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Design and Control of Jumping Mechanism for a Kangaroo-inspired Robot

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Abstract—**This paper presents the design and control of a jumping mechanism of a Kangaroo-like robot (Kangarobo). The robot is purposely designed to not only jump as high as possible but also to walk with two legs and one tail while carrying all the body weights. The leg is designed by a four-bar linkage structure. Energy saving mechanism for the leg is designed with springs and releasing mechanism is designed with a cam structure. The cam has been designed and modified many times by using a 3D printer to optimize the jumping power. In addition, an optimal spring constant is chosen on the basis of experimental studies. Controllers of a jumping motion are implemented on the DSP and experimental results of successive jumping motions are tested.**

***Index Terms*—Jumping motion, Kangaroo-like robot, cam structure, spring selection**

I. INTRODUCTION

OPtimal motions for robots can often be learned from animals in the mother nature. In the area of biomimetics, robots mimic biological systems in various aspects of motions like crawling, locomotion, jumping, running and flying.

Biomimetics includes not only animals but also insects. Bigdog is one of biomimetic robots that have four legs mimicking a dog. Bigdog has been aimed to carry heavy objects in its terrain, not only flat ground but even slanted ground such as mountains by maintaining balance. Bigdog has been tested for the robustness from outer disturbance such that it can maintain balance all the time under hits [1,2].

Recently, cheetah robots have been developed at MIT by mimicking a real animal cheetah aiming for fast running. Cheetah robots can run as fast as Cheetah and jump over the barrier when they are running [3]. The role of the tail has been investigated for the fast movement of Cheetah [4,5].

Another challenging motion for robots to mimic is jumping. When robots jump, landing is the most important concern to maintain stable balance [6]. Tail balancing techniques have been presented for the stable balance [7,8].

When the lizard robot jumps high in the air and lands on the ground, the tail is used to maintain upright position all the time [7]. The robot position has been determined by sensors and the appropriate tail movement is controlled to maintain upright position. The tail can be used for maintaining the balance of fast turning [8].

Most of small-scaled robots are made after insects. In the framework of small jumping robots, locust-like insect robots have been developed [9-11]. Frog-like robots has been developed [12,13]. Jumping motion of MOWGLI has been accomplished by several links actuated by pneumatic artificial muscles. One defect of using pneumatic actuators like in MOWGLI is the impossibility of carrying power source. Jump motion control of a humanoid leg with multiple links has been presented as well [14,15]

Kangaroo is an animal that jumps with two legs in a synchronous phase. Bio-inspired robots for Kangaroo have been developed in the literature [16-18]. Bionic Kangaroo has been developed by FESTO to mimic Kangaroo's jumping motion. The robot tries to resemble a real Kangaroo such that it has a similar size of a real small Kangaroo. Jumping actuation has been successfully demonstrated by pneumatic actuators [16]. A small-sized Kangaroo robot has been designed with half circular legs that can store energy for a jumping motion [17]. In the category of monopod locomotion of Kangaroo, one leg robot has been presented for controlling hopping motion [18].

Therefore, in this paper, a miniature of Kangaroo-like robot (Kangarobo) is designed to jump with two legs and one tail. Kangarobo is aimed to keep jumping as high as possible while carrying all the body weights. The current version maintains balance on the ground by three contact points with two legs and one tail. Jumping motion can be achieved by a four bar mechanism with a cam structure.

Fig. 1 Kangaroo jumping motion

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II. DESIGN OF JUMPING MECHANISM

A. Design concept

One easier design for the jumping mechanism is to have a multiple linkage structure that uses motor torques to have jumping motion like MOWGLI in [7]. However, our major concern here is the simple design with less actuators to satisfy the successive jumping motion.

The main goal of Kangarobo is to jump with a leg design of a four bar linkage structure with a cam and the jumping energy can be stored at a spring as shown in Fig. 2.

