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Flea Inspired Catapult Mechanism with Active Energy Storage and Release for Small Scale Jumping Robot

Je-Sung Koh, *Student Member, IEEE,* Sun-Pill Jung, Minkyun Noh,
Seung-Won Kim, *Student Member, IEEE a*nd Kyu-Jin Cho, *Member, IEEE*

Abstract— **Fleas have a unique catapult mechanism with a special muscle configuration. Energy is stored in an elastic material, resilin, and the extensor muscle. Force is applied by the extensor muscle to generate a torque. Energy is released as a small triggering muscle reverses the direction of the aforementioned torque. A flea can jump 150 times its body length using this elastic catapult mechanism. In this paper, a flea-inspired catapult mechanism is presented. This mechanism can be categorized as an active storage and active release elastic catapult. Owing to its unique stiffness change characteristic, a shape-memory-alloy coil spring actuator enables the mimicking of the flea's catapult mechanism. Two types of flea-inspired jumping mechanisms were developed for verifying the feasibility of applying the concept to an efficient jumping robot. The first prototype has a flea-like appearance and the second is simplified to contain just the essential components of the flea-inspired catapult mechanism. The two prototypes are 20-mm- and 30-mm-long and can jump 64 cm and 120 cm, respectively. This unique catapult mechanism can be used not only for jumping robots but also for other small-sized robots to generate fast-releasing motion.**

I. INTRODUCTION

Jumping robots use catapult mechanisms to jump much higher than their body length. Most small scale jumping robots to date use an escapement cam mechanism as the catapult mechanism. Recently, a novel jumping mechanism that uses the flea's jumping mechanism has been developed, as shown in fig.1 (a) [12]. This mechanism uses the flea's torque reversal principle.

The flea has a unique jumping leg composed of a special configuration of muscles, a cuticle exoskeleton, and an elastic material (resilin). This leg acts a catapult. Using this leg, the flea, an insect shorter in length than 1 mm, can jump 150 mm, which is 150 times its body length. From the engineering viewpoint, it is considered as the smallest elastic catapult mechanism, that is, a system that generates a fast objective projectile using an elastic driving force. However, the flea's

(a) (b)

Fig. 1 Two prototypes of flea- inspired jumping mechanism. [12]

catapult mechanism is completely different from conventional elastic catapult mechanisms such as an escapement cam with a spring, a trebuchet, or a bow. Nonetheless, all these mechanisms consist of two sub-mechanisms: energy storage and release. The differences lie in their respective methods of storing and releasing elastic energy.

In the next section, we put the flea's jumping mechanism into context by categorizing catapult mechanisms using two methods of two subcomponents: active and passive energy storage and release. This categorization allows for a clear understanding of the advantages and disadvantages of the flea's jumping mechanism and for further development of said mechanism to exploit its advantages. Under this categorization, the flea's elastic catapult mechanism is considered as an active storage and active release mechanism. In contrast, the escapement cam mechanism with a spring, a conventional elastic catapult mechanism that is commonly used for small-sized jumping robots, is considered as a passive storage and passive release mechanism. The escapement cam mechanism uses a cam with a diameter that decreases abruptly after increasing continuously. An elastic spring actuated by such a cam is compressed and is released quickly at the point where the cam diameter decreases. This escapement cam mechanism can be conveniently implemented with motors. Many jumping robots are based on the same principle but use different components such as torsional springs, linear springs, toothless rack and pinion, toothless worm gears [3],[5]-[7] and one-way bearings [8].

The passive storage and passive release mechanisms have evolved and have been implemented using various methods. However, only one robot has been built using an active storage and active release mechanism based on the flea's elastic catapult mechanism [12]. We believe that it is possible to build a more effective jumping robot based on the flea's jumping mechanism.

