JUMPBiE: Jumping Leg with Passive Bi-articular Elements, its Design and Propulsion Control using Equivalent Spring Model

Yunha Kim* Student Member
Shinta Sonokawa* Student Member
Sehoon Oh* Member
Yoichi Hori** Fellow

This paper presents a novel design and control methods for a jumping leg using passive bi-articular elements, JUMPBiE. The robotic leg consists of the mono-bi-configuration, i.e., is using one motor as a mono-articular actuator, and two springs as passive bi-articular elements. The net output force of the robotic leg is the vector sum of the torque outputs of the motor and springs. By using a simple P control, the robotic leg jumps in place, forward, and backward. Experimental results are shown with discussion.

Keywords: Bi-articular actuator, Two-link manipulator, Jumping robot, Passive elements, Propulsion control, Mono-Bi-configuration

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. The types and the control mechanisms for those are various, and also the purposes for the research are full of variety. 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 Another important contribution of the research on walking robots is that it provides a better understanding of human and animal locomotion. Despite the skill that we apply in using our own legs for locomotion, we are still at a primitive stage in understanding the control principles that underlie walking and running. By building legged machines, we can obtain new insights into the problems and learn about possible solutions, which can guide biological research by suggesting specific models for experimental testing and verification.

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 such societies, the demand for animal-like companion robots such as Aibo from Sony is also expected to grow in the near future. 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.

2.1 Kinematics of the 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

* Graduate School of Engineering,
The University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656 Japan
** Graduate School of Frontier Sciences,
The University of Tokyo
5-1-5, Kashiwanoha, Kashiwa-shi, Chiba, 277-8561 Japan

Fig. 1. The experimental robotic leg, JUMPBiE.

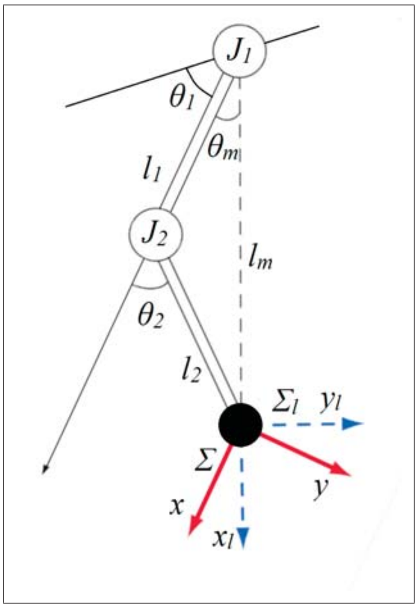

Fig. 2. The system schematic of JUMPBiE. Σ and Σ_l represent the absolute space and the leg space coordinates, respectively.

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. and the kinematics of the system can be described as:

$$\begin{pmatrix}\tau_1\\ \tau_{12}\end{pmatrix}=\frac{1}{l_m}\begin{pmatrix} l_1 l_2 \sin\theta_2 & l_1(l_1+l_2\cos\theta_2)\\ -l_1 l_2\sin\theta_2 & l_2(l_1\cos\theta_2+l_2)\end{pmatrix}\begin{pmatrix} f_l^x\\ f_l^y\end{pmatrix} \quad (1)$$

$$\begin{pmatrix} f_l^x\\ f_l^y\end{pmatrix}=\frac{1}{l_m\sin\theta_2}\begin{pmatrix}\cos\theta_2+\frac{l_2}{l_1} & -\frac{l_1}{l_2}-\cos\theta_2\\ \sin\theta_2 & \sin\theta_2\end{pmatrix}\begin{pmatrix}\tau_1\\ \tau_{12}\end{pmatrix} \quad \cdots\cdots (2)$$

and if $l_1 = l_2 = l$, the kinematics is simplified as follows.

