are presented for both cases.

In the following section we introduce the structure of the biped robot and its walking gaits. In the third section the control mechanism will be developed. The fourth section will be devoted to the discussion of the experiments including standing and walking. Finally, the work is summarized in the fifth section.

II. The SD-2 Biped Robot

The target of this study is a biped robot called SD-2 (Fig. 1) which was originally designed and built at Clemson University and is now at The Ohio State University([4]). In this section we will describe the structure of the robot and the static gaits that the robot uses to walk.

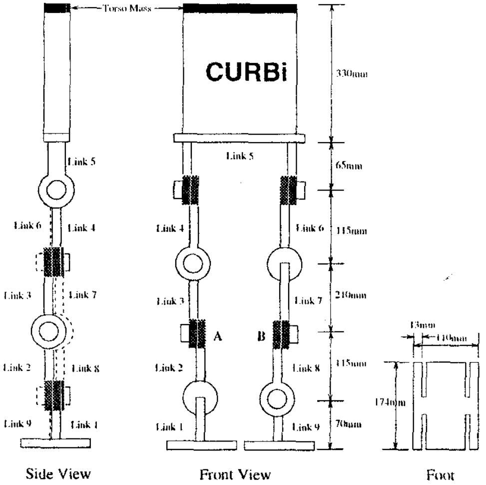

Fig. 2. The structure of SD-2 robot.

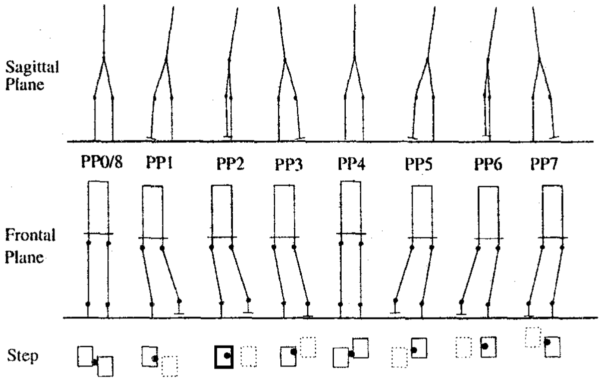

Fig. 3. The walking gait for the biped.

A. The Structure of the SD-2 Biped Robot

The SD-2 has nine links and eight joints as depicted in Fig. 2. Four joints control the motion in the sagittal (fore-and-aft) plane and the other four for the frontal (left-and-right) plane. Each leg has four degrees of freedom. The top two joints of each leg emulate the hip joint while the bottom two are for the ankle joint. Note that the robot has no knee joints. All the joints are actuated by the same type of DC motors which supply the same maximum power. For this particular research, however, the maximum power of the two ankle joints in the sagittal plane (joints marked with A and B) is reduced to a lower level.

B. The Gait of the SD-2 Biped Robot

The static walking gait for the SD-2 biped robot is shown in Fig. 3. In the figure, the dotted squares represent the feet in air, and the big dots represent the vertical projection of the center of gravity (COG). PPn, $n = 0,..7$, represent the primitive configurations of the robot. Between two primitive configurations is a phase of walking. When the biped takes a step it goes through eight phases. At the start of walking (home position), the COG is at the center of the two-foot supporting area, which does not require a large ankle power.

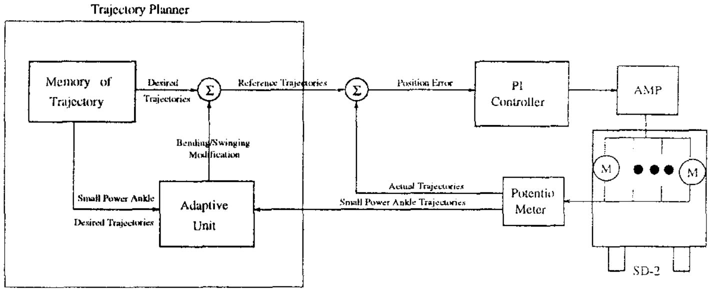

Fig. 4. System configuration of the controller.