In this paper, first, the catapult mechanism is categorized to distinguish the flea's jumping mechanism. Second, a new,

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K. J. Cho is with the Biorobotics Laboratory, School of Mechanical & Aerospace Engineering/IAMD, Seoul National University, Seoul, Republic of Korea (corresponding author to provide phone: 82-2-880-1663; e-mail: kjcho@snu.ac.kr).

J. S. Koh, S. P. Jung and S. W. Kim are with the Biorobotics Laboratory, School of Mechanical & Aerospace Engineering, Seoul National University, Seoul, Republic of Korea (email : kjs15@snu.ac.kr, sunpill20@snu.ac.kr, demian05@snu.ac.kr)

M. K. Noh was with Seoul National University, Seoul, Republic of Korea. He is now with the Dept. Mechanical Engineering, Massachusetts Institute of Technology, USA (e-mail: minkyun@mit.edu).

simplified design of the flea-inspired catapult mechanism is presented. A prototype based on the new design is tested and compared with the previous prototype for verifying the feasibility of the underlying mechanism. The 2-cm-long prototype based on the previous version of the flea-inspired catapult mechanism jumps a distance of 64 cm [12]. Its appearance is similar to that of an actual flea. However, several parts in that prototype are not needed for jumping, e.g., a large body structure. Our modified design uses a single four-bar linkage as the full body structure, as shown in Fig. 1(b). In addition, this design eliminates assembly- and alignment-related problems by using single-sheet pattern design. A single composite-material sheet is folded in three dimensions and held in place using adhesives to form the prototype's structure. Shape-memory-alloy (SMA) coil spring actuators impart unique stiffness change characteristics to this catapult mechanism. The high power density of the SMA used allows for the miniaturization of the robot mechanism.

II. Categorization of Elastic Catapult Mechanisms

A catapult system generates a fast objective projectile using a mechanical driving force. Jumping robots use catapult mechanisms to store and rapidly release energy for jumping. There are various types of catapult mechanisms depending on the medium of force transmission: leverage, pneumatic, and elastic. Owing to the ease of miniaturization, the elastic catapult is widely used in small-scale jumping robots.

The elastic catapult mechanism can be divided into two submechanisms: energy storage and release. The energy storage submechanism involves gradually increasing the elastic energy stored in the catapult. The elastic energy stored is determined by elastic element's stiffness and extent of deformation. The stiffness is derived from the material's characteristic. The strain, or the extent of deformation, is determined using an external constraint. To increase the elastic energy stored, either the stiffness or the deformation of the elastic element should be increased. Therefore, energy storage mechanisms were categorized into two types: passive storage and active storage. In the passive storage mechanism, the elastic energy stored is increased only through passive deformation of an elastic element. In contrast, in the active storage mechanism, the elastic energy stored can be increased without passive deformation because the stiffness of the elastic element can be varied actively.

In the passive storage mechanism, the amount of elastic energy stored is determined by mechanical work input. In this case, the stiffness of the elastic material is generally constant and energy storage is a function of passive deformation, e.g., the energy stored in a simple spring or in an elastic rubber band. Therefore, a passive storage mechanism accompanies additional transmission systems such as an eccentric cam, and lead screw and gear that help suppress the restitution force.

TABLE I
Categorization of Catapult Mechanisms

Symbol	Passive Storage	Active Storage
Passive Release	Grillo [5] 7g robot [3] Closed elastic [4] Jollbot [6] Mini-Whegs [7]	Not yet
Active Release	Circular robot [9] Jumping microrobot [10] Hooper [11]	FLEA [12]

In the active storage mechanism, the amount of elastic energy stored is determined using the energy input from other sources, e.g., thermal and electrical. To employ the active storage mechanism, a variable-stiffness element is essential. For example, the isometric contraction of an SMA spring is one case. The stiffness of an SMA spring changes with temperature. At room temperature, the SMA is in the martensite phase and has low stiffness. Therefore, it can actively store the elastic energy under isometric conditions, or without deformation.

