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A HIP JOINT STRUCTURE FOR BIPED ROBOT WITH REDUCED DOF'S OF MOTION

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In this paper, we propose a new hip joint structure for a biped robot that uses a small number of DoFs, reducing the number of actuators required, and thereby conserving weight. First, we will discuss the necessary number of DoFs to walk on a sloped surface without irregularities. Consequently, we designed a kneeless biped robot with six DoFs, two DoFs for each ankle, and the remaining two for the hip joint structure. The hip joint structure is required to produce two kinds of movements: the alternative swings between the left and right leg as well as the lateral weight shift required to lift up a foot. We invented a mechanism to realize these two movements using two actuators: a similar structure to the differential gear was applied to enable the leg to swing in the sagittal plane, and the parallel link structure was applied to produce lateral motions. In addition, we actually constructed a robot with the proposed mechanisms, and demonstrated the biped walking on a slope.

Keywords: biped robot, reduced DoF, hip joint structure, slope walk, CoP feedback

1. Introduction

Weight reduction is an important specification in mechanical design. This especially holds true for mobile machinery that changes its own spatial positions. When they are utilized as transportation vehicles, weight savings increase the total amount of baggage or passengers. More importantly, even if the machines do not transport anything, for instance, in the case of autonomous machines such as biped robots, weight savings directly reflects in the resulting energy efficiency. Some papers actually study the mechanical structure of biped robots.[1,2]

We studied biped robots and in particular, considered the way they walk in uncertain environments, such as with a variable ground gradient. One of the final goals in the development of biped robots is usually the ability to use robots or mechanical assemblies to accomplish human tasks, especially ones that necessitate spatial movement on uneven floors. Our main focus, in the field of biped robot study, is on the establishment of stability during upright standing or walking periods. The zero moment point (ZMP) criterion provides an effective method to generate a locomotion pattern, desired trajectories of joint angles or the center of mass (CoM) for the whole body in the motion planning stage, and a tracking control for trajectories designed to enable biped robots to progress using their legs without falling down even if disturbances are applied during their walk.

Our research group proposes a control method for the maintenance of balance using feedback from ground reaction forces, in particular, the center of pressure (CoP) of the ground reaction forces,[3] and applies it to weight shifting in the double support phase of movement[4] and the in-place stepping motion.[5] Our goal to experimentally confirm the validity of our control method is for a biped to walk on a slope with an unknown but constant gradient. However, we have not yet achieved this with the robots that we are developing. The main reason is the shortness of the joint torques: we designed the robot with many DoFs which require several servo motors. Most commercial servo motors have a low power-to-weight ratio, leading to the robot being excessively heavy in comparison with the torque of the motors.

For most servo-motors, radio control units used in hobby cars, planes, and helicopters generate a high output with respect to their weight. Some biped robots adopt these types of motors, or originally developed motors, and successfully produce certain agile human-like motions.[6–8] However, this kind of servo-system occasionally utilizes position control based on the pulse width of the digital output. Our control method, essentially torque control, is difficult to apply in its original form. In addition, angular sensors such as rotary encoders are not contained in the servo-motor, forcing us to install them on the robot afterwards. This is the reason that we are developing a biped robot ourselves. To reduce the weight of the robot, our present aim is to reduce the number of motors by designing a structure to couple some DoFs required for bipedal walking. This enables us to utilize high spec servo-motors that torque control is applicable to.

2. Design of a biped robot

2.1. *Purpose of our biped robot*

Our main objective is to demonstrate the effectiveness of our control method: accordingly, the goal of our bipedal robot is to walk not only on flat but also on sloping ground. In this paper, we achieved this goal using a new lighter hip structure with a reduced number of motors.

Bipedal robots move by repeating the support leg exchanges between the right and left legs.

For the hip joints, at least one DoF is required if the legs are swung symmetrically in the anterior-posterior direction within the sagittal plane. In the frontal plane, the robot's weight has to be moved in a lateral direction before lifting and swinging a leg. By constraining the legs such that they are parallel to each other, this can be accomplished with one DoF, although the ankle joints must then move in a coordinated manner. Mechanically integrating the sagittal and frontal plane movements at the hip joint structure reduces the required DoFs.

