Design and Propulsion Control of a Robotic Leg with Passive Bi-articular Actuators

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1. Background

Legged robots have been developed since late 19th century and there have been made many research works around world concerning the walking locomotion and robots. Among many reasons for these efforts being made, there are two important aspect and contribution of the research on walking robots to point out: high mobility and understanding of animal locomotion [1]. And these two are forming the two main streams of the research in the field.

1·1 High Mobility

One reason legs provide better mobility in rough terrain is that they use isolated footholds that optimize support and traction, meanwhile a wheel needs a continuous path of support. Another advantage of legs is that they can provide an active suspension that decouples the path of the body from the paths of the feet. The payload is free to travel smoothly despite pronounced variations in the terrain. For these and many other reasons, legged vehicles have been developed in various fields including industrial, agricultural, aerospace and military applications.

1·2 Understanding of Animal Locomotion

In many aging societies, including countries like Japan and Korea, the demands for nursing and rehabilitation in the field of medical service, are expected to grow rapidly. In-depth understanding of human and animal motion will greatly contribute to the field in many ways. Many research groups including the authors have been working on this topic. Research works of Oh [2], Salvucci [3], and Kimura [4] made great contributions in the field by providing in-depth insights in animal muscle dynamics.

1·3 Outline of this Work

This work presents a novel design and propulsion control method using an equivalent spring model for a robotic leg with passive bi-articular elements and the mono- bi- configuration, anticipating the legged personal mobility applications. The design philosophy and the control strategy are introduced and discussed with experimental results.

2. Design of JUMPBiE

An experimental robotic leg, JUMPBiE (Jumping Leg using Passive Bi-articular Elements) is designed and fabricated (See Fig. 1.). JUMPBiE has one motor which is attached to the upper joint, and two passive bi-articular elements – springs which apply torque to the upper and the lower joint simultaneously. The system configuration and its mathematical description are elaborated in detail with their theoretical backgrounds in this section.

Fig.1 The experimental robotic leg, JUMPBiE.

2·1 Kinematics of Mono-Bi Configuration

Oh et al. showed the effectiveness of the mono-bi-configuration in the two-link manipulator [5]. When considering economy and performance, it is shown that using the mono-articular actuator in the upper joint and the bi-articular one between the upper and the lower joints. Based on this observation, recently, Sonokawa et al. introduced a novel leg space coordinate system and velocity control method for two link robotic arm equipped with mono-bi-actuators [6].

This work is based on the results of those works. The system schematic is shown in Fig. 2. Assuming that the length of each link is identical, i.e.:

$$l_1 = l_2 = l \tag{1}$$

the kinematics of the system can be described as:

$$\begin{bmatrix} \tau_{motor} \\ \tau_{spring} \end{bmatrix} = \frac{1}{l_m} \begin{bmatrix} l^2 s_2 & l^2(1+c_2) \\ -l^2 s_2 & l^2(1+c_2) \end{bmatrix} \begin{bmatrix} F_{X_l} \\ F_{Y_l} \end{bmatrix} \tag{2}$$

$$\begin{aligned} \begin{bmatrix} F_{X_l} \\ F_{Y_l} \end{bmatrix} &= \frac{1}{l_m s_2} \begin{bmatrix} c_2+1 & -c_2-1 \\ s_2 & s_2 \end{bmatrix} \begin{bmatrix} \tau_{motor} \\ \tau_{spring} \end{bmatrix} \\ &= \frac{1}{l_m s_2} \begin{bmatrix} (1+c_2)(\tau_{motor} - \tau_{spring}) \\ s_2(\tau_{motor} + \tau_{spring}) \end{bmatrix} \end{aligned} \tag{3}$$

where $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$.

