A Miniature Jumping Robot
with Flea-inspired Catapult System: Active Latch and Trigger

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1. Introduction

Small creatures have inherent mobility problems due to their stride limitation and small body size compared to surroundings. Meanwhile, some of them, such as locusts and fleas, have evolved to acquire better mobility by employing saltatorial (jumping) locomotion. In the similar context, the mobility of small-scale robots can be improved by jumping. To date, several small-scale jumping robots have been developed; the jumping robot Grillo is designed for long and consecutive jumping gait [1]. A steerable miniature jumping robot shows great jumping height and steering ability [2]. The closed elastica robot employs snap-through buckling for jumping [3]. They commonly employ the catapult system with passive latch; each of the mechanism lacks active trigger.

This paper presents 1g flea-inspired jumping robot. A flea is well-known for its dramatic jumping ability: 100 times as high as its body length. This outstanding performance is contributed to the special catapult system. Known as active latch and trigger, the system generates excellent catapult motion in the cramped anatomy [4][5]. This inspired us to develop extremely small and light jumping robot without conceding the performances. Shape memory alloy (SMA) spring is employed not only as actuator but also as energy storage element in the robot. In fabrication, smart composite microstructure (SCM) process is used for several advantages in small-scale robots: embedded electrical circuit design, machining efficacy, and light weight of the robot [6][7].

In the following sections, we first introduce the detailed mechanism of active latch and trigger system. Equation of motion and its numerical solution are presented to predict the theoretical jumping performance of the robot. Jumping motion of the prototype is captured by high speed camera and analyzed.

2. Bio-inspiration

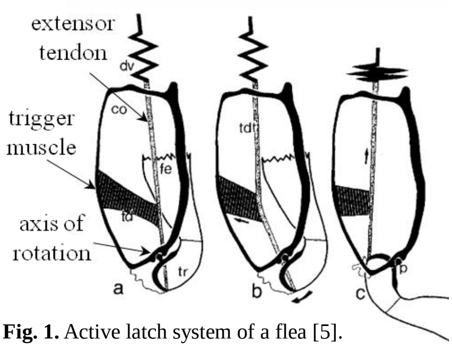

Fig. 1. Active latch system of a flea [5].

In this paper, we reinterpreted the flea's active latch system in the mechanical point of view. The kernel of the mechanism is expeditious reversal of joint torque. When the leg is full-flexed, counter clock-wise latching torque is generated as the extensor applies tensile force (Fig.1.a). Due to the structural constraint, the full flexion of the leg, the torque does not generate any motion. However large tensile force the extensor applies, the system does not un-lock, rather latches itself more firmly.

When the trigger pulls the extensor tendon left (Fig.1.b), the line of tensile force moves slightly but creates a completely different situation; the latching torque is reversed to clock-wise actuating torque. At this moment, the triggering requires only small force and stroke. Thus, the torque is reversed efficiently and quickly. As the leg extends, the moment arm increases, thereby increasing the actuating torque and producing a large impulse for jumping. To our knowledge, this unique torque-reversing active latch system has never been implemented on a jumping robot.

3. Design

We employed the flea-inspired mechanism to our jumping robot. Following is a schematic design of the robot and its detailed mechanism.

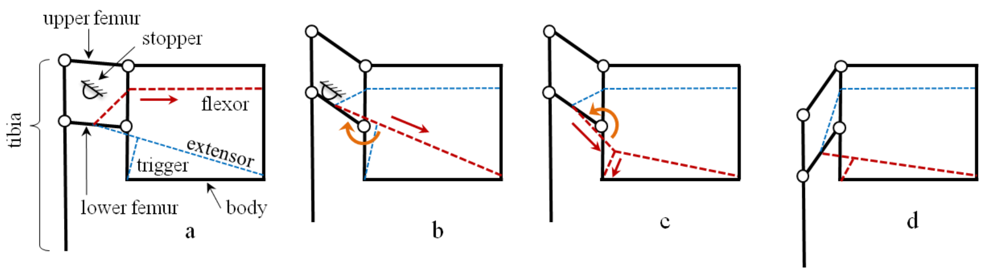

Fig. 2. Schematic diagrams of the flea-inspired robot. Red dashed-line represents activated SMA spring, while blue dashed line represents un-activated SMA spring. Hollow circles represent R- joints. In reality, stopper is attached on the body.