$$\begin{pmatrix}\tau_1\\ \tau_{12}\end{pmatrix}=\frac{1}{l_m}\begin{pmatrix} l^2\sin\theta_2 & l^2(1+\cos\theta_2)\\ -l^2\sin\theta_2 & l^2(1+\cos\theta_2)\end{pmatrix}\begin{pmatrix} f_l^x\\ f_l^y\end{pmatrix}$$
$$=\frac{l^2\sin\theta_2}{l_m}\begin{pmatrix}1\\ -1\end{pmatrix}f_l^x+\frac{l^2(\cos\theta_2+1)}{l_m}\begin{pmatrix}1\\ 1\end{pmatrix}f_l^y \quad (3)$$

$$\begin{pmatrix} f_l^x\\ f_l^y\end{pmatrix}=\frac{1}{l_m\sin\theta_2}\begin{pmatrix}\cos\theta_2+1 & -\cos\theta_2-1\\ \sin\theta_2 & \sin\theta_2\end{pmatrix}\begin{pmatrix}\tau_1\\ \tau_{12}\end{pmatrix}$$
$$=\frac{1}{l_m\sin\theta_2}\begin{pmatrix}(1+\cos\theta_2)(\tau_1-\tau_{12})\\ \sin\theta_2(\tau_1+\tau_{12})\end{pmatrix} \quad \cdots\cdots (4)$$

Force at the end-effector along x_l, y_l axes also can be designed by the common mode and difference mode independently; $\tau_1 - \tau_{12}$ generates f_l^x and $\tau_1 + \tau_{12}$ generates f_l^y. 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. Physical Parameters

Parameters	Meanings	Values
M	Total mass	8 kg
I_{l1}	Inertia moment of l_1 at the hip joint	0.0808 kgm^2
I_{l2}	Inertia moment of l_2 at the knee joint	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 (4), we can calculate the necessary tau_1 given that the weight of the robot is known as 80N. For example, assuming that the resting position of the robot is at θ_1=30 degrees and θ_2=60 degrees, 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.

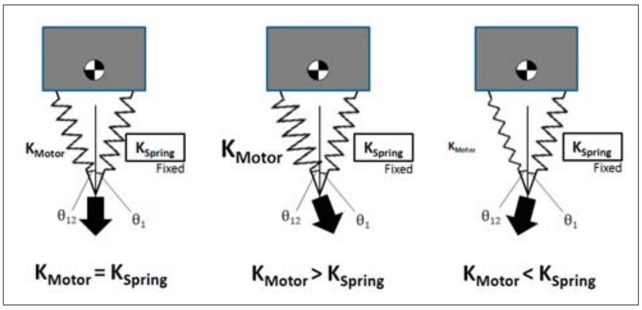

Fig. 3. Equivalent spring model. Mono-bi-configuration.

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.

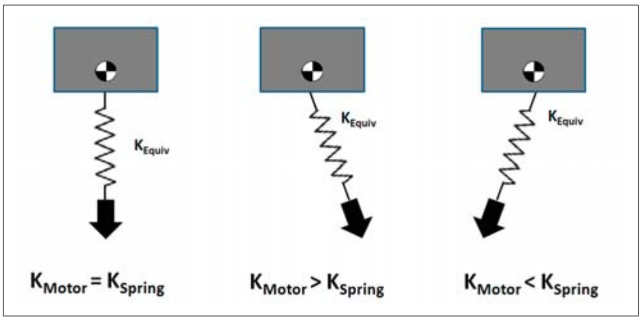

Fig. 4. Equivalent spring model. The net stiffness seen at the end-effector.

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.

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.

Then the robotic leg acts like a basketball, bouncing on the ground with a controlled reaction force. The experimental results are shown in the following section.

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.6.7. and 8. show

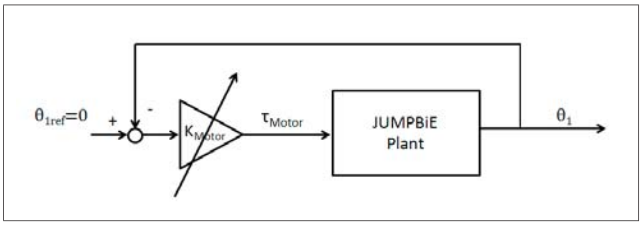

Fig. 5. Feedback control loop.

the stroboscope pictures taken at every 10ms from release. Time flows from left to right, and from top to bottom.

4.1 Jumping in place By setting K_{Motor} equals to K_{Spring}, JUMPBiE jumps in place without moving its center of mass laterally (See Fig.6). The lowest point comes at t=90ms, in the 10th frame.