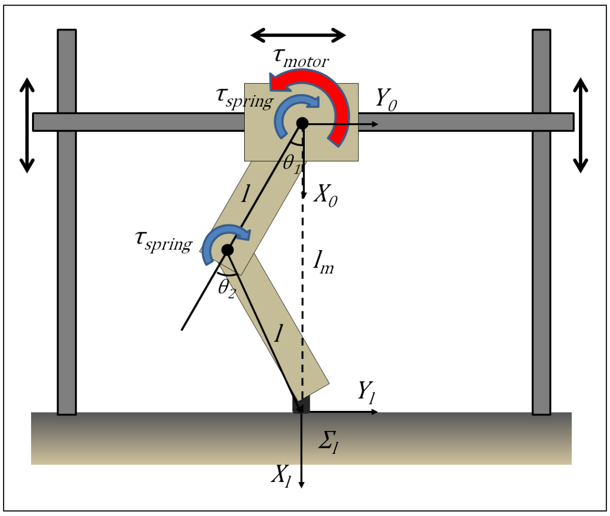

Fig.2 The system schematic and the frame of reference of JUMPBiE.

Output force at the end-effector along X_l, Y_l axes also can be designed by the common mode and difference mode independently; $\tau_{motor} - \tau_{spring}$ generates F_{X_l} and $\tau_{motor} + \tau_{spring}$ generates F_{Y_l}. This property of the system enables a simple control.

2·2 Mechanical Design

The most fundamental components of a robotic leg are mechanical structure, actuators, and electrical system. The structure of the robot leg and body is made of ABS, which is the toughest engineering plastic with over 300 J/m of Izod impact strength, equivalently the half of aluminum. At the same time the specific weight of ABS is 1.05, which is much lighter than aluminum (2.69), and still strong enough to endure the impact from jumping. From the specification of the material and the geometrical dimensions, physical parameters of the links can be calculated as shown in Table 1 below.

Table 1 Mechanical Parameters

Par.	Meanings	Values
M	Total mass	8 kg
I_1	Inertia moment, l_1 at J_1	0.0808 kgm^2
I_2	Inertia moment, l_2 at J_2	0.0019 kgm^2
l_1	Length of l_1	0.3 m
l_2	Length of l_2	0.3 m

From the mechanical design of the robot, the necessary torque and power for jumping can be calculated using Jacobian. Due to the kinematics of the bi-articular linkage, the motor only need to compensate the horizontal force exerted from the bi-articular spring. By using (3), we can calculate the necessary τ_{motor} given that the weight of the robot is known as 80N. For example, assuming that the resting position of the robot is at $\theta_1 = -\frac{\pi}{6}$ and $\theta_2 = \frac{\pi}{3}$, the necessary net force which should be exerted by both the motor and spring is equal to the weight of the robot, i.e. say 80N including the weight of the linear guide. Thus the spring should exert 270N, and regarding the range of the leg rotation, the spring constant should be around 20N/mm and its initial length should be less than 10cm. To compensate the horizontal force exerted by the spring, which is around 140N at the resting position. Based on this consideration, a 200W motor with 1/40-reduction ratio was chosen together with appropriate spring constants. Two encoders are attached to each joint to measure the angular displacements, and the cRIO chassis of National Instruments Corp. is used as the controller.

3. Propulsion Control using Equivalent Spring Model

3·1 The Equivalent Spring Model

By using the mono-bi configuration, the output stiffness seen at the end-effector can be modeled as Fig.3. Since the bi-articular torque is given by passive elements, the stiffness of the springs K_{Spring} is fixed.

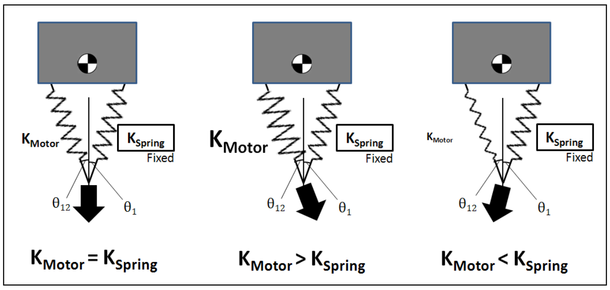

Fig.3 Equivalent spring model of the mono-bi configuration. Note that $\theta_{12} = \theta_1 + \theta_2$.

