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Procedia Engineering 41 (2012) 113 – 119

Engineering Procedia

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International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)

Stability Control of Minimalist Bipedal Robot in Single Support Phase

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Abstract

This paper presents the conceptual design of a new four degree-of-freedom minimalist bipedal walking robot and specifically discusses on the physical development of the robot's sagittal balancing mechanism and its control in a single support phase. The proposed mechanism combines a novel method for stability sensing and balancing of the robot during the strides. The sensing mechanism utilizes an additional flexible ankle joint which is able to provide responsive and accurate measurement of the sagittal instability of the bipedal robot. The use of double balancing mass and the developed control algorithm are responsible to maintain the sideway stability of the robot during single support phase. The proposed method enables the walking control algorithms to be decoupled from the robot stability control algorithms and also simplifies the overall robot motion control and reduces the requirements of computing power. Furthermore, the use of two different masses for the balancing helps to improve response time and efficiency of the balancing system. In this paper, the proposed method is tested on the physical prototype and the experimental results are presented.

Keywords: bipedal walking; single support phase; sagittal balancing.

Nomenclature

T_{dist}	external disturbance to robot body (Nm)
m_L	lumped mass of the hanging leg (kg)
m_{B1}	major balancing mass (kg)
m_{B2}	minor balancing mass (kg)
r	distance from free ankle joint to robot hip (m)
d	distance between two legs (m)
d_S	distance of major balancing mass from the standing leg
a	distance of minor balancing mass from the standing leg
Greek symbols	
θ	body tilt angle (rad)

1. Introduction

Nowadays, the applications of machines and robots to assist human in performing their tasks has become increasingly extensive. In industrial applications, the use of robotics system has reached the level which surpasses human ability in terms of speed and accuracy. On the other hand, in the field of domestic robots or service robots, the developments are still far

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doi:10.1016/j.proeng.2012.07.150

from perfection. The main factor that distinguishes industrial robots from service robots is their working environment. For a service robot to perfectly perform its tasks, it needs to be able to adapt and cope with the normal human living environment. From the practical point of view, bipedal robot is the most suitable robot structure due to its similarity of physical configuration with human especially in terms of locomotion method. However, the realization of bipedal robot is more challenging compared to other types of mobile robot due the unstable nature of bipedal walking. Therefore, many studies have been carried out especially concerning the stability sensing and control strategies of bipedal robot.

The common approach in defining the stability of bipedal robot is by using the “Zero Moment Point” (ZMP) criterion [1]. The simplest implementation of ZMP is to generate the joint trajectories based on the pre-planned walking gait while maintaining the ZMP at the given references, but this approach has a limitation in maintaining the balance if there is any unknown external disturbance [2-5]. Many studies specifically focus on the techniques to monitor the real-time ZMP position from the physical system and used it as the feedback component [6-9]. Takanishi and Kato [7] proposed a method to monitor the ZMP position by measuring the force and moment acting on the robot’s shank by using universal force-moment sensor. Another method utilizes an array of force sensitive resistor placed on the sole of the robot’s foot to obtain the ground reaction force at different locations of the foot. The reaction forces measured from the sensor array is then used to compute the position of the center of pressure which reflects the position of the ZMP [9].

The inverted pendulum technique is another alternative for analyzing the robot stability [10]. This method monitor the instability by constantly reading the body acceleration and tilt angle by means of accelerometer and gyroscope. However, the readings from both sensors are subject to noise and drift during the operation and the effort to apply filters in correcting the measurements often requires considerable amount of computing power [11].

This paper proposed a novel method for sensing and stability control of bipedal robot. The use of specially designed flexible ankle joint allows fast detection and prediction of robot sideway instability. Placing an additional one degree-of-freedom rotary joint with built-in angle detection sensor at the robot ankle allows the robot’s body to tilt freely in any sideway direction and detect the tendency of imbalance that may potentially occur. Based on this essential sensor’s information, the controller will quickly adjust position of the counterbalance mass located at the robot waist in order to restore the sideway balance of the robot. The advantage of using counterbalance mass and rotary joint at the ankle is to allow the walking subsystem and sideway balancing subsystem of the robot to be decoupled from each other and work in independently controlled modes. It is different from the traditional approach when the robot’s posture is corrected to satisfy both conditions at once, smooth forward walking and continuous sideway (sagittal) stability.