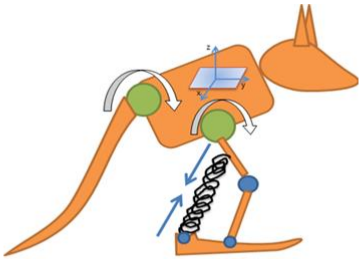
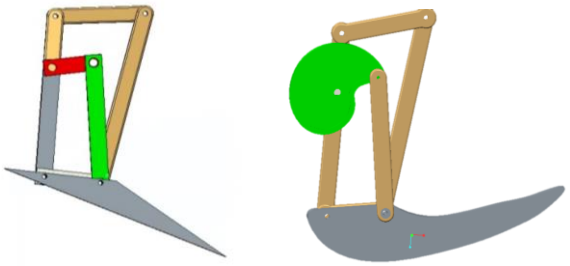


Fig. 2 Concept of a bio-inspired Kangarobo

B. Leg link design

Instead of using a serial linkage structure, here a parallel linkage structure is used for generating monopod locomotion. The detailed leg design with four bar linkages with a foot is shown in Fig. 3 (a). The crank-rocker mechanism is adopted to generate repeated motions of shrinking and stretching of the leg for a jumping motion from the ground to in the air by a rotational actuator. Link lengths of four bar linkage are determined to allow a rotation of a foot in the limited space. The actuator is placed at the location where the jumping motion of a foot is possible. The cam is located to generate the instant force for jumping as shown in Fig. 3 (b).



(a)Four bar with a foot *(b) Four bar with a cam*

Fig. 3 Four bar mechanism with a foot and a cam

The crank-rocker mechanism is used to determine each allowable link length. Based on the crank-rocker mechanism, angles for the four bar linkage can be calculated for determining the trajectory of B_1, B_2. Fig. 4 shows two extreme cases of the stretching and shrinking motions of the leg.

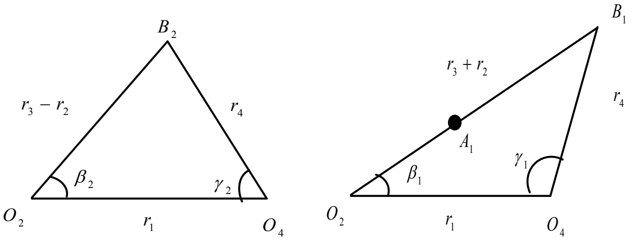


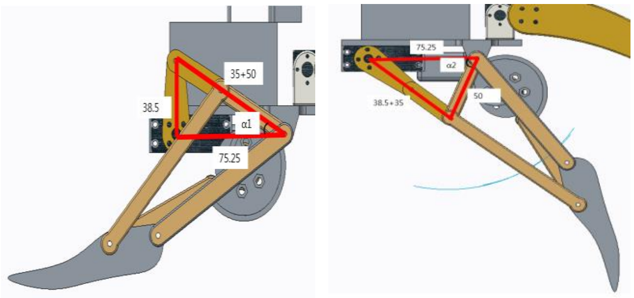
Fig. 4 The crank-rocker mechanism

The minimum and maximum angles can be calculated.

$$\gamma_1 = \cos^{-1}\left(\frac{r_1^2-(r_3+r_2)^2+r_4^2}{2r_1r_4}\right), \gamma_2 = \cos^{-1}\left(\frac{r_1^2-(r_3-r_2)^2+r_4^2}{2r_1r_4}\right) \quad (1)$$

Link length can be adjusted on the basis of the minimum and maximum angles.

Fig. 5 shows the four bar linkage attached to the body. Angles of α_1, α_2 are calculated as 26.9 and 68.5, respectively. The body can jump with the structure shown in Fig. 5.



(a)Shrink *(b) Stretch*

Fig. 5 Body and foot link

C. Cam design

To maximize the instant jumping force is important for the robot to jump from the ground. Based on the four bar structure shown in Fig. 5 (b), a cam structure is designed and placed at the rotating joint for jumping motion.

Cam design is one of typical design for Kangarobo and crucial such that it determines the cycle of jumping motion. After many modifications, final cam design is done as shown in Fig. 6. The cam is attached to the four bar link as shown in Fig. 6. Holes in the cam are intentionally designed to place magnets in association with hall sensors for the absolute position of an encoder sensor. The rotating joint and the distance are empirically determined as 15mm to maximize the spring force.