Energy release, which involves latch-actuated rapid discharge of the elastic energy stored in a system, is the second submechanism of an elastic catapult. The latch is defined as the locking mechanism of the catapult and can confine the elastic energy stored regardless of magnitude. Latch release entails a separate unlocking or triggering step. Release mechanisms can be categorized into two types: active and passive. The active release mechanism has an active latch, whereas the passive release mechanism does not.

In the active release mechanism, the elastic energy confined by the latch is discharged via a separate triggering action. For example, in a crossbow, the elastic energy stored in the bow is confined by a latch. With active triggering, an archer can shoot an arrow at the desired time. The active release mechanism is advantageous for time-based operation. In addition, it is convenient for establishing the control strategy of a jumping robot because the mechanism requires simple on-off signals.

In the passive release mechanism, continued energy storing leads to release, which implies that energy storage and release are coupled. The locking mechanism, or latch, does not exist. Therefore, it does not require a separate unlocking or triggering step, e.g., the release mechanism of an escapement cam [2],[3], which uses the principle of Leonardo da Vinci's eccentric cam to move the hammer. A catapult using the snap-through motion of a closed elastic strip [4] is another example; it stores elastic energy as the elastic strip deforms. When the deformation meets the buckling criteria, the storing action leads to energy release without the need for a separate triggering step. The passive release mechanism has the advantage of reducing the number of actuators. Furthermore, it is useful for generating periodic jumping motion.

To summarize, the catapult mechanism consists of two submechanisms: storage and release. Each submechanism is divided into active and passive mechanisms. The four types of elastic catapult mechanisms presented in this paper and the corresponding examples of elastic-catapult-based jumping robots are listed in Table I.

III. Catapult Mechanism of The Flea

The flea's catapult mechanism is of the active storage and active release mechanism type, according to Table I. The

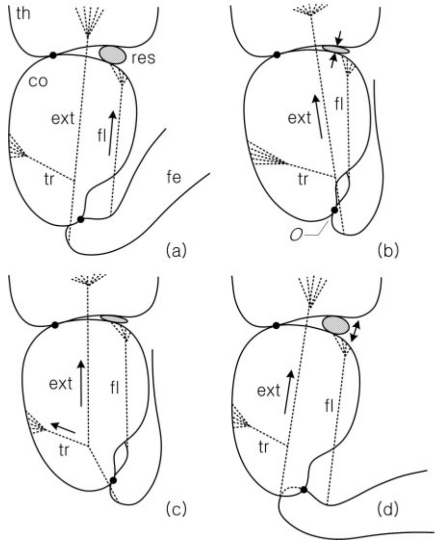


Fig. 2 Schematic diagram of a flea's catapult. It is composed of three exoskeletal links: *th* is the thorax, *co* is the coxa, and *fe* is the femur. The joint connecting the coxa and the femur is the reversal joint. A resilin pad (*res*) functions as the compression spring. Three muscles are arranged in the leg: *fl* is the flexor, *ext* is the extensor, and *tr* is the trigger muscle [12]

flea's jumping leg consists of cuticles, an extensor muscle, a flexure muscle, trigger muscle, and elastic materials, as shown in Fig. 2 [13]. The flea jumps using a combination of these elements. First, the flexor positions the leg for jumping (Fig. 2(a)). Thereafter, the extensor muscle pulls the leg in the same direction with the flexor and stores the resulting energy in the muscle and resilin (Fig. 2(b)). At that moment, the cuticle structure blocks the leg from rotating. To release the elastic energy, the small trigger muscle pulls the extensor muscle and changes the force direction of the extensor, thus reversing the torque (Fig. 2(c)). After triggering, the elastic energy stored in the muscle and resilin is rapidly discharged and the leg starts to rotate (Fig. 2(d)). To apply the flea's jumping principle to the jumping robot design, the flea's catapult mechanism was simplified as shown in Fig. 3. The mechanism consists of the leg linkage, the extensor, trigger, and stopper. This mechanism produces a single catapult motion because it does not have the flexor. The components essential for jumping are retained in the simplified diagram.