Details of the proposed method are presented as follows. In section 2 the locomotion mechanism, ankle structure, sensing technique and balancing strategy are introduced. Section 3 discusses the mathematical model of the system. In section 4 experiment method is discussed and the viability of the proposed system is proven by the experimental result. Finally, the conclusions are described in section 5.

2. Mechanical Structure of Biped Robot

2.1. Robot locomotion mechanism

The biped robot is designed to realize two dimensional walking with minimum number of actuations. The locomotion system of the robot consists of four actuators, two for the hip joints and two for the knee joints. The ankle joint is not actuated by any actuators but instead it utilizes a series of parallelogram mechanism to passively control the ankle joint in order to maintain the position of the foot. The usage of parallelogram mechanism provides benefits by reducing the number of actuators needed which results in the simplification of the mechanism design and reduction of the overall robot’s weight.

Fig 1(a) shows the stick diagram of the leg in different configuration. The orientation of link *a* is always parallel to the hip due to the constraint applied by link *1* and link *2*. The orientation of link *b* which represents the foot is always parallel to link *a* due to the constraint applied by link *3* and link *4*. Therefore, the foot is always kept parallel by the parallelogram mechanism regardless of any configuration of the leg. Fig 1(b), (c) show the physical implementation of the parallel leg in different postures.

The prototype of the biped robot is mainly constructed using hollow sections of extruded aluminium due to its lightness and strength. The overall height of the biped robot is 0.9 m with the total weight of 7 kg. The length for both thigh and shank are 0.3 m and the spacing between two legs is 0.15 m.

For the actuation, each joint is equipped with Robotis Dynamixel RX-64 Smart Actuator, which combines gear transmission, controller, driver and network function in a single package. The output of the hip motor is connected directly to the hip joint and the output of the knee motor is transmitted to the knee joint via a four bar linkage. The purpose of placing the actuators on the hip is to reduce the weight of the leg which will minimize the dynamics forces created by the leg movement. The other advantage of this structural arrangement is that the angular count at each joint is always referenced to the fixed vertical axis of the stationary world coordinate frame regardless of the leg postures.

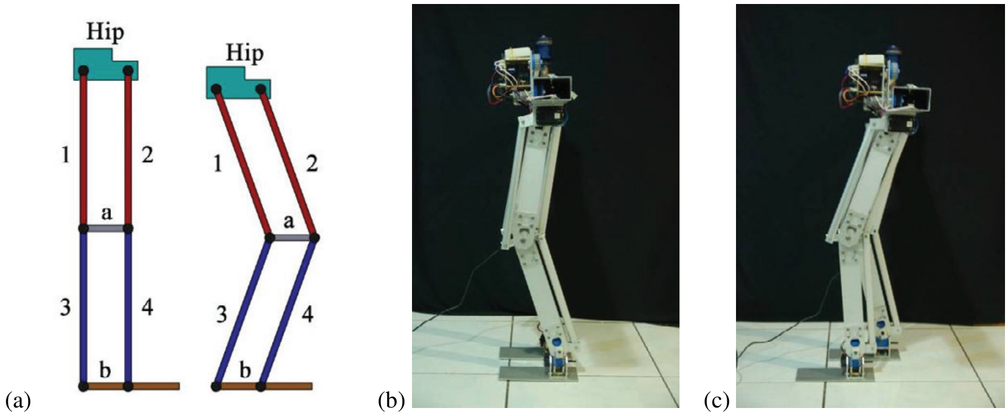

Fig. 1. (a) Stick diagram of parallelogram leg; (b), (c) Robot standing with different leg configurations

2.2. Flexible ankle joint to utilize stability measurement

In order to achieve a stable walk on a biped robot, the ability to accurately detect any possible instability is quite crucial. This paper introduces a new approach of sensing the instability by introducing an additional degree of freedom in sideway direction next to the ankle joint. Fig 2(a) shows the structure of that degree of freedom where the free rotary joint on the frontal plane is placed at the ankle between the foot and ankle joint. It will let the unconstrained robot body standing on one leg to tilt (angle θ) freely in sideway (sagittal) direction for any possible disturbance in that direction. By installing a rotary sensor on the free joint the controller will be able to detect instantly any instability and immediately react to restore the balance.

