Walking of a Biped Robot with Compliant Ankle Joints: Implementation with KUBCA[†]

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Abstract

This paper presents a compliant ankle mechanism and its implementation for a biped robot without actuators for the ankle joints. Ankle joints have been built using springs and mechanical constraints, which give a flexibility of joint within a predefined range and stiffness beyond the range.

The biped with compliant ankles proposed here makes foot landing easy, and weight and cost of legs are also reduced. As the cost of the advantages, however, the control problem becomes more difficult because the control torque of the ankle joint to put the biped in a desired walking gait cannot be provided from the compliant ankle joint.

To overcome this problem, we proposed a pseudo static walking gait with dynamic gait modification method by adjusting the position of a hip joint. Experimental results with the biped KUBCA are given to show the validity of the proposed controller.

1. Introduction

Human like robots are about to appear in front of our life. Honda has announced the biped like an astronaut, which is the result of the more than 10 years work as a next stage of the automotive manufacturing. After that point, both research and development of biped robots have become very active because of the needs to save human beings not in the manufacturing industries but also in the service area such as patient care or disabled person assistant.

Biped has better mobility than the other mobile robot, especially in rough terrain. They can use isolated footholds as legged robots do, whereas the others equipped with wheels require a continuous path of support. Preparing a special arrangement such as ramps to allow them moving around is not required for the biped even though the most of all industrial environments have been built for human beings. Payload can also 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. Moreover, robot can move along narrow paths where a broad base of support is impossible. Building a biped robot is more cost effective than the other legged robots since the cost of actuators is considerable; a biped has less actuator than legged robot.

To realize these advantages a great deal of research has been done in view of implementing practical robots [1,2,3,4,5]. However, research on a biped robot has been making slow progress due to the difficulty of control to maintain stable locomotion while the biped is walking on different floor conditions. Even though there is no practical biped robot nowadays, recent research results tell us that biped robots will be common in our near future life. Zheng and Shen developed a biped robot that can climb sloping floors based on the measuring of the slope angle using on-off force sensors underneath the heels and toes [6]. Kajita and Tani presented a dynamic biped locomotion on rugged terrain using the linear inverted pendulum mode [7]. Hodgins and Raibert demonstrated a biped running on the rough terrain by adjusting step length [8]. Besides these, dynamic walking [9,10], compass type bipedal walking [11], running of the hopping robot[12] have been implemented. Analyses on walking and standing of human being also have been performed [13,14,15], which reveal that the ankle of human being has small torque and very flexible within a certain range (very stiff near and beyond this range). The flexibility of the ankle joint of human being makes foot easily compliant, which reduces the impacts caused by touching ground while foot is landing. It also gives a good and firm contact between its sole and the ground, which makes it easy to install a force sensor underneath the foot for measuring the COG (center of gravity) changes of the biped.

This time we implement the characteristics using springs and mechanical constraints whereas our former work has been done by using a small DC motor for the ankle joints in sagittal plane[16] and a simulated version of compliant ankle joints[17]. Control problems, however, are still needed to be solved since the lack of the ankle joint torque disturbs the changing of the gaits for walking. We

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believe that ankle joint without actuator makes a biped more useful if the problem mention before is recovered. Thus, the target of our research is addressed to develop the control method to solve the problem for the new ankle mechanism proposed. Moreover, we employ the distributed control scheme using CAN network to make cable connection simple with our own controller which has two motor drivers and CAN interface.

In the following section we introduce the structure of the biped robot with compliant ankle joints and its walking gaits. In the third section the control mechanism will be developed. Experimental results for walking on level floor and walking in air will be discussed in the fourth section. Finally, we conclude the works done here in the fifth section.