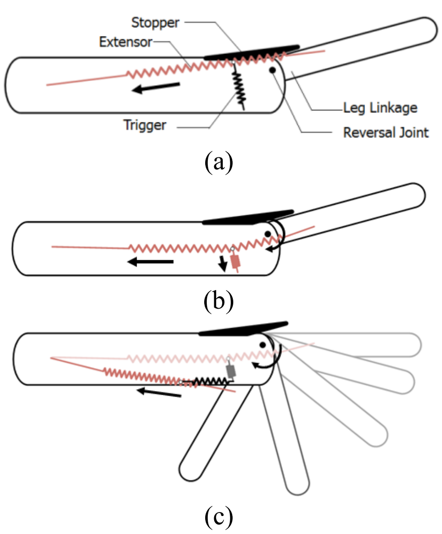


Fig. 3 Schematic diagram of torque reversal mechanisms inspired by the flea's jumping leg. (a) storing energy in latched position, (b) triggering, and (c) discharging elastic energy.

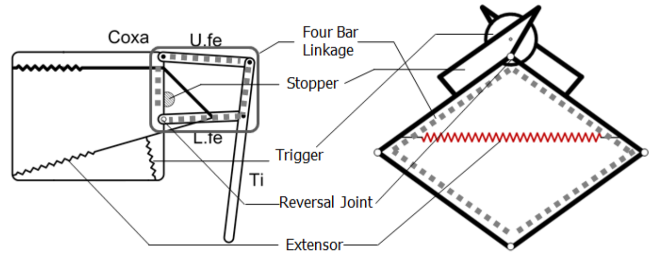


Fig. 4 Comparison of two flea-inspired jumping mechanisms. Previous design [12] (Left) and current design (Right).

This catapult mechanism has four elements: extensor, trigger, leg linkage, and stopper. The extensor pulls the leg linkage blocked by the stopper and stores the elastic energy by increasing the stiffness (Fig. 3 (a)). The trigger pulls the extensor slightly to change the direction of the torque (Fig. 3(b)). For changing the torque direction, the reversal joint should be designed such that the extensor can pass through the joint. Immediately after the extensor passes through the reversal joint, it pulls the leg and produces rapid rotation. In the presence of a flexor, it can repeat this motion. With this mechanism, Noh et al. [12] developed a light jumping robot with a similar configuration to that of the flea's leg. In this study, the flea's catapult mechanism is simplified and generalized for application to various jumping robots or other machines requiring rapid catapult motion.

IV. Robot Design

The jumping mechanism design was simplified by retaining only the parts required for jumping. Fig. 4 shows a comparison of the existing and proposed mechanism designs. The main difference between the two mechanisms is that the modified one does not have the coxa, or the body for attaching the actuators. The current design has only the four-bar linkage body, indicated by the gray dotted lines, whereas the previous design has the coxa and the tibia attached to the four-bar linkage. In addition, the current design detaches the trigger and the extensor. The trigger pushes the extensor in the opposite direction with a separate pusher attached atop the four-bar linkage, as shown in Fig. 5(a).

Fig. 5 describes the jumping procedure of the current design. First, the extensor pulls the two upper links of the