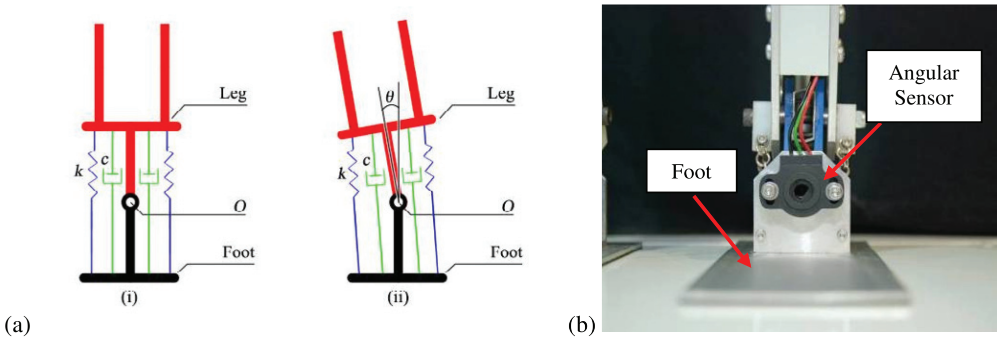

Fig. 2 (a) Schematic picture of the flexible ankle structure; (b) Physical implementation of flexible ankle

2.3. Split balancing mass for faster system response

The walking cycle of bipedal robot consists of single support phase and double support phase which are executed sequentially and repeatedly. In single support phase, the robot is standing on one leg while another leg is transferred forward. During this phase, the robot body will be tilted sideways due to the unbalanced torque created by the weight of the lifted leg and the dynamic forces generated due to the leg movement.

In order to maintain stability of the robot, a set of counterbalance masses are located at a specific position to compensate the unbalanced mass of the lifted leg and other possible disturbance. Fig 3 shows the simplified 3-masses model of bipedal robot: m_L represents the lumped mass of the hanging leg, m_{B1} represents the major balancing mass and m_{B2} represents the minor balancing mass.

Major balancing mass is mainly used to compensate the weight of the lifted leg. This mass is positioned at a pre-calculated location in order to balance the torque created by the mass of the lifted leg m_L. The minor balancing mass m_{B2} is continuously repositioned based on the information gathered from the sensor located at the additional ankle joint. This mass works as a counterbalance to maintain the robot to be always vertical regardless of any external sideway disturbance.

The use of two separate counterbalance masses provides several advantages such as:

- Faster response time can be achieved by only moving small inertia counterbalancing mass instead of moving a larger one,
- Energy efficiency can be improved by reducing load of the motor that drives a smaller inertia counterbalancing mass.

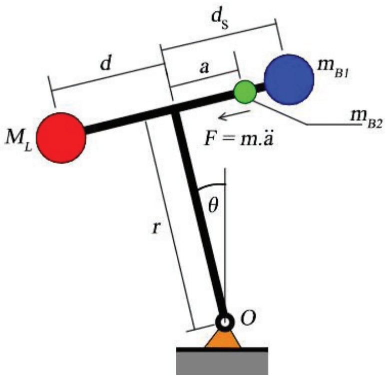

Fig. 3 Simplified model of the bipedal robot

3. System modeling and control

From the diagram on Fig 3, the dynamic equation using Newton's second law about point O gives:

$$\sum T_O = I\ddot{\theta}$$
$$T_{dist} + m_L g\left(d\cos\theta + r\sin\theta\right) - m_{B2} g\left(a\cos\theta + r\sin\theta\right) - m_{B1} g\left(d_S\cos\theta + r\sin\theta\right) + m_{B2}\ddot{a}r - c\dot{\theta} - k\theta = \tag{1}$$
$$\ddot{\theta}\left(m_L\left(r^2+d^2\right) + m_{B2}\left(r^2+a^2\right) + m_{B1}\left(d_S{}^2+r^2\right)\right)$$