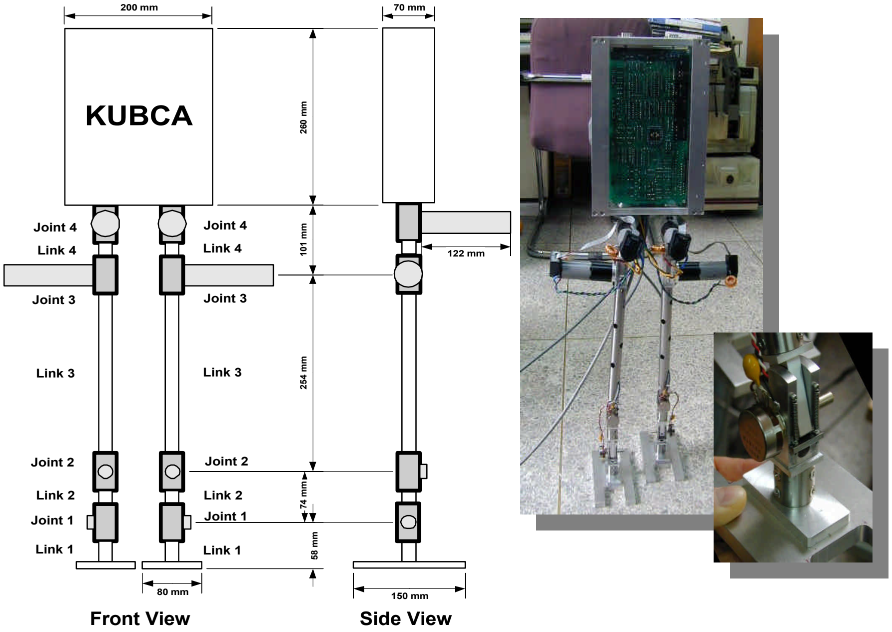

Fig. 1 KUBCA

2. The KUBCA Biped Robot

The target robot, KUBCA (Kwangwoon University Biped robot with Compliant Ankle), has built which is similar type of SD-2 robot by Zheng[5] except the compliant ankle joints. As mentioned in Introduction the motivation of the compliant ankle is to reduce the number of actuators to make a biped more useful. In this section we will describe the details on this including the structure of the KUBCA biped robot.

2.1. The structure of the biped robot

The KUBCA consists of nine links and eight joints as shown in Fig. 1. Four joints control the motion in the sagittal plane and the other four for the frontal plane. Each leg has four degrees of freedom. The top two joints of each leg emulate the hip joint while the bottom two are the ankle joints. Note that the robot has no knee joints and no actuators for the ankle joints.

Upper four joints are actuated by the same type of DC motors with planetary gears and pulse encoders. One can notice that, from the side view, upper two motors are attached in same direction to make the center of the gravity a bit forward, which makes walking convenient with less body motion than our previous work. Large square box, we call it as a torso, on the top of the biped is used for mounting position controller and controlling the center of mass.

Lower four joints for the ankles have been built with the new mechanism shown in Fig.2 (Assembled one is shown in center and others are parts disassembled).

The upper link (A in figure) and the lower link (E) are linked with the shaft of a potentiometer that is attached using the plate (F). Springs are installed between the lower link and the plate that is pushing the upper link up while it is rotated. The bottom of the upper link has been cut flat (not rounded but right angled) to get the push back force when the joint is rotated. T-shaped nut(C) restricts the displacement of the plate (B) by adjusting the bolt (D) mounting at the bottom. As a consequence, joint angles can be rotated as the plate goes down until it meets T-shaped nut.

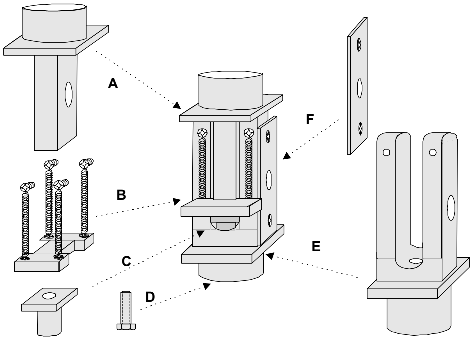

Fig. 2 Compliant ankle mechanism

2.2. Walking gait

The pseudo static walking gait for the KUBCA biped robot consists of eight primitive points (PPs) as shown in Fig. 3. This gait is the same one as we used before except the dotted line that comes from the compliance of the ankle and the posture of the biped naturally.