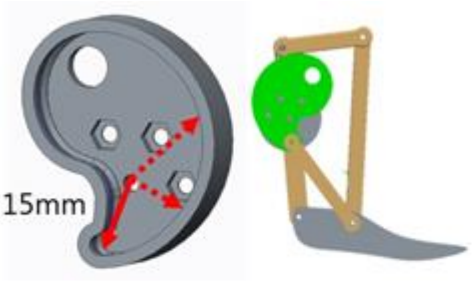


Fig. 6 Cam design

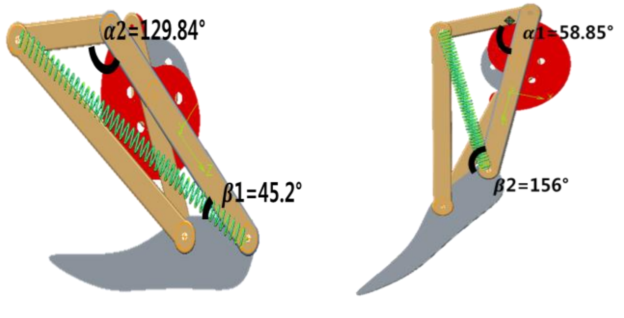
D. Spring design

Next is to determine a spring constant to store enough energy to jump. Firstly, the length of a spring is calculated on the basis of two configurations shown in Fig. 7. The maximum value of the length is 140mm for stretching and the minimum 88.2mm for shrinking. So the deviation length for energy storing becomes 51.8mm.

Based on the deviation length, the spring stiffness constant k can be calculated as

$$k = \frac{2mgh}{x^2} = 1578\ (N/m^2) \tag{2}$$

where m is the mass, g is the gravitational acceleration, and h is the height.



(a)Shrink *(b) Stretch*

Fig. 7 Four bar mechanism with a foot and a cam

III. KANGAROBO SYSTEM

A. Overall system

Based on the design of each part, overall Kangarobo system is built with ease by 3 D printing technology. The robot is composed of three parts: two legs, one tail, and control hardware as shown in Fig. 8. Hardware is located on the top of the system. Each leg consists of a spring, a cam and links. Two DC motors and three servo motors are used for the actuation. Battery is intentionally located on the tail to increase the tail reaction for helping jump motion and stable landing.

Initially, Kangarobo stabilizes itself by maintaining contact with the ground with two legs and one tail as shown in Fig. 8.

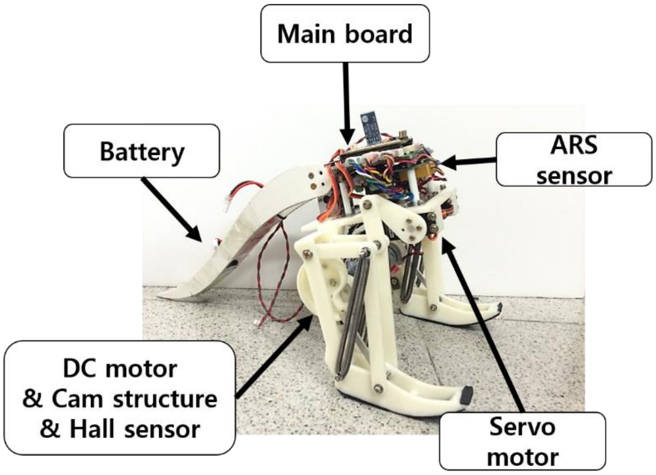


Fig. 8 Kangarobo

B. Control hardware

The overall hardware block diagram is shown in Fig.9. Two DC motors are controlled for leg jumping, two servo motors for leg walking, and one servo motor for the tail movement. DSP is a main controller and an ARS (attitude reference system) sensor is used for measuring the attitude of Kangarobo. The ARS sensor is the attitude reference system that contains 3-axis gyro and 3-axis-accellometer. A hall sensor is used to measure the rotation of the cam in association with magnets installed in the cam.

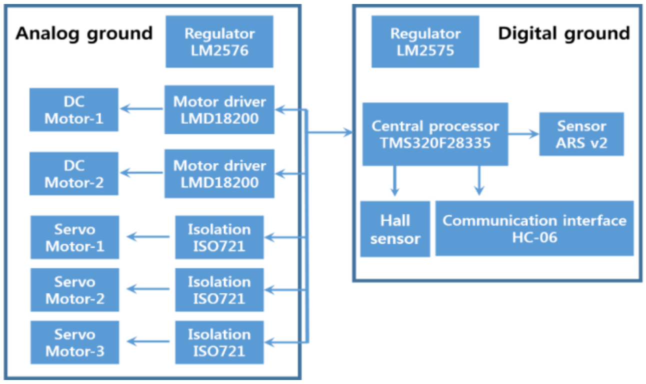


Fig. 9 Overall hardware block diagram

C. Synchronization and control of two motors for legs

To maximize the jumping force, monopod locomotion should be guaranteed in phase. This means that the movements of two legs must be synchronized before conducting any jumping experiments since the specification of two motors is different although those motors are same brand manufactured by the same company.