Since the major balancing mass m_{B1} is mainly use to compensate for the torque created by the weight of the hanging leg m_L, the major balancing mass can be positioned at the pre-calculated location on the opposite side of the hanging leg. The required position of the major balancing mass d_S can be calculated based on the equilibrium of torque at point O as follows:

$$\sum T_O = 0$$
$$m_L d - m_{B1} d_S = 0$$
$$m_L d = m_{B1} d_S \tag{2}$$
$$d_S = \frac{m_L}{m_{B1}} d$$

Substituting d_S from Eq.(2) into L.H.S of Eq.(1) gives:

$$T_{dist} + m_L g\left(d\cos\theta + r\sin\theta\right) - m_{B2} g\left(a\cos\theta + r\sin\theta\right) - m_{B1} g\left(\frac{m_L}{m_{B1}} d\cos\theta + r\sin\theta\right) + m_{B2}\ddot{a}r - c\dot{\theta} - k\theta =$$
$$\ddot{\theta}\left(m_L\left(r^2+d^2\right) + m_{B2}\left(r^2+a^2\right) + m_{B1}\left(d_S{}^2+r^2\right)\right)$$

$$T_{dist} + g\cos\theta\left(m_L d - m_L d - m_{B2}a\right) + gr\sin\theta\left(m_L + m_{B2} + m_{B1}\right) + m_{B2}\ddot{a}r - c\dot{\theta} - k\theta = \ddot{\theta}\left(m_L\left(r^2 + d^2\right) + m_{B2}\left(r^2 + a^2\right) + m_{B1}\left(d_S{}^2 + r^2\right)\right) \quad (3)$$

Rearranging the differential equation from Eq.(3) gives:

$$T_{dist} - m_{B2}g \cdot a\cos\theta + \left(m_L + m_{B2} + m_{B1}\right)g \cdot r\sin\theta + m_{B2}\ddot{a}r - m_{B2}a^2\ddot{\theta} = \ddot{\theta}\left(m_L\left(r^2 + d^2\right) + m_{B2}r^2 + m_{B1}\left(d_S{}^2 + r^2\right)\right) + c\dot{\theta} + k\theta \quad (4)$$

The differential equation in Eq.(4) has two distinct parts. The right hand side only presents parts of the ordinary differential equation with constant time invariant coefficients and the left hand side presents all remaining parts of the equation. Therefore, the left hand side includes:

- Non-linear functions of the main dependent argument θ, namely sin θ, cos θ
- Additional but independent from the main argument θ parameter $\ddot{a}$
- The parameters that comprises both a and θ arguments, namely $m_{B2}a^2\ddot{\theta}$

Fig 4 shows the simplified control block diagram of the balancing system. The PID controller constantly monitors the tilt angle *(θ)* from the sensor of the additional ankle joint and compares the reading with that of the desired angle. If any tilt is detected, the controller will actuate the balancing mass to the opposite direction in order to regain the balance.

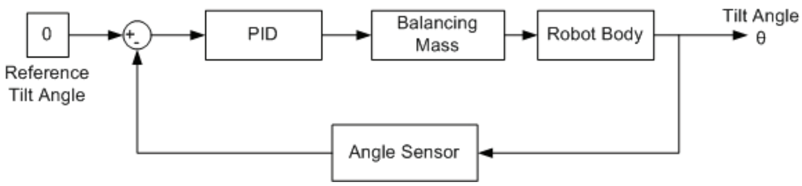

Fig. 4 Simplified block diagram of the stability control system

4. Experimental results

The experiment is carried out to verify the effectiveness of the proposed mechanical structure and control strategies in maintaining the robot's balance in single support phase. During the experiment, the robot is standing on one leg with another leg lifted up and floating. The external disturbance is applied by making a push on the edge of the robot's hip which will cause the robot to tilt sideways (Fig 5(a)). The intensity of the pushing force is measured by a force sensor mounted on the hip (Fig 5(b)).