In the figure, the dotted squares represent the feet in air, and big dots near squares stand for the vertical projection of the COG. Ankle joints marked with circle need a torque to maintain the corresponding gait configuration, which will be done by the indirect torque from the control mechanism proposed here. The dotted lines from the ankle joints at each PP of which has foot in air are the

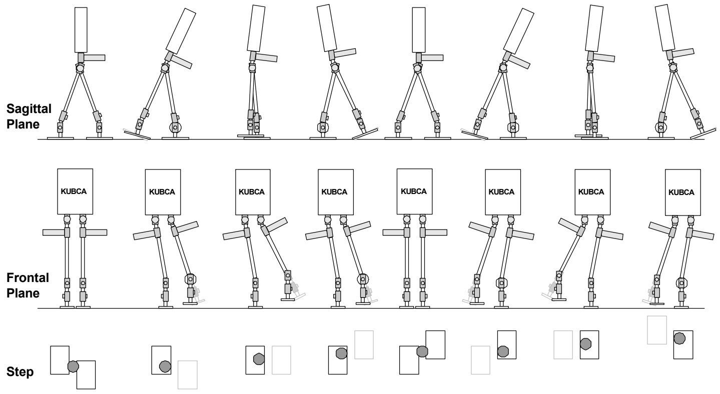

Fig. 3 The walking gait for the biped.

actual position of the links stretched by the springs attached.

When the biped takes a step it goes through eight phases that are defined as between two contiguous PPs. The trajectories for each phase are calculated by connecting two PPs using a linear line. Walking can be done as follows:

Step 1: Move COG to the supporting leg.

Step 2: Swing the leg in air to the straight up standing position such as PP2 and PP6.

Step 3: Swing further the leg in air to the landing position.

Step 4: Landing and move COG to the center

One foot step has been completed after pass through these steps and another step also can be done by taking the same sequence except the supporting leg. The reason why the leg swing is divided into two steps (Step 2 and Step 3) is to obtain the clearance between the ground and foot, which need to be programmed to avoid the possible collision against ground.

3. Controller for compliant ankle joints

As mentioned above, compliant ankle joint makes foot landing easy and gives a good and firm contact to the ground. However, we cannot use the static walking gaits shown in Fig. 3 directly when the ankle joint needs torque (marked with circle). This torque can be supplied indirectly if we adjust the gait in proper way.

3.1. Controller structure

The structure of the controller is shown in Fig. 4. Host PC has the functions for user interface and the generation of global trajectory according to the position data obtained from the Communication Unit. The predefined PPs are stored in the Memory of Trajectory and the Adaptive Unit is responsible for generating the actual trajectories named reference trajectories.

Three controllers built with i196CA microprocessor have CAN (Controller Area Network) in which two of them have PWM motor drivers (LMD18200), encoder interfaces (HCTL2020) and analog to digital converters (i196CA internal). Position signal from the potentiometer is amplified 10 times since the angle variation is small, only 20/270, so that the resulting output is also small.

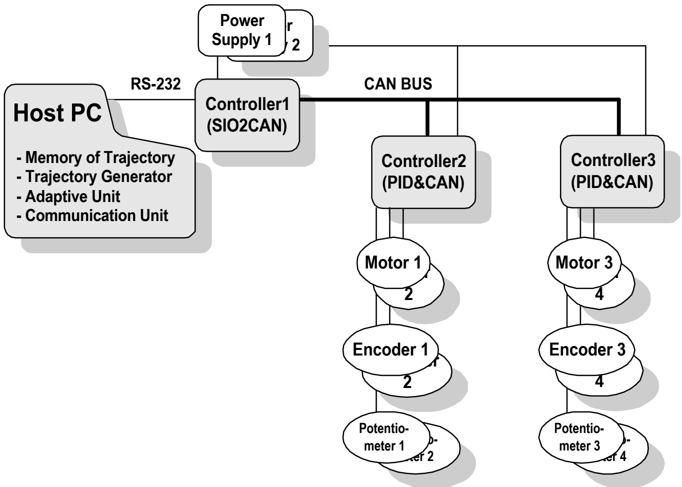

Fig. 4 System configuration of the controller

Controller 1 has the function for distributing the serial command from the Host to CAN for each controller 2 and controller 3, and for collecting the CAN data from each controller to send them to the host. Controller 2 is the position controller to drive the joint motors by employing PID control. Controller 3 is same as controller 2 except for the joint motors of other leg.