4.2 Jumping Forward By setting K_{Motor} smaller than K_{Spring}, JUMPBiE jumps forward, to the right in the picture (See Fig.7). The lowest point comes at t=140ms, in the 15th frame.

4.3 Jumping Backward By setting K_{Motor} larger than K_{Spring}, JUMPBiE jumps backward, to the left in the picture (See Fig.8). The lowest point comes at t=70ms, in the 8th frame.

4.4 Discussion 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

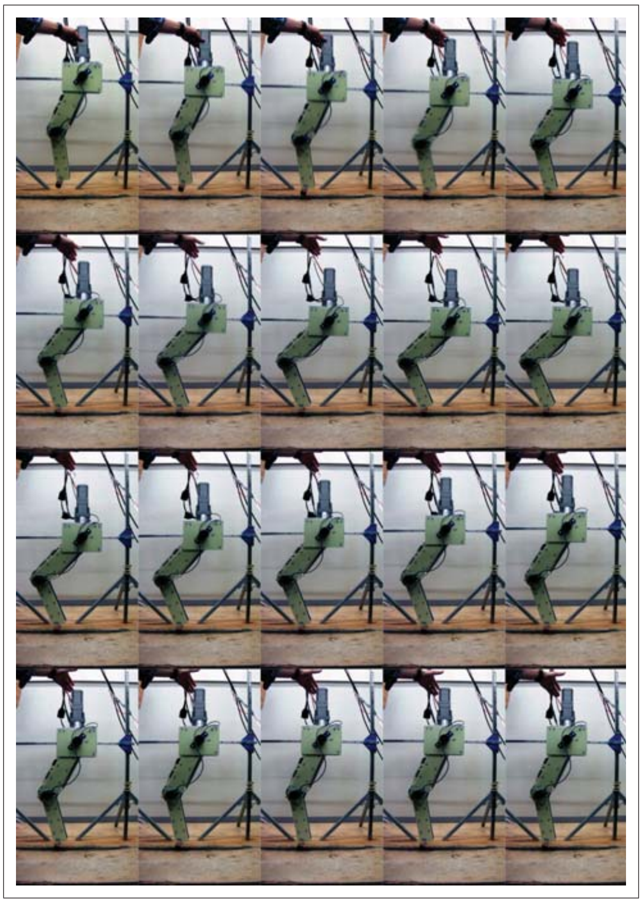

Fig. 6. Jumping in place. K_{Motor} equals to K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=90ms.