Fig 6 shows the measurement of the tilt angle θ from the additional ankle joint, balancing mass position a and the disturbance force when the external disturbance is applied. It is apparent from the figure that once the disturbance is applied the sensor detects change in tilt angle and the controller immediately reacts by moving the mass to the opposite direction of the tilt in order to regain the balance. Fig 7 shows the measurement when an excessive disturbance force is applied approximately at the 37th seconds, the tilt angle changes abruptly and the balancing mass is not able to recover the balance. The saturated angle measurement at the end of the plots indicates that the robot is falling. It is due to the fact that the value of minor mass m_{B2} and the allowable range of its motion a are limited in this design. The overall resistance to the externally generated force can be increased by either increasing m_{B2} or a.

(a) (b)

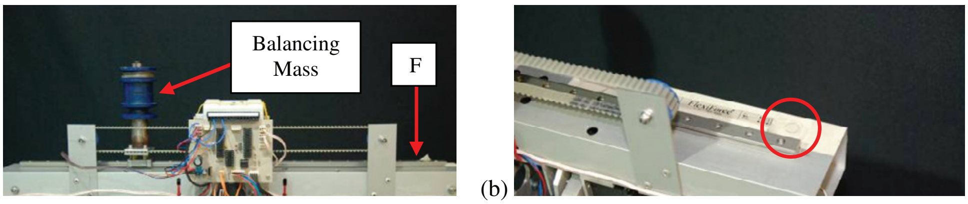

Fig. 5 (a) Hip plane of the robot; (b) Force sensor attachment to measure applied disturbance force