Knee joints are needed to lift the foot over obstacles or rough ground. In this paper, however, we limited ourselves to even sloping ground with no obstacles. Thus, a knee joint is unnecessary, and the hip joint can perform the lifting necessary for walking. This again reduces the DoF count.

To adapt to the slope in the single support phase, an ankle joint needs to have two DoFs for pitch and roll.

In summary, the bipedal robot used 6 DoFs with 2 in each ankle and 2 in the hip joint structure.

2.2. *DoF reduction*

2.3. *A new reduced structure of hip joint*

Based on the ideas presented above, we designed the actual structure of the robot as depicted in Figs. 1 and 2.

Fig. 1 details the sagittal swing motions. The differential gear appears on the left of the figure. A central pinion gear drives two side gears to swing the legs simultaneously in opposite directions. The differential gear mechanism itself limits the distance between the two hip joints in the frontal plane. This is the reason that we synchronized the function of the center gear shared with two coupled gears that were mechanically connected, for example, using a timing belt, as shown in the figure on the left. When driven, connected beveled gears produce rotation at right angles to the drive axis, but in opposite directions, to produce leg swing motions in the

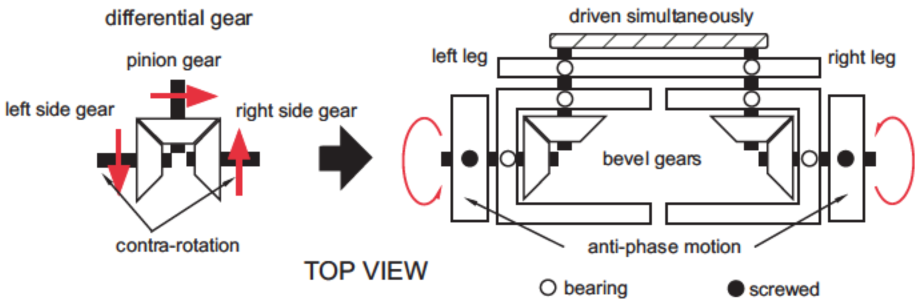

Fig. 1. Mechanism for alternative leg swing.

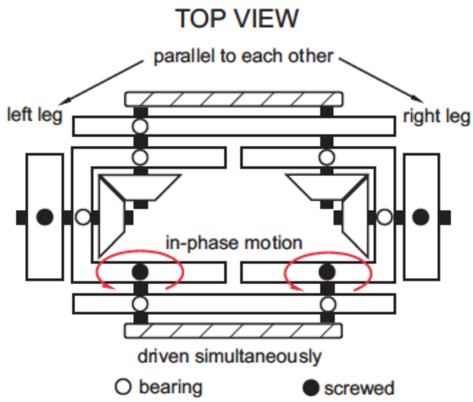

Fig. 2. Mechanisms to keep legs parallel.

sagittal plane.

For lateral motion, we introduced U-shaped bases, shown on the right in Fig. 1. Rotating the two U-shaped bases in phase as shown in Fig. 2 enables the realization of lateral movements. Another axis is set in the opposite direction to support the U-shaped base, sharing the rotation axis for the leg swing motion. A timing belt links the units across the front. When this belt is driven, the two U-shaped units slant together laterally. This is a kind of parallel link structure always keeping two legs parallel each other.

2.4. *Robot construction*

For easy handling of the robot during the experiment, we set a design goal of a small sized robot of around 30 cm in height and 3.5 kg in weight. This is

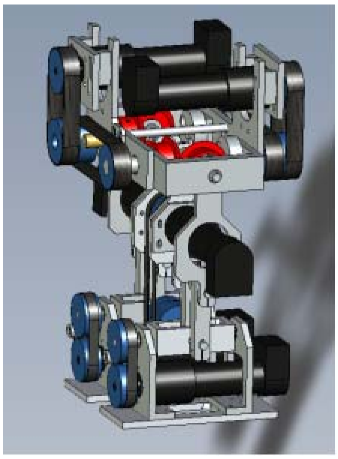

Fig. 3. Motor configuration.