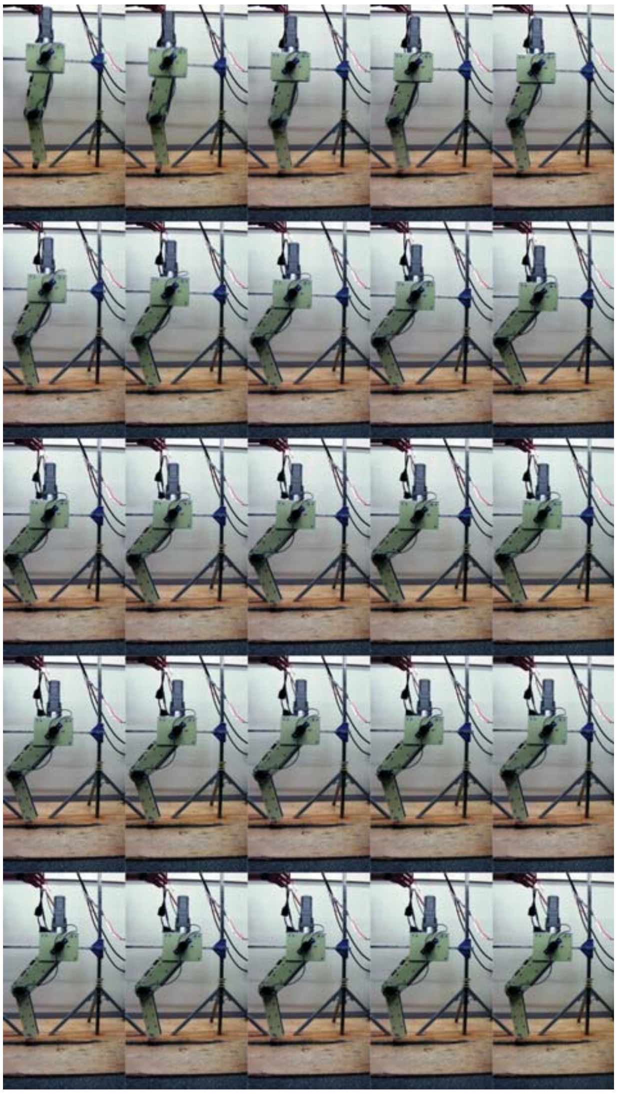

Fig. 7. Jumping forward. K_{Motor} is smaller than K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=140ms.

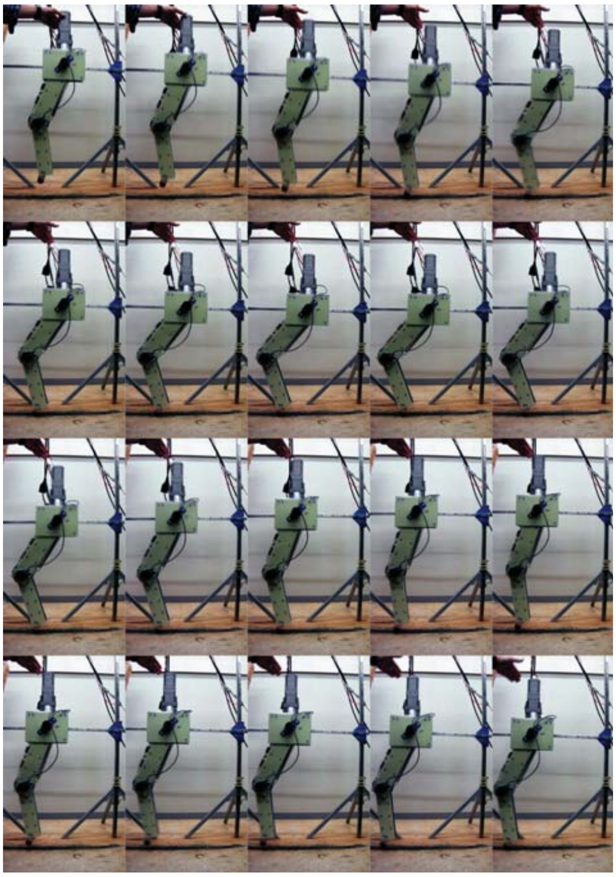

Fig. 8. Jumping backward. K_{Motor} is larger than K_{Spring}. Taken at every 10ms from release. The lowest point comes at t=70ms.

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 throughly.

5. Conclusion and Future Work

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. However, there are some problems to solve in order to apply this method in legged mobility applications, which include stability, and the change in jumping frequency.

Future work will include making solutions to these problems.

References

(1) E. Garcia, et al., "The Evolution of Robotics Research," IEEE Robotics and Automation Magazine, March 2007, pp.90-103

(2) S. Oh and Y. Hori, "Development of two-degree-of-freedom control for robot manipulator with bi-articular muscle torque," Proc. American Control Conference 2009

(3) V. Salvucci, Y. Kimura, S. Oh, and Y. Hori, "BiWi: Bi-articularly actuated and wire driven robot arm," Proc. International Conference on Mechatronics 2011, pp.827-833

(4) Y. Kimura, S. Oh, and Y. Hori, "Novel robot arm with bi-articular driving system using a planetary gear system and disturbance observer," Proc. IEEE International Workshop on Advanced Motion Control 2010, pp.815-820

(5) S. Oh, V. Salvucci, Y. Kimura, and Y. Hori, "Mathematical and Experimental Verification of Efficient Force Transmission by Biarticular Muscle Actuator," Proc. World Congress of the International Federation of Automatic Control (IFAC) 2011, pp.13516-13521

(6) Shinta Sonokawa, Yasuto Kimura, Sehoon Oh, and Yoichi Hori, "Center of Mass Velocity Control during Stance Phase by Endeffector Force Control in the Leg Coordinate for Biarticularly-actuated Leg System," Proc. IEE of Japan Technical Meeting Record (IIC) 2012, pp.117-122