In phase 1, the joints in the frontal plane are rotated such that the support to the robot is moved to the left foot. In phase 2, the right leg is swung forward using the hip joint in the sagittal plane, and the ankle joint of the left leg and the hip joints in the sagittal plane are moved to transfer the COG forward. At the same time the hip joints in the frontal plane are further rotated to lift the swinging leg; this is required because the SD-2 has no knee joint. Lifting the swinging foot can eliminate the possible collision between the foot and the floor. At the end of this phase the swinging foot keeps being parallel with the floor. In phase 3, joints in both the sagittal and frontal planes move simultaneously to make the right foot touch the floor while the COG remains over the left foot. During these two phases large ankle torque is required to move the COG. In phase 4, all the joints are rotated to shift the COG to the center of the two-foot supporting area again. These four phases are the first half of the cycle. The same procedure is repeated for the next half of the cycle, i.e., phases 5 through 8.

III. Controller for Reduced Ankle Power

The ankle of human being is very flexible, which gives a good contact between the sole and the ground. As mentioned in Introduction, this characteristic can be implemented in a biped robot by using a small DC motor. A small motor is sufficient to control the motion of the foot when the foot is in the air, and will make the leg light which can reduce the energy consumption of other joints and enable the robot walk fast. Furthermore, a small DC motor will make the mechanical structure simple. Recall that many biped robots use a complex transmission mechanism to transfer the power from the DC motor, which is installed on the other part of the robot, to the ankle joint. This is because the ankle is near the end of the leg, any weight increase will substantially increase the moment of the leg. By using a small motor at the ankle joint, the complex transmission mechanism becomes unnecessary, while the moment of the leg is still small. However, a small motor for the ankle joint is not sufficient to make walking stable if a static gait is used. To solve this problem, we propose a feedback control using the displacement of the ankle joint as the input.

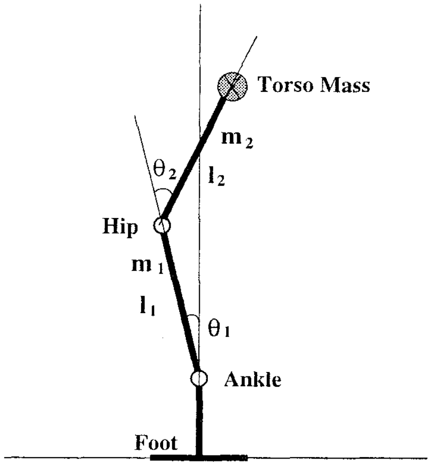

Fig. 5. Joint displacement in sagittal plane.

A. Control System Structure

The structure of the control system is shown in Fig. 4. In the figure, the PI controller is composed of a conventional position control to drive the eight joint motors. The Trajectory Planner specifies the trajectories of every joint. These joint trajectories were previously developed for static walking for the SD-2 when the ankle joints had the same amount of power as the other joints. With the ankle power reduced, the trajectories must be modified. This is the responsibility of the Adaptive Unit (AU). The Adaptive Unit uses a feedback control mechanism which will be discussed in the next subsection.

Both the Trajectory Planner and the PI controller are programmed on a PC-486 using the C language, and sampling time is $3.5ms$. To interface the signals between PC-486 and the amplifier/sensor a DDA-08, Metrabyte digital to analog converter, and a DAS-8, Metrabyte analog to digital converter with programmable interval timer, are installed inside the PC-486. The amplifier is built with a single component power operational amplifier, Apex Microtechnology PA02, for each joint. This amplifier can drive up to 12 volts and 2 amperes in each direction for every joint. However, the maximum voltage for two ankle joints in the sagittal plane is limited to $2.5V$. This limited voltage is enough to control the motion of the foot when it is in the air but represents a substantial power reduction from normal power supply.