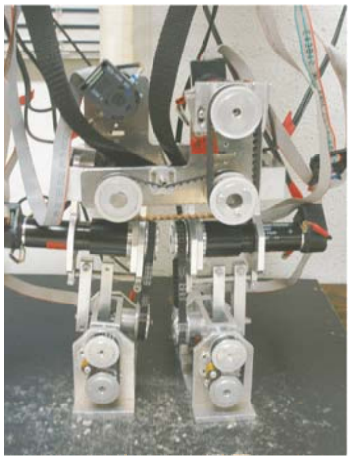

Fig. 4. Constructed biped robot.

sufficient for our purpose in this paper, i.e., to demonstrate the effectiveness of our control law.

Once the hip joint structure is realized, the motor configuration needs to be considered to avoid mechanical interference between links of the robot. Two motors were symmetrically installed on this hip joint structure for its actuation to balance the weight, as shown in Fig. 3. The timing belts transmit the driving force from the motor axis to the hip joint DoFs, and its tension can reduce the backlash between them.

The sagittal DoFs of the ankle joint are actuated by the motor placed in the middle of the leg, while the frontal ones are driven by the motor at the foot. To detect the position of the CoP, four load cells (KYOWA LMA-A-50N-P) were attached on the corner of each square sole.

The same motors, Maxon RE25 with 130g weight and 24.2mNm maximal continuous torque, were utilized for all DoF actuation. Figure 4 depicts the robot. It uses just six servomotors. It is 290 mm in height, 270 mm wide, and weighs 4.12 kg. Its feet are 160 mm long. The weight is greater than expected because of the large bevel gear.

3. Experiments

3.1. *Setups*

We used a personal computer (PC) as the controller, running a real-time operating system, ART-Linux. This computes the required torques for each

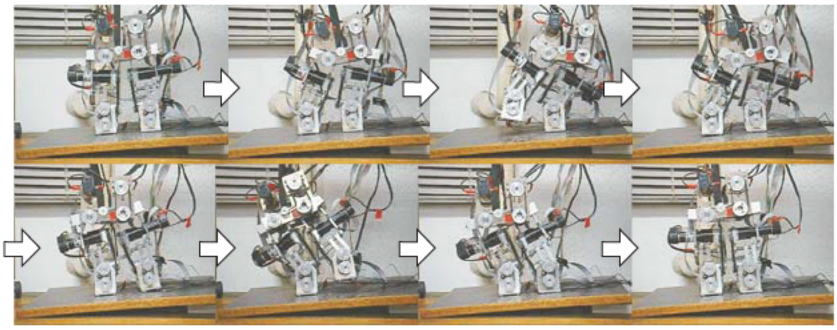

Fig. 5. Experiment on a leftward slope.

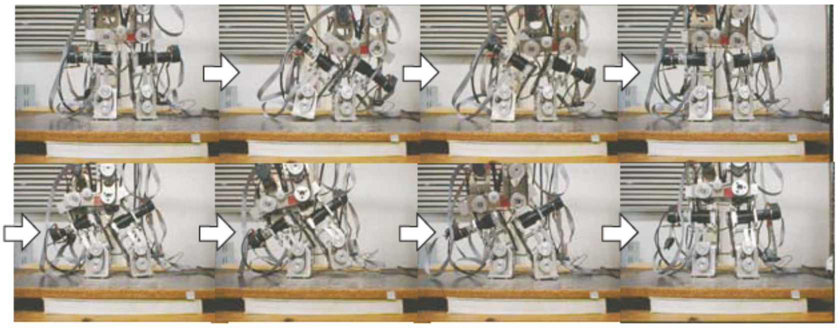

Fig. 6. Experiment on an upward slope.

of the six motors. It then outputs, using a D/A converter board (Interface PCI-3336), analog voltage corresponding to the magnitude of the torques, which is then applied to the motor drivers (TITECH Driver PC0121-1). These motor drivers supply the servo-motor with electric current from a 24V external power supply (ETA electric industry FHH24SX-U) to generate the required torque. The PC receives the joint angle information using the encoder counter board connected to the rotary encoder of the servo-motors. It also acquires, via the A/D converter board (Interface PCI-3153), information about the ground reaction force from load cells, the output of which is amplified in a multi-signal conditioner (KYOWA DPM-8K). The data detection and torque output process is executed every 1 ms.