The body and the lower femur mainly construct the active latch and generate catapult motion with three SMA springs: flexor, extensor, and trigger. SMA springs are activated by electrical heating. The other two links, the upper femur and the tibia, transmit impulse from the catapult to the ground, and produce jumping motion.

In the flexion stage (Fig.2.a), the flexor is activated and contracts to flex the leg. As the flexor contracts, the extensor passes through a joint between the body and the lower femur. The flexor stops contracting when the lower femur touches a stopper on the body.

The next step is extensor activation (Fig.2.b). In contrast to the flexor, the extensor does not contract immediately after the activation due to a structural latch: a stopper on the body. Thus, the activated extensor produces latching torque and locks the system, storing potential energy for jumping.

The third is triggering stage (Fig.2.c). While the extensor is active, the trigger contracts and pulls the extensor past center of rotation of the lower femur. This changes the direction of the torque by the extensor. This actuating torque unlocks the structural latch and extends the leg quickly. As the leg rotates, the extensor moves further away from the center of rotation; the moment arm increases, thereby increasing the torque. The leg applies force on the ground and finally the robot jumps upward (Fig.2.d).

4. Dynamic Modeling

Equation of motion during the third stage is derived by Lagrangian formulation. Assuming no slip on the foot, the point where the tibia touches the ground can be considered as a rotational joint (Fig.3.a). Two generalized coordinates, θ_1 and θ_2, are chosen to represent kinematics of each link. Total kinetic energy includes translational and rotational energy of each link. Total potential energy includes gravitational potential energy of each link and elastic potential energy of the extensor. Friction in each joint and mass of spring are neglected. The extensor is considered as simple spring because it is fully activated, or in perfect austenite phase. The spring constant of 93.43 N/m is used, which was acquired from actual tensile test of the SMA coil actuator. By applying Lagrangian formulation, we obtained an initial value problem with two non-linear second order differential equations with respect to θ_1 and θ_2. The problem is solved numerically using MATLAB. The reaction force on the foot and the velocity of the robot's center of mass are also calculated. The normal reaction force becomes zero 12ms after triggering (Fig.3.b). At this point, the robot jumps and shows a parabolic motion. The speed of the robot at that time is calculated to be 2.03m/s theoretically (Fig.3.c). The jumping angle is about 45° with respect to the ground.

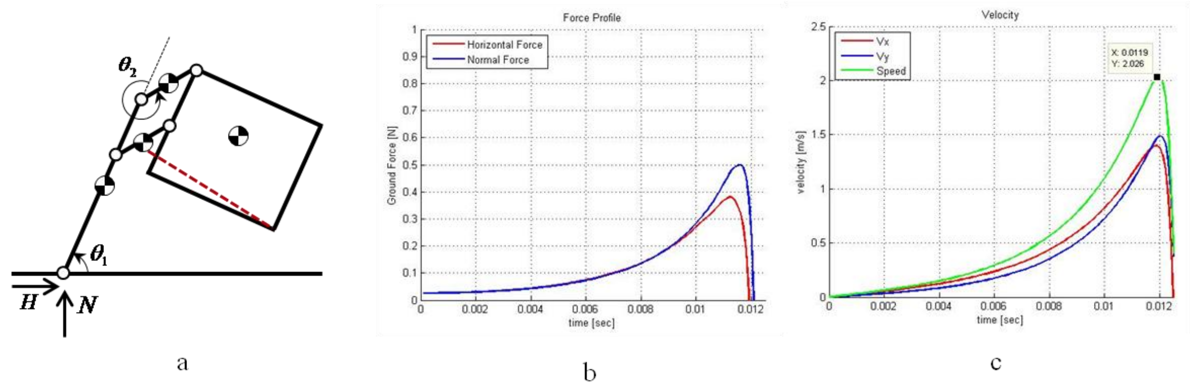

Fig. 3. Dynamic model of the robot (a) and its numerical solutions: ground force profile (b) and velocity profile (c). H and N represents horizontal force and normal force respectively.

5. Fabrication

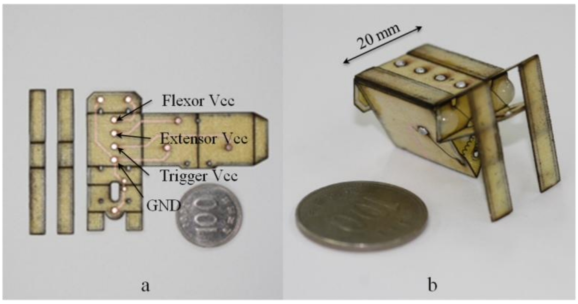

Fig. 4. Planar SCM(a), and the flea-inspired jumping robot(b).