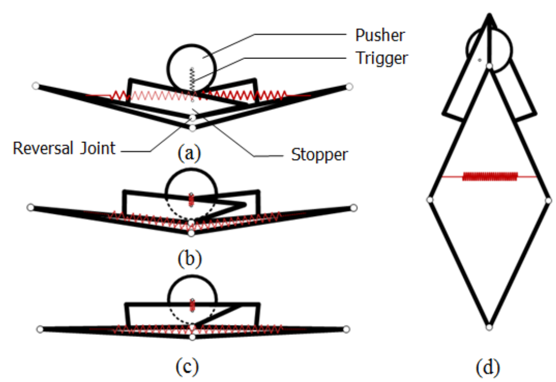


Fig. 5 Schematic of jumping procedure

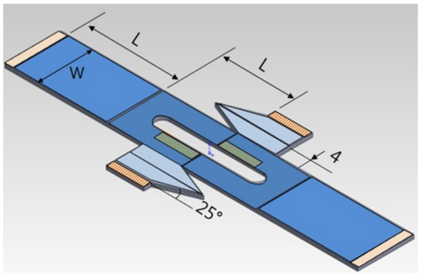


Fig. 6 Planar body design for current prototype of the jumping mechanism. Planar structure becomes 3D structure by folding and adhesion.

four-bar linkage's blocked direction using the stopper, and the links are blocked by the two stoppers attached symmetrically on the upper links (Fig. 5(a)). The trigger is contracted and pulls the pusher. The pusher pushes the extensor to pass through the reversal joint, which has a singular point of the torque (Fig. 5(b)). The two upper links begin to rotate (Fig. 5(c)). The moment arm increases and the torque gradually increases as the links rotate (Fig. 5(d)). This mechanism jumps with the vertical diamond shape. This diamond shape reduces the angle of contact with air and the area facing the jump direction. Therefore, it can be considered that the diamond shape can reduce air drag.

To simplify manufacturing and assembly, we integrated all parts of the robot body on a two-dimensional (2D) plane, as shown in Fig. 6, at the design stage. Four blue planar links represent the four-bar linkage body and the sky-blue planar links represent the stoppers. The black lines are the folding lines and the hatching surfaces are for adhesion. The two blue links seen in the middle in this figure are specially designed as a reversal joint for the extensor to pass through the folding joint. The stoppers have a 25° angle and they represent the robot's initial shape, as shown in Fig. 5(a). The 25° angle was determined to be suitable for the extensor to maintain the initial energy storage shape, as shown in Fig. 5(a).

The body structure is designed such that all the parts can be connected on a single sheet. This design shortens the assembly process and minimizes the number of adhered parts.

TABLE II
SPECIFICATIONS OF TWO PROTOTYPES OF FLEA INSPIRED JUMPING ROBOT

	3cm Link	2cm Link
	Robot Body Structures	
Weight	2.25 g	1.11 g
Width	30 mm	15 mm
	SMA Coil Spring Actuators	
Wire Dia. (d)	370 µm	250 µm
Coil Dia. (D)	2 mm	1.25 mm
Spring Index (D/d)	5.4	5
Coil Number (n)	23	19
Spring Const.(k) (actuation)	232.4 N/m	240.2 N/m
Initial Length	50 mm	33.6 mm
Final Length	26 mm	17 mm
Stored Elastic Energy	0.067 J	0.033 J
Max. Force	5.57 N	4 N

At small scales, misalignment can occur easily during manual assembly. The single-sheet design can reduce the occurrence of such misalignment. In addition, we can reduce the bonding process using adhesives, a laborious task that results in the misalignment and migration of parts.

The four-bar linkage has links of equal length (L) to achieve maximum stroke length during rotation. Immediately before jumping, the linkage assumes a flat shape, as shown in Fig. 5(c), because the links are of equal length. Two prototypes having 20-mm- and 30-mm-long links were fabricated for the jumping experiments. The widths (w) of the robot mechanisms were 30 mm (30-mm link) and 15 mm (20-mm link). The link length and width are strongly related to the magnitude of the stored energy and the jumping efficiency because these parameters govern the actuation stroke length and the air drag characteristics.