By arranging the magnitude of the motor stiffness K_{Motor}, the net stiffness seen at the end-effector can be controlled in the vicinity of the resting position. This concept is described in Fig.4.

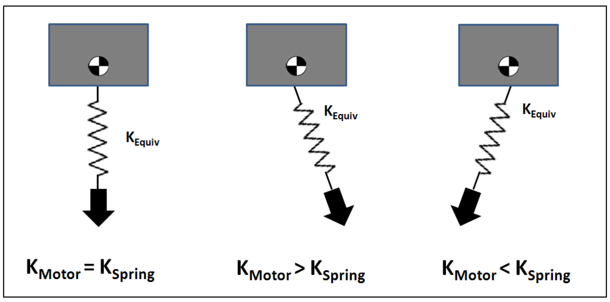

Fig.4 Equivalent spring model. The net stiffness seen at the end-effector.

The direction of the net stiffness at the end-effector can be controlled by changing the motor stiffness of the upper joint J_1. For the propulsion control of JUMPBiE, the net stiffness model shown in Fig.4– the equivalent spring model is used.

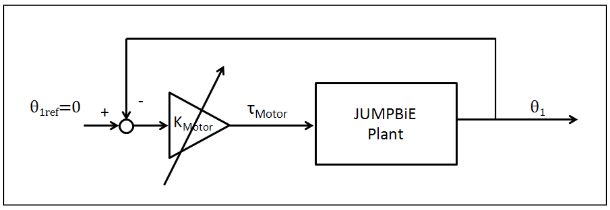

Fig.5 Feedback control loop.

Note that the magnitude of the net stiffness also changes along with the direction.

3·2 Propulsion Control using Equivalent Spring Model

For the implementation of the concept, a simple feedback control loop (Fig.5.) is designed. The initial resting position is given, and the control loop tries to regulate the position at the initial. Then the feedback gain K_{Motor} is seen as the stiffness of the motor, as the motor applies torque to the upper joint J_1 with a magnitude which is proportional to the angular displacement of J_1.

Considering the mechanical design and the control logic of the robotic leg:

$$\tau_{motor} = -K_M \Delta\theta_1 \quad (4)$$

$$\tau_{spring} = -K_S \Delta(\theta_1 + \theta_2 + R) \quad (5)$$

where R means the residual displacement of the spring, its mathematical model, equation (3) can be rewritten as:

$$\begin{bmatrix} F_{X_l} \\ F_{Y_l} \end{bmatrix} = \begin{bmatrix} \frac{1+c_2}{s_2 l_m}\left((K_S - K_M)\Delta\theta_1 + K_S\Delta\theta_2 + K_S R\right) \\ -\frac{1}{l_m}\left((K_S + K_M)\Delta\theta_1 + K_S\Delta\theta_2 + K_S R\right) \end{bmatrix} \quad (6)$$

Around the vicinity of the initial position where θ_1 and θ_2 are given, the net stiffness seen at the end-effector changes in its magnitude and direction as shown in Fig. 6. Then the robotic leg acts like a ball, bouncing on the ground with a controlled ground reaction force.

4. Experimental Results

With the control concept shown in the previous section, simple experiments are done. While changing the motor stiffness K_{Motor}, JUMPBiE was dropped from a certain height to see the direction and the magnitude of the reaction force at the ground. Fig.7.8. and 9. show the stroboscope pictures taken at every 10ms from release. Time flows from left to right, and from top to bottom.

By setting K_{Motor} equals to K_{Spring}, JUMPBiE jumps in place without moving its center of mass laterally (See Fig.7). The lowest point comes at t=90ms, in the 10th frame.

By setting K_{Motor} smaller than K_{Spring}, JUMPBiE jumps forward, to the right in the picture (See Fig.8). The lowest point comes at t=140ms, in the 15th frame.