B. Control Mechanism

Fig. 5 shows the standing posture of the biped in the sagittal plane. Let the desired posture be a straight standing and θ_n, l_n, and m_n represent the displacement angle, the length of link, and the mass of link, respectively, with n standing for the link number. Note that m_1 and l_1 represent the body of the robot. Also a torso mass is attached to the top end of the body which makes the body more effective in balancing the robot. Since the torque of the ankle joint is weak, i.e., θ_1 is almost passive, we can only make the system stable by controlling the hip joint (θ_2). Since the masses of the motor and the speed reduction mechanism are relatively heavy, and they are installed at the top end of each link, we can assume that the mass of a link is concentrated at the top end of the link.

Consequently, the moment at the equilibrium point can be expressed as follows:

$$m_1 l_1 \sin\theta_1 = m_2(l_2 \sin(\theta_2 - \theta_1) - l_1 \sin\theta_1). \qquad (1)$$

From the above, we can obtain the required angle of the hip joint for adjusting the ankle joint as:

$$\begin{aligned} \theta_2 &= \theta_1 + \sin^{-1}(K_m \sin\theta_1), \qquad (2) \\ K_m &= \frac{l_1(m_1 + m_2)}{l_2 m_2}. \end{aligned}$$

From (2) and Fig. 5, one can see that if θ_2 is greater than the right side of (2), the torso mass tends to fall forward which reduces θ_1. This scheme can be used to adjust the ankle joint and balancing the robot for both standing and walking. As mentioned in Introduction, there is another method to adjust the ankle joint, i.e., swinging the non-supporting leg. This method can be applied during one leg supporting phase, phases 2, 3, 6, and 7. Since the weight of the leg of the SD-2 is heavy, this method is effective for standing. However, the method is not adequate for walking because the legs have to follow a specified pattern of motion during walking.

For the SD-2, K_m is less then 2 and θ_1 is less than 10. As a result, 2 can be written as follows:

$$\theta_2 = (1 + K_m)\theta_1. \qquad (3)$$

The displacement of the ankle joint can be calculated by the adaptive unit (AU) (see Fig. 4) to generate the reference trajectories as following:

$$E_s = \theta_d - \theta_s. \qquad (4)$$

where θ_d is the desired angle of the ankle joint, θ_s is the measured angle of the ankle joint, and E_s is the required modification to the ankle joint. When the biped is in the two-foot supporting case, any ankle joint can be selected to control the robot because both displacements are very small in this case. Thus, we select to modify the left ankle during phases 1 to 4 and the right ankle during phases 5 to 8. Now, the AU can generate the modification to the desired trajectory of the hip joint θ_r in walking and standing by using the following equation:

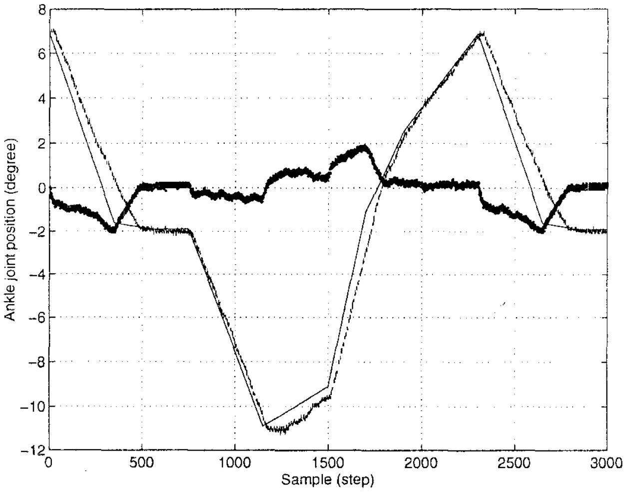

Fig. 6. The ankle joint position error with the voltage limit $2.5V$ while the biped is walking in air.

$$\begin{aligned} \theta_r &= \theta_d + K_P E_s + K_I \int E_s, \qquad (5) \\ K_P &= K_p(1 + K_m), \\ K_I &= K_i(1 + K_m), \end{aligned}$$

where K_p and K_i are the proportional gain and the integral gain, respectively. Note that only the trajectories of the hip joints in the sagittal plane are modified by 5.