The extensor and the trigger are SMA coil spring actuators. The SMA coil spring actuator has characteristics similar to those of a muscle that produces axial force and stroke by itself. The stiffness of the SMA coil spring actuator can be changed by heating. At low temperatures, it can be elongated easily by application of a low-magnitude external force. It can then be contracted by increasing the stiffness at high temperatures. The actuator does not need an extra power transmission, and its stiffness can be controlled by temperature depending on electric current. Therefore, the developed robot system is very simple and compact. Three parameters are crucial in the design of the SMA coil spring actuator: wire diameter (d), coil diameter (D), number of turns (n). These parameters are set considering geometrical constraints and the structure's strength. In this study, the SMA coil spring actuator was designed to be as large as possible under the geometrical constraints [14]. The parameters are listed in Table II. The coil diameter was set to the largest allowable in the volume for actuator position. The wire diameter was set to be large as possible considering manufacturing possibilities. A spring index (D/d) smaller than 4–5 causes manufacturing problems.

V. FABRICATION

The robot prototypes were fabricated by laser machining and laminating glass fiber composites and polyimide film. The glass fiber composites were patterned as the rigid links and the polyimide film acted as a rotational joint after laminating and curing. This process is called Smart composite microstructures (SCM) and is used for fabricating microrobotic flies [15]. After folding and adhesion, the 2D pattern of composites becomes the 3D robot structure, as shown in fig.7.

The glass fiber prepreg is cut using a laser cutter (CO_2

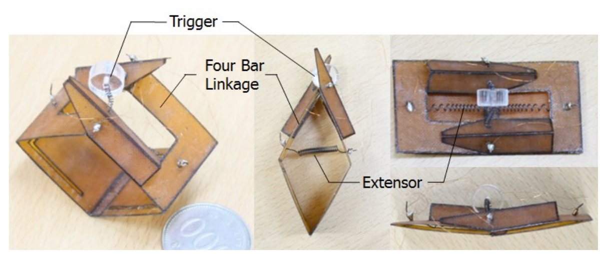


Fig. 7 Prototype of flea-inspired jumping mechanism

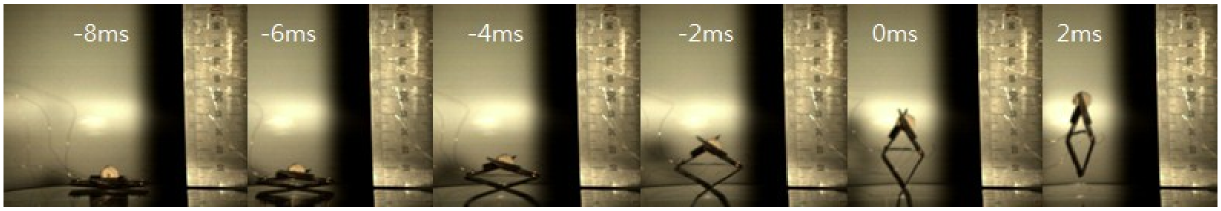


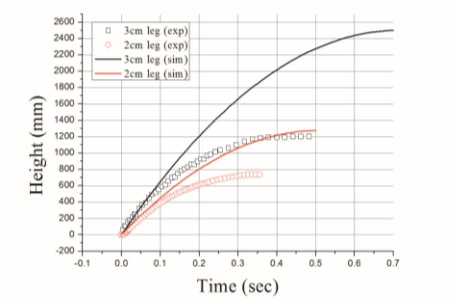
Fig. 8 Sequential high-speed images of jumping mechanism at takeoff.

laser, Universal Laser, Co.) along the pattern line shown in Fig. 6. The polyimide film is cut along the outer pattern line. The film connects the entire separated glass fiber prepregs and becomes the rotational joint when folded. The SMA coil spring actuators act as artificial muscle and replace the extensor and trigger muscles. The SMA coil spring is made by winding an SMA wire (Dynalloy Co.) [16], and their design is based on the conventional spring equation ($F = (Gd^4/8D^3)\delta$). The force–deflection relationship of the SMA is assumed as linear in the actuation phase [17]. Dimensions of the SMA coil spring actuators are listed in Table II. The SMA coil spring actuators are clamped onto the composite body and electric current is applied through an enameled wire.