3.2. Control of the compliant ankle joint : Frontal plane

The motion of the biped with the compliant ankle joints in the frontal plane can be easily obtained by controlling two upper joints. That is, one leg supporting PPs can be obtained by rotating two upper joints until the support ankle joint meets the restriction that can be predefined by adjusting the bolt. And then one upper joint is rotated further to lift one leg in air.

The only concern to maintain the stable gait is holding the ankle joint at the restriction angle, which results in the COG remaining within the supporting foot since we set the restriction angle holding the condition needed. This angle should be carefully selected in experiment. Small or too large angle makes gait less stable. Additional control can be involved to improve the stability margin as following section.

3.3. Control of the compliant ankle joint : Sagittal plane

A biped with compliant ankles supported by one foot can be modeled as a two links inverted pendulum with one actuator as shown in Fig. 5. When the biped is supported by one foot, double-feet supporting phase is not addressed since the phase is stable itself, torso mass varies according to the phase changes since the position of the body and leg in air also changed.

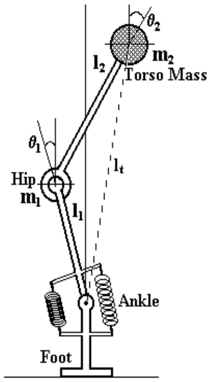

Fig. 5 Two links inverted pendulum.

The ankle joint has sufficiently small elasticity so that it can recover its original position, straight-line shape, while the foot is in air and complies against the force applied when the foot is touching ground. Thus, we can ignore the torque generated by the springs, i.e., the torque applied to the ankle joint can be obtained by calculating the gravity effect of the torso mass and the hip mass. Consequently, the torque exerted on the ankle joint is obtained as following, (1), with the assumption that the biped is standing and the mass of the link is concentrated at the top of the link.

$$T_1 = -m_1 g l_1 + m_2 g (l_2 \sin\theta_2 - l_1 \sin\theta_1) \qquad (1)$$

Since the torque applied should be zero when the joint is coinciding with the desired position, the angle of the hip joint to get the certain angle of the ankle joint is as:

$$\theta_2 = \sin^{-1}\left(\frac{m_1 + m_2 \sin\theta_1}{m_2} \frac{l_1}{l_2}\right) \qquad (2)$$

For the SD-2, K_m is less than 2 and the angle limit of the ankle joint is 10^o, we can rewrite the (2) as following:

$$\theta_2 = K_m \theta_1 \qquad (3)$$

where

$$K_m = \frac{(m_1 + m_2) l_1}{m_2 l_2}.$$

When the biped is walking, however, the position of the torso mass is not a constant but the mass varying with the changes of the phase. As a result (3) need to be modified as follows:

$$\theta_2 = K(pp)\theta_1 \qquad (4)$$

where

$$K(pp) = \frac{(m_1 + m_2) l_1}{m_2} \frac{1}{l_2(pp)}$$

The variable K(pp) can be estimated in off line for the corresponding PPs. One should be noticed that the ankle joint, θ_1, can be controlled by modifying the angle of the hip joint, θ_2, which is our previous work [17]. However, erroneous modeling and sensor noise causes undesirable result. Instead of using (4) with the estimation of K(pp), this time, we apply the correction function which is used in the AU (Fig. 4) to get the displacement of the hip joint to control the ankle joint.

Adding the correction function to the desired trajectory, we can get a new reference trajectory. The first part of the trapezoid initiates ankle rotation and the second part makes further rotation and foot landing ease. DISmax and the slop of the function shown in figure need to be selected in experiment. Too big slope yields fast motion which results in the biped falling down, too small or excessive DISmax also leads the biped falling down backward or forward. Reference trajectory modification for the rest of PPs is repeated again with same type of function.