IV. Experiments

We performed two experiments, standing and walking, to show the validity of the proposed mechanism. The voltage limit of the ankle joint was defined experimentally. Fig. 6 shows the tracking characteristics of the ankle joint while the biped is walking in air (the biped was hung in the rack with no contact to the ground). In the figure, the dashed line represents the trajectories measured, the solid line is for the reference trajectories, and the thick solid line shows the differences between the two trajectories. The x aixs indicates the Sample Steps during the locomotion. Every Step represents $3.5ms$. We summarize the results with different voltage limits in Table I. One can see that high voltage limit gives better tracking performance. In the case of $1.5V$, the reference trajectories can not be followed, i.e., the ankle actuator does not have enough power to move the foot. When the voltage limit is increased to $2.5V$, the tracking error is reduced to an acceptable range. We therefore chose $2.5V$ to be the voltage limit which however is not enough to enable a static walking. The feedback control mechanism as developed in the previous section has to be employed for standing and walking.

TABLE I

VOLTAGE LIMITS AND TRACKING ERROR OF THE ANKLE JOINT.

Voltage Limit (Volt)	Max. error (degree)	Min. error (degree)	Variation (degree)
1.5	2.5	-15.8	18.3
2.0	4.5	-6.9	11.4
2.5	2.3	-2.0	4.3
3.0	1.1	-1.0	2.1
4.0	1.1	0.8	1.9

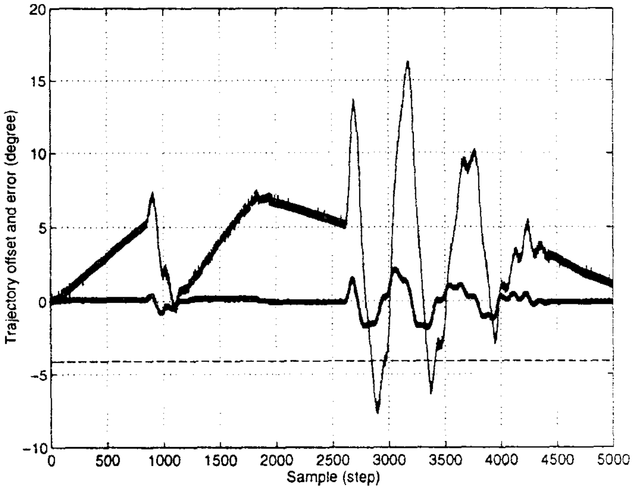

Fig. 7. Trajectory offset for hip joints and the error of the ankle joint.

A. Standing

The biped is standing with the phase 2 configuration in which the robot is supported by the left foot. Bending the body and swinging the non-supporting leg are used to control the ankle joint of the supporting leg in the sagittal plane. To test the performance of the controller, we pushes the biped twice with a small force and a larger force respectively.

Fig. 7 shows the result of the experiment. The dashed line represents the desired angle of the ankle joint θ_d, the thick solid line stands for the error measured E_s, and the solid line is the offset angle of the hip joint to be adjusted $\theta_r - \theta_d$. The first disturbance was applied at around Step 900, and the second disturbance is applied around Step 2,600. One can see that the biped regained its stable position after the disturbance was vanished. The second case took longer time because the disturbance was larger than the first. The offset values during the interval between Steps 1500 and 2500 shows that the error is gradually reduced by the increasing offset, and the offset is also decreasing from Step 1800 on since the error has become smaller. The results prove that the proposed control system is effective for standing.