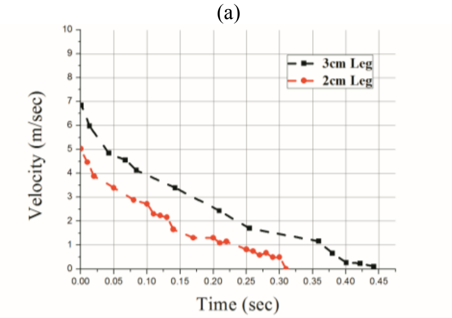
The trigger has a circular pusher. The pusher is pulled by the trigger and pushes the extensor to pass through the specially designed reversal joint. The pusher is designed as a wheel so that a constant trigger–extensor distance is maintained even if the pusher rotates.

VI. RESULT

The robot takes off at 8 ms after triggering, as shown in Fig. 8. The takeoff velocities of the prototypes with 30-mm- and 20-mm-long links were 7 m/s and 5 m/s, respectively. Theoretical jumping heights of the two prototypes are 2.5 m and 1.27 m, respectively, without considering air drag and other payloads such as wires. However, in experiments, the mechanisms jumped 1.2 m (30-mm link) and 0.7 m (20-mm link), as shown in Fig. 9(a). The 30-mm- and 20-mm link mechanisms jump up to 48% and 55% of the theoretical jumping height. This is ascribed to the tethered power wire and air drag. The difference between theoretical and experimental jump heights of the larger mechanism is considerably larger than that of the smaller mechanism. This is ascribed to the higher air drag acting on the larger mechanism owing to its greater planar link area. The planar link causes severe air drag. For reducing air drag, the width of the planar link should be decreased.



(a)

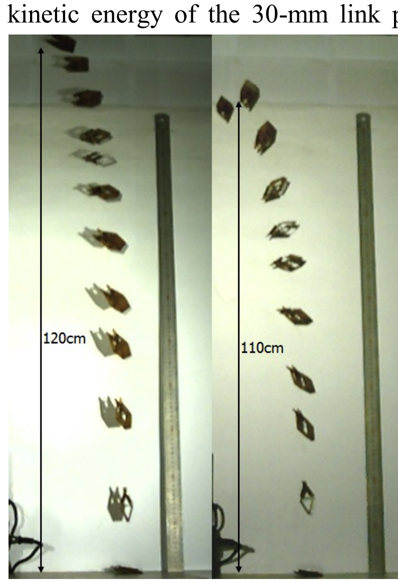


(b)

Fig. 9 (a) Jump height profile of two mechanisms. The solid lines represent theoretical profile without air drag and wire payload. (b) Velocity profiles of two jumping experiments.

As shown in Fig. 9(b), the slope of the mechanism's velocity profile fluctuates at many points. The slope represents acceleration, and the fluctuations therein indicate interruption by an external force. This external force originates from the tethered power wiring. The robot weighs less than 2.5 g. Therefore, even a small payload (enameled wire) effects a drastic reduction in the jumping height.

This jumping mechanism operates by converting the elastic energy to kinetic energy. To evaluate the efficiency of the jumping mechanism, we computed the proportion of elastic energy converted to kinetic energy during jumping. The elastic energy stored in the SMA coil spring actuators was computed using the elastic energy equation ($E_e = kx^2/2$, x: spring deflection). The resulting values are listed in Table II. The kinetic energy is computed using the kinetic energy equation ($E_k = mv^2/2$). Initial jumping speed is used for this calculation to eliminate the effects of air drag and the tethered wire's weight. In the experiments, the initial velocities of the jumping mechanisms were 7 m/s and 5 m/s, respectively. At takeoff, the kinetic energy of the 30-mm link prototype is



(a) (b)

Fig. 10 Jumping trajectory of the flea inspired jumping mechanism. The SMA stiffness is controlled by current input and jumping height can be changed. (a) 0.9A current input, (b) 0.8A current input