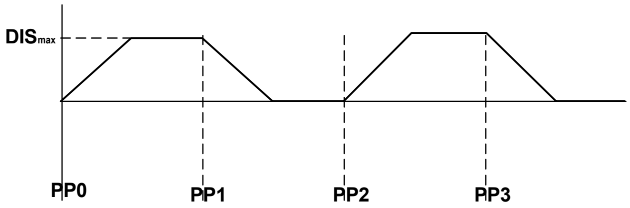

Fig. 6 Correction function for the displacement angle of hip joint

Now, we employ a conventional PI control excited with following modified error to control the hip joint.

$$E_s = (\theta_{r2} - \theta_{s2}) + (\theta_{d1} - \theta_{s1}) \qquad (5)$$

where θ_{r2}, θ_{s2}, θ_{d1} and θ_{s1} are reference angle of the hip joint, measured hip joint angle, desired angle of the ankle joint, and measured ankle joint angle, respectively. The second term in (5) acts like the relation in (4); the term makes the reference angle of hip joint bigger if the desired ankle joint angle is smaller than the measured angle, and vise versa.

4. Experiments

Two types of walking experiments were conducted, walking in air and walking on level floor, to see how effective the proposed controller is. We only show the data for the sagittal plane since the control for the frontal plane is so simple for our biped robot as mentioned before. The trajectories walked on the level floor with active ankle are depicted in Fig. 7 for comparison. Step 2300 is the point of one foot step completed. Solid lines represent reference trajectories, these are same as desired trajectories, and dotted lines for the trajectories measured. All trajectories are following their references with small errors.

4.1. Walking in air

We put the biped in the rack and examine its walking characteristics. We have to note that the reference trajectories of the hip joint should be changed to generate the torque for the ankle joint and the ankle joint trajectories measured remain same since the joints have no actuator.

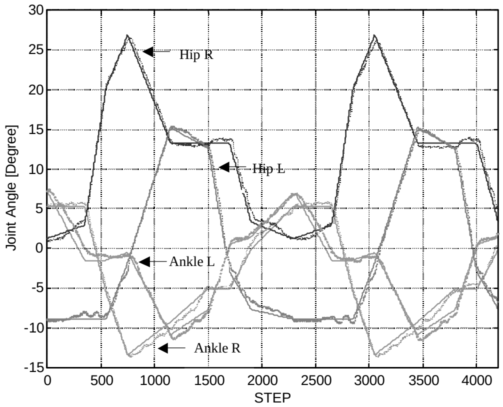

Fig. 7 Joint trajectories for active ankles

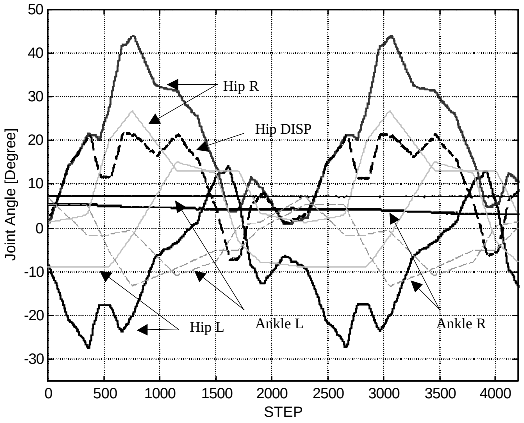

Fig. 8 Joint trajectories for compliant ankles
(walking in air)

According to the Fig. 8., both left ankle and right ankle joints remain same (dark solid lines), these are not needed to be zero since potentiometers are installed with some offset values, regardless the desired trajectories (gray dotted lines) because those are compliant. However, trajectories of the hip joints (dark solid lines) are changed a lot from the desired trajectories (gray solid lines), reference trajectories are not shown since those are close to the measured trajectories as shown in Fig. 7. The difference between the desired trajectories of the left hip joint and the measured one is shown as thick dotted line, the difference for the right hip joint is same but other direction, which decides the amount of the hip joint bending. The amount seems too much considering the correction function of which maximum value was set 10 in degree in this experiment. This is because the supporting ankle was not controlled by the hip adjustment since it was in air (refer equation (5)).