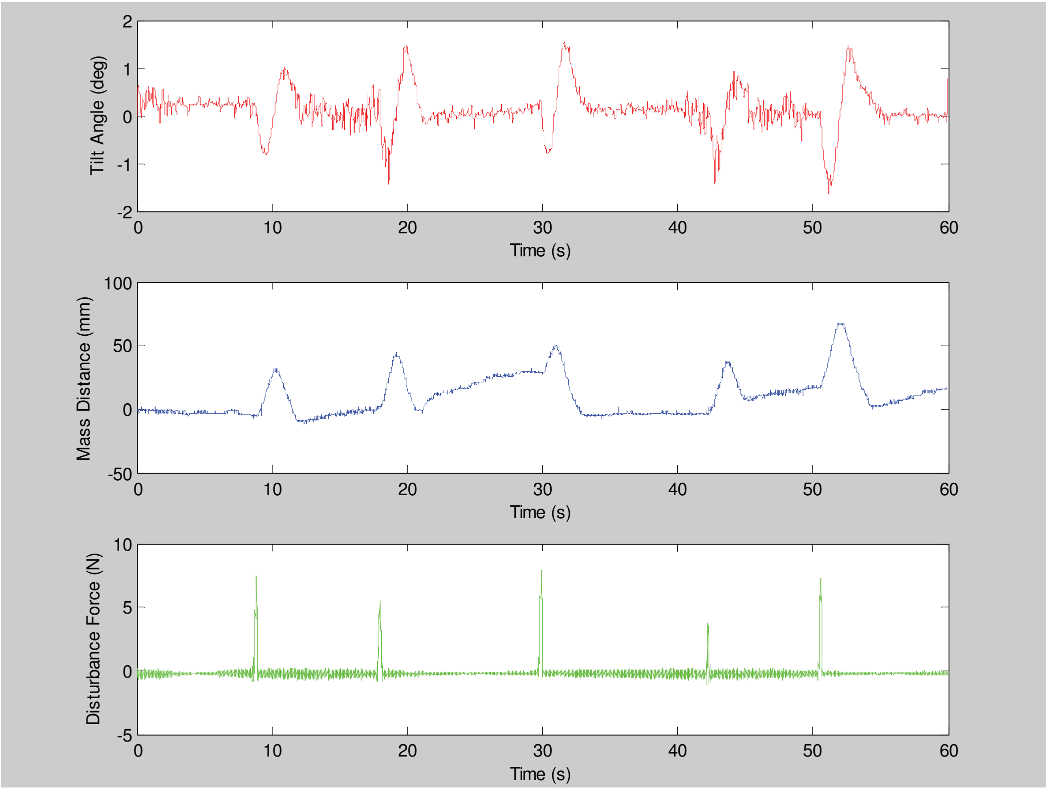

Fig. 6. System response to disturbance (balance maintained)

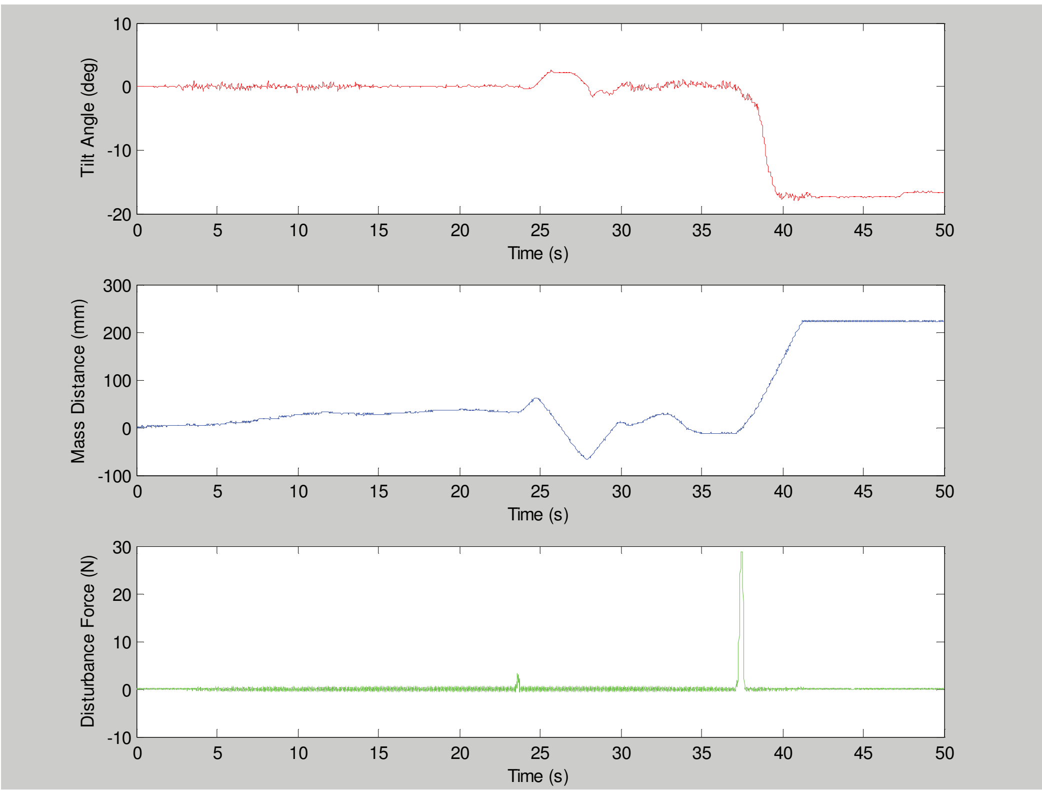

Fig. 7. System response to disturbance (excessive force applied)

5. Conclusion

This paper presents stability control method for bipedal walking robot which includes the leg design with additional (redundant) degree of freedom at the ankle joint and split balancing mass. The proposed method enables the sensing, control and balancing of bipedal robot to be implemented in a simple yet cost effective manner. The effectiveness of the design method is proven by the experimental results. The implementation of this method also allows the walk controlling algorithms to be decoupled from the stability control algorithms to increase the system response time.

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