By setting K_{Motor} larger than K_{Spring}, JUMPBiE

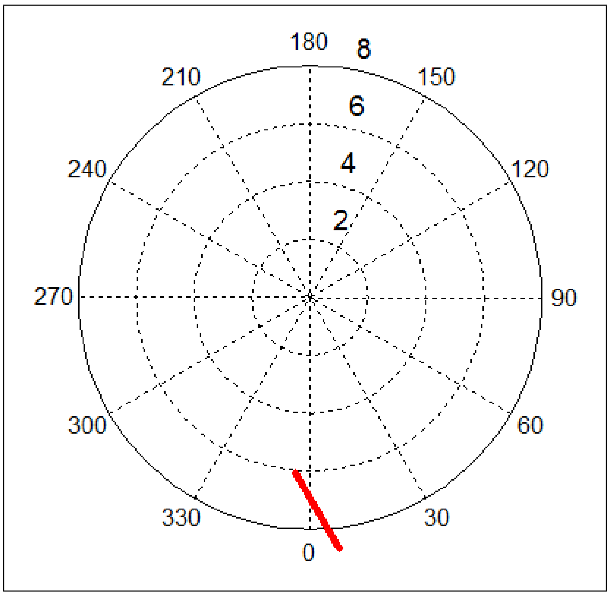

Fig.6 The net stiffness K_{equiv} with changing K_M. The magnitude is in N/mm, given that $\theta_1 = -\frac{\pi}{6}$ and $\theta_2 = \frac{\pi}{3}$. (Calculated)

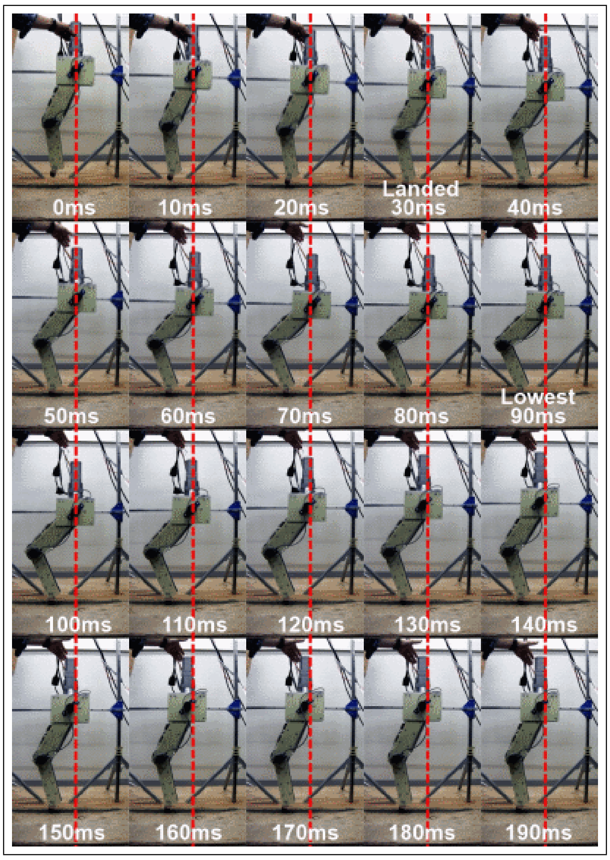

Fig.7 Jumping in place. K_{Motor} equals to K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=90ms.