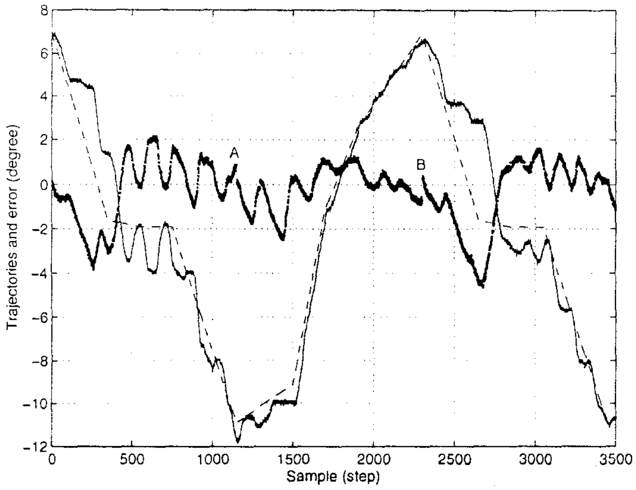

Fig. 8. The reference trajectory and the ankle trajectory measured.

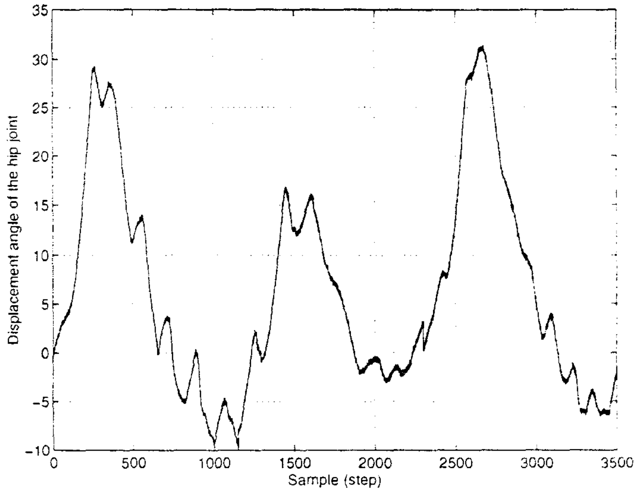

Fig. 9. The displacement angle of the hip joint.

B. Walking

The biped walks on flat floor using the gait designed previously, which is suitable for a strong ankle joint. This gait is not suitable when the ankle power is reduced. The biped falls backward when the phase is changed from two-foot supporting to single-foot supporting. Furthermore, when the swinging foot lands the ground, there is a sudden change of the foot position because of the impact with the ground. This gives the error signal an abrupt increase. Too small power of the ankle joint will not be able to correct the position error even with the compensation of the body motion.

The result of walking is depicted in Fig. 8 and Fig. 9. In both figures the robot completes a walking cycle from Steps 0 to 2300. In Fig 8, the dashed line represents the desired trajectory of the ankle joint θ_d, the solid line stands for the actual trajectory of the ankle joint θ_s, and the thick solid line is the displacement angle E_s. There are two discontinuous points, marked as A and B at which the support to the robot is switched from one leg to the other. During the period from Step 0 to point A, E_s is obtained from the left ankle, and during the interval between A and B, it is obtained from the right ankle. Fig 9 shows the displacement angle of the hip joint $\theta_r - \theta_d$ which controls the position of the ankle joint. From the figure, one can see that the body is bent forward during phases 1 and 2 (Steps 200 to 600) and bent backward during phase 3 (Steps 900-1200). The displacement is small for phase 4. During the second half of walking, the robot is supported by the right foot (after Step 1150). One can see from Fig. 8 that the second half has the same pattern of the body motion as in the first half. One can also see from Fig. 8 that the ankle joint follows the desired trajectory well because the error is bounded.

V. Conclusions

Locomotion of a biped robot with reduced ankle power is studied in this paper. The flexibility of ankle joints is implemented by using a small motor as the actuator of the ankle joints. Attaching a small motor also reduces the weight and moment of the leg which renders a fast walking of the robot. With reduced ankle power, however, biped locomotion becomes more difficult to control. To solve this problem, a new controller has been developed.

The controller uses a feedback control mechanism which is not a low level servo-control, but a high level motion compensation. The mechanism balances the robot by dynamically moving the body and swinging leg of the robot.

Experimental results have shown that the proposed approach is valid for the SD-2 biped robot.

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