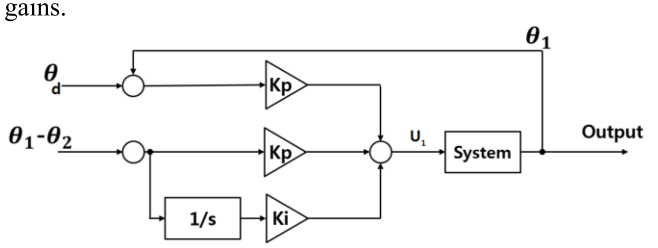
The synchronization difference between two motors can be minimized by software programming of a PI control method while two motors are controlled by PID controllers. PI controllers minimize the deviation error between two DC motors as shown in Fig. 10 (a) and (b).

The control inputs to DC motors are given as

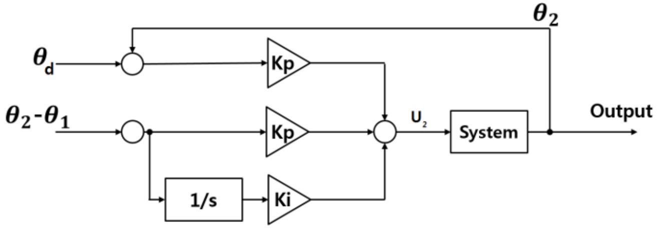
$$u_1(t) = k_p(\theta_d(t) - \theta_1(t)) + k_p(\theta_1(t) - \theta_2(t)) + k_i\int(\theta_1(t) - \theta_2(t))dt \quad (3)$$

$$u_2(t) = k_p(\theta_d(t) - \theta_2(t)) + k_p(\theta_2(t) - \theta_1(t)) + k_i\int(\theta_2(t) - \theta_1(t))dt \quad (4)$$

where θ_d is the desired angle, θ_1 is the angle of DC motor 1, θ_2 is the angle of DC motor 2, and k_p, k_i are the controller gains.



(a) DC motor of a right leg for jumping



(b) DC motor of a left leg for jumping

Fig. 10 Synchronization of two DC motors

D. Control of legs and a tail

Control for leg walking and tail movement uses PD controllers as shown in Fig. 11 (a) and (b). For the leg walking control,

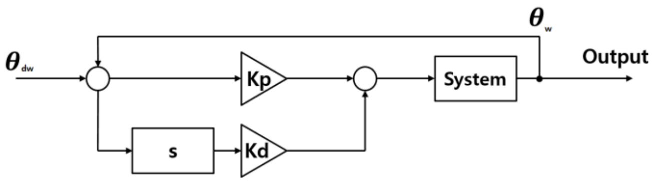
$$u_w(t) = k_{pw}(\theta_{dw}(t) - \theta_w(t)) + k_{dw}(\dot{\theta}_{dw}(t) - \dot{\theta}_w(t)) \quad (5)$$

where k_{pw}, k_{dw} are the controller gains.

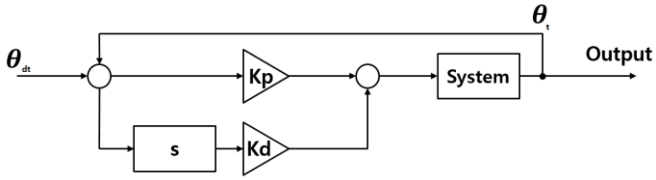
For the tail control,

$$u_t(t) = k_{pt}(\theta_{dt}(t) - \theta_t(t)) + k_{dt}(\dot{\theta}_{dt}(t) - \dot{\theta}_t(t)) \quad (6)$$

where k_{pt}, k_{dt} are the controller gains.



(a) Servo motors of two legs for walking



(b) Servo motors for a tail

Fig. 11 Control for leg walking and tail

IV. EXPERIMENTAL STUDIES

A. Experimental setup

Since Kangarobo is required to make successive jumps, same repeated steps are required. The jumping process can be divided into several steps. Fig. 12 shows the jumping steps. Initially, Kangarobo is set at the resting condition by maintaining three contact points with the ground. Then the ready state enables the body to lean forward based on the determination from ARS sensor information. This step maintains the balance with two legs. Next is the jump step. Finally, Kangarobo lands on the ground. The landing step is important to stabilize Kangarobo. Here the tail is lowered down to make three point contact for the stable pose. Then the ready state is prepared by lifting the tail and leaning the body forward for the next jump. This cycle goes on for the successive jumps.