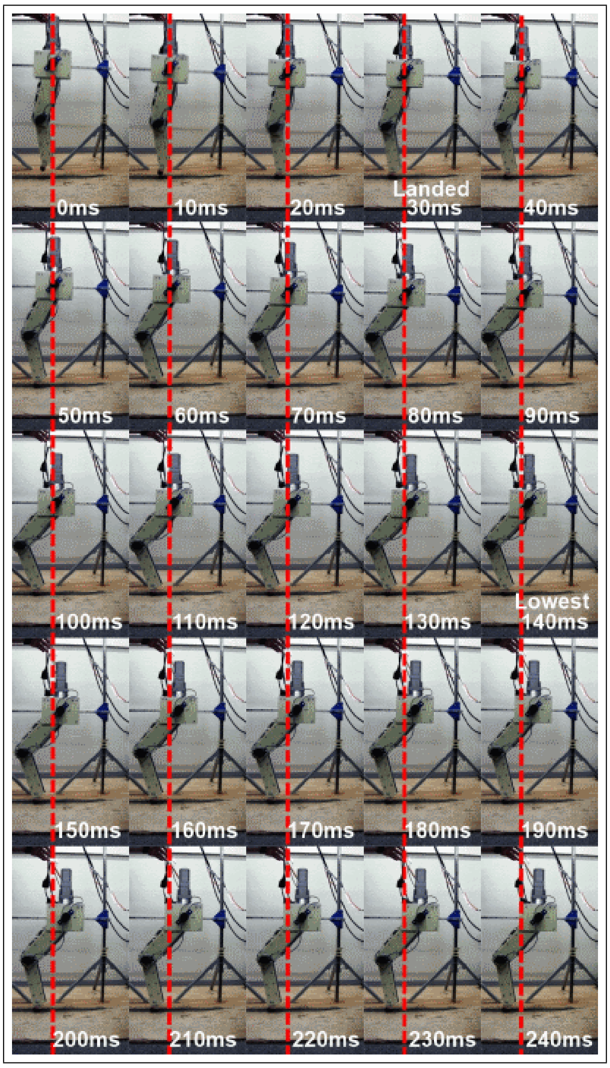

Fig.8 Jumping forward. K_{Motor} is smaller than K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=140ms.

jumps backward, to the left in the picture (See Fig.9). The lowest point comes at t=70ms, in the 8th frame.

It is shown that the mono-bi-configuration with passive bi-articular elements can be an effective solution for the propulsion for a robotic leg only using a simple feedback control. However, as noted in 3.1, the magnitude of the net stiffness changes along with the direction, which causes the change in jumping frequency. As it can be observed in the experimental results, when the net stiffness is large (jumping backwards) the frequency is high, while the frequency is low if the net stiffness is small (jumping forward). This property needs to be studied more thoroughly.

5. Conclusion

A novel design and control methods for a jumping leg using passive bi-articular elements are proposed. The robotic leg consists of the mono-bi-configuration, which is shown to be effective in legged locomotion. By using a simple P control, the robotic leg is controlled to jump in place, forward, and backward.

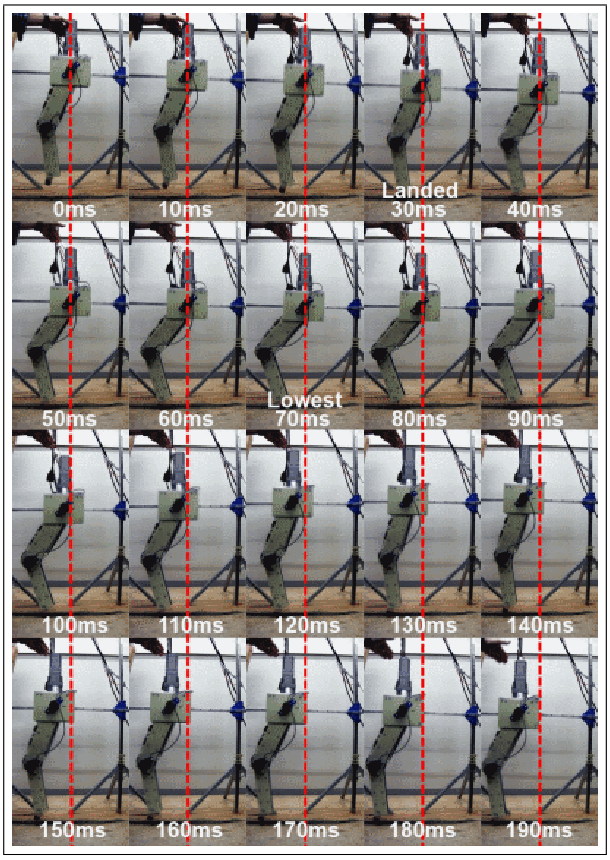

Fig.9 Jumping backward. K_{Motor} is larger than K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=70ms.

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