4.2. Walking on level floor

The biped walked on the level floor using the mechanism for the compliant ankle proposed here. The result is depicted in Fig. 9, ankle joint trajectories, and Fig. 10, hip joint trajectories.

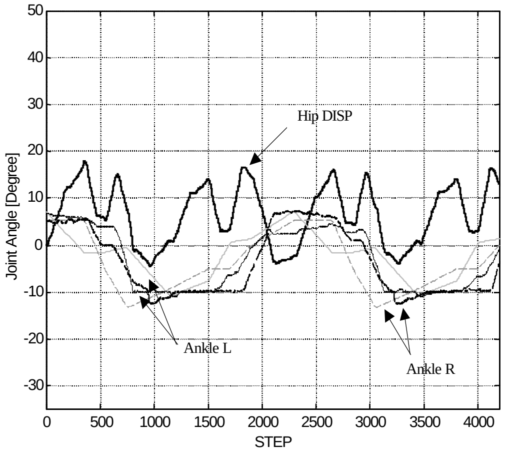

Fig. 9 Ankle joint trajectories for the compliant ankles
(walking on the level floor)

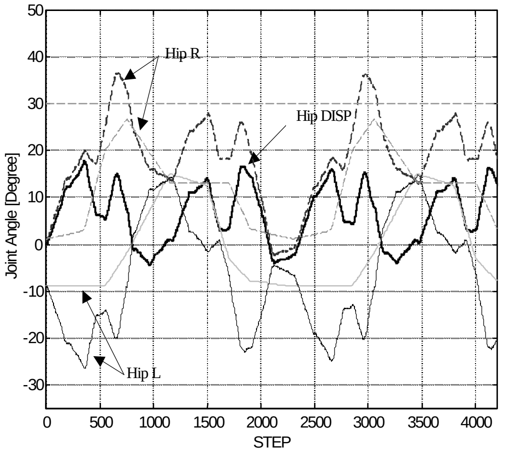

Fig. 10 Hip joint trajectories for the compliant ankles
(walking on the level floor)

Grey lines represent desired trajectories, and thick solid lines named 'HipDISP' in both figures stand for the difference between the desired trajectory of the left hip joint and the measured one. The HipDISP (same line is put in two figures on purpose) is different from the one in Fig. 8 but it is close to the correction function in Fig. 6 except the three concavities at the maximum and zero areas. These concavities come from the additional reference modification to make ankle torque from the second term in (5) as mentioned before. The reason why the additional modification is needed is that the compliant ankle developed here had large static friction between the bottom of upper link (A in Fig. 2) and the surface of the plate (B in Fig. 2). Selecting proper material for both can reduce this; one should have harder material than the other. (We use aluminum for the part A and iron for the part B).

Ankle joint in air is also remained same as shown in Fig. 9, this should be go back to the position where the links stretched in line (angle shown in Fig. 8), because of the same reason. Actually, the foot landing characteristics was humiliated a bit from our expectation, but walking on the level floor has accomplished.

In conclusion, we have demonstrated a biped walking with compliant ankle joints even thought the biped built was not tuned well; it just a prototype at this point (We will get the better result before the conference presentation). We are going to show other motions such as walking on the slope and stairs in the near future.

5. Conclusions

The biped robot with compliant ankle joints and its controller are proposed. The ankle joints are built with springs and mechanical constraints, which gives a good contact between its sole and the ground and makes foot landing soft.

Walking with compliant ankle has been done using the controller that has two feedbacks, inner feedback for motor control and outer feedback for reference trajectory control. Inner feedback controller, distributed position controller, has implemented with the lab made hardware that has two motor drivers and CAN interface. Outer feedback controller has implemented with PC with additional CAN interface controller we built.

Experimental results show the potential of the cost effective practical biped robot without actuator for the ankle joints.

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