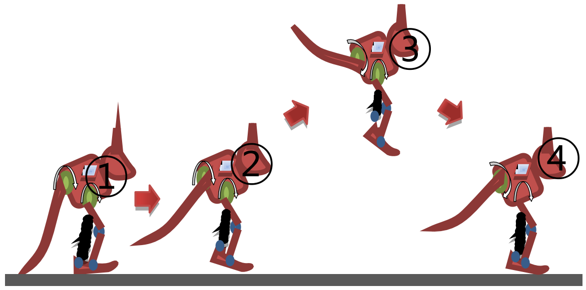


Fig. 12 Jumping steps

① Ready
② Ready to jump
③ Jumping state
④ Landing state

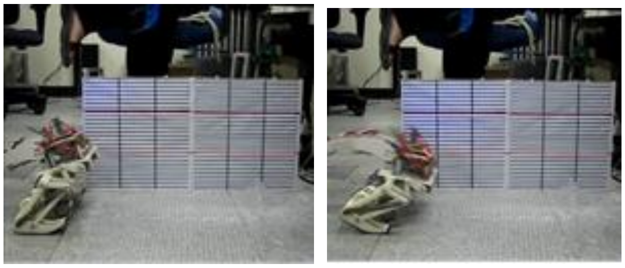
B. Experimental results

Jumping tests have been conducted on the floor by following steps shown in Fig. 12. We have experienced through the failure of many experimental tests. When the body does not lean forward in the ready state, Kagarobo could not maintain the initial pose but rotated after jumping.

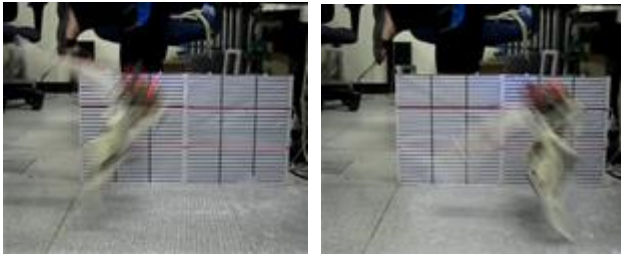
Therefore, Fig. 13 (b) shows the images when Kangarobo leans forward before jumping. One important point here for the successful jump is to find the appropriate leaning angle which can be obtained from the intensive empirical studies. A hall sensor has been located at the cam where the appropriate position found for the ready to jump.

Although Kangarobo can keep jumping, one jumping feature is considered here in Fig. 13. The real jumping motions are captured and plotted in Fig. 13. Kangarobo made successful jumps as high as 0.1m from the ground. Six images are shown from the ready to the resting state.

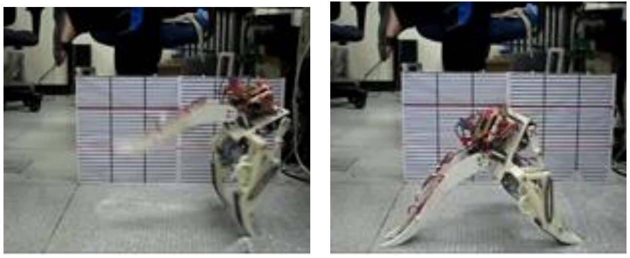
It is noted that the heading angle of Fig. 13 (f) is same as before jumping as shown in Fig. 13 (a) after jumping. This is quite an interesting point.



(a) Ready (b) Start jumping



(c) Jumping in the air (d) Before landing



(e) Landing (f) Rest

Fig. 13 Jumping motion

At the start-jumping state shown in Fig. 13 (b), we can see Kangarobo leaning forward with two legs compared with Fig. 13 (a). The tail is lifted up so that two legs maintain balance. This helps Kangarobo to increase the forward moving speed. Two legs are stretched for leaping as shown in Fig. 13 (c). Then Kangarobo jumps high in the air and lands. To stabilize the system after landing, the tail is lowered down to make three point contact with the ground as shown in Fig. 13 (f). Then it goes to Fig. 13 (a) for the next jump.

Although jumping tasks were successfully performed as desired, the tail is used to stabilize the body. Therefore, the next challenging research topic is to solve the balancing with two legs after landing.

V. CONCLUSION

One of characteristics of Kangaroo is jumping with the simultaneous movements of two legs. The kangaroo jumping motion has been studied for designing a Kangaroo-like robot, Kangarobo. After many modifications of mechanical design and parameters, Kangarobo has been implemented not only for walking but also for jumping. A successive jumping task of Kangarobo has been successfully demonstrated. Kangarobo was able to jump as high as 0.1m from the ground.

However, the robot design and control are still required to be improved. The tail is used for stable position on the ground with two legs. A next challenging step is to control Kangarobo making balance without help from the tail for the stable pose on the ground.

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