3.2. *Control law*

The control method required to demonstrate the effectiveness of our solution is described in our previous paper.[5] It basically adopts CoP position

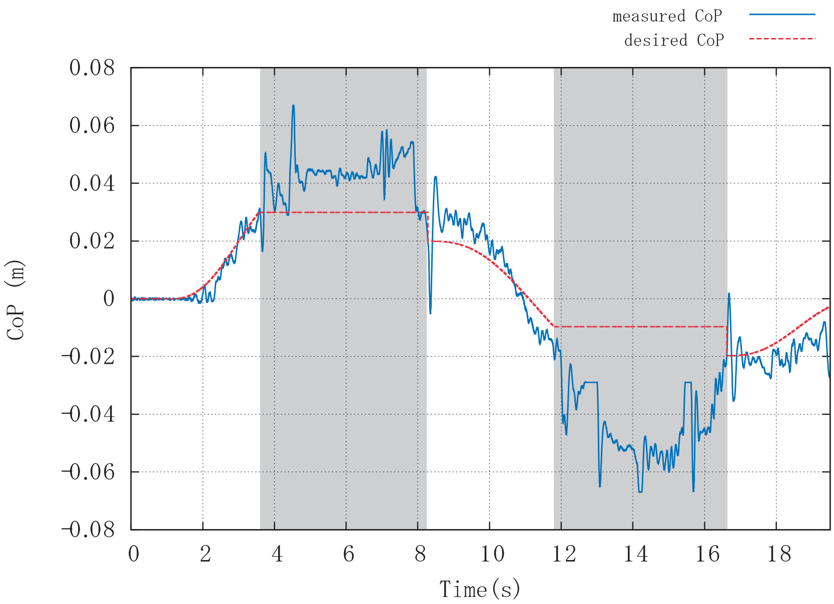

Fig. 7. Time course of CoP during the experiment.

feedback to maintain the balance of the biped robot.

$$\tau_\phi = -K_d\dot{\phi} + K_P(\phi_d - \phi) + K_f \int (P_d - P_{CoP})dt \tag{1}$$

where ϕ denotes the CoM of the whole robot, P_{CoP} is the position of CoP obtained from the load cells and P_d is a desired trajectory of CoP. K_d, K_p and K_f are the feedback gains. This ensures the local convergence of the CoP position if its desired trajectory varies slowly enough. Because the direct trajectory of the CoP is usually the same even if the slope of the ground is varied, this method allows biped robots to adapt to the slope without changing the control law.

3.3. *Results*

Bipedal walking was tried in two different conditions: a leftward slope and an upward slope. We used the robot described in the previous section. Figure 5 presents a sequence of photos showing actual walking on slopes for a leftward slope. An upward slope is shown in Fig. 6. Bipedal walking was achieved in both cases. The time course of the CoP position in the lateral direction is depicted with its desired trajectory in Fig. 7. The trajectory tracking of CoP was achieved in the double support phases (unshaded range).

4. Concluding remarks

To achieve bipedal walks on a sloping surface using the control law that we proposed, we required a biped robot with a control system that enables us to introduce torque control and measure joint angles and ground reaction forces. Thus far, we attempted to construct biped robots, but encountered a lack of motor power . We therefore invented a new, lighter hip joint structure with reduced DoFs that produces the leg alternative swing motion as well as the lateral sway motion. Adopting this new structure, we actually managed to construct a robot and achieved bipedal walks on a leftward and an upward slope. This demonstrates that this hip joint structure works well for an actual biped robot, and that our control law is effective for bipedal walk on a slope. For future walks, we intend to improve the speed of the bipedal walk, and to try walking on uneven ground with various gradient magnitudes along the route.

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