The body and legs are fabricated by SCM process. At first, a sheet of copper-Kapton laminate is etched with the mask tailored to desired circuits. With additional laser cutting, flexible Kapton layer is fabricated with three independent circuits on it: flexor, extensor, and trigger circuits. The flexible layer becomes laminated with glass fiber segments which become rigid links after vacuum-curing. Thus far, planar SCM has been fabricated. (Fig. 4.a) The flexible gaps between glass fiber segments act as rotational joints of the robot. Secondly, SMA springs are fabricated by coiling up SMA wire to steel rod and annealing it in a furnace. The Final process is to assemble the planar SCM with SMA springs. By folding the planar SCM with adhesive, three dimensional SCM is built (Fig.4.b). The structure has electrical nodes on its surface, where each tip of SMA spring is soldered with flux. The final prototype is 1.07g in weight, 20mm in width, and 25mm in height. Vcc of each circuit and GND is on the head of the prototype and connected to external power supply.

6. Experimental Results

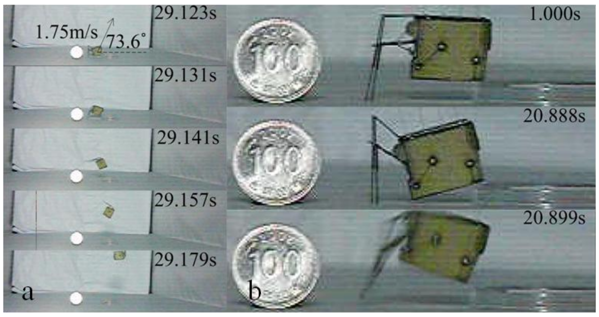

Fig. 5. High speed camera pictures: distant (a) and close view (b).

Jumping of the robot is captured with a high speed camera at1000 frames per second, and analyzed using a motion capture program, ProAnalyst. The frontal body of the robot was supported by a platform due to lack of fore-leg. As electric current flows through the flexor, extensor, and trigger circuits in order, the robot shows flexion, triggering and jumping, respectively.

The jumping was first recorded at distant view (Fig.5.a). The jumping speed at take-off was 1.75m/s and the jumping angle was 73.6° with respect to the ground. The vertical jumping height was 15 cm, 7.5 times as high as its body length. The second recording was done by close-range view in order to observe detailed triggering process, which took 11ms (Fig.5.b).

Compared to the theoretical jumping speed of 2.03m/s, derived from the dynamic model, there was a 13% loss in the actual jumping speed. One of the dominant causes is a slippage on foot just before take-off, which disagrees with the assumption of our dynamic model. Slippage occurs because the impulse force from the tibia gets out of the friction cone on ground. Also, the four-bar link of the prototype is not an exact parallelogram due to the error in fabrication, which does not correspond with the dynamic model. There are other minor reasons: additional load due to power supply line and air drag force.

The difference in jumping angle between the dynamic model and the experiment derives different initial conditions between them. Though the initial θ_1 seems to be about 90° in the second row of Fig.5.b which is the same condition as the dynamic model, the body of the robot is not parallel to the ground due to errors in fabrication. As a result, the actual jumping angle has increased from 45° to 73.6°.

7. Conclusion

In this paper, we presented an extremely small and light-weight jumping robot: 2cm in body length and 1g in weight. The downsizing was possible due to the flea-inspired catapult system. Though our current jumping robot can jump only 7.5 times its body length, the flea's dramatic capability suggests that this value can be improved drastically. Actuator and the link structure will be optimized to reach this goal. Since the robot can actively latch and trigger its catapult system with simple mechanism, the robot can perform punctual jumping; the robot can jump immediately when it decides to jump. When it comes to sudden danger or specific mission that requires critical timing, punctual jumping can be an important characteristic of a jumping robot.

Dynamic modeling and its numerical solution are derived, compared to experimental results of the prototype, and differences between them have been discussed. The prototype is manufactured using SCM process, which is advantageous for small-scale robots. The future works will include proper 4-bar design of leg for anti-slippage, structural optimization for better performance, and development of un-tethered robot with battery and controller being on-board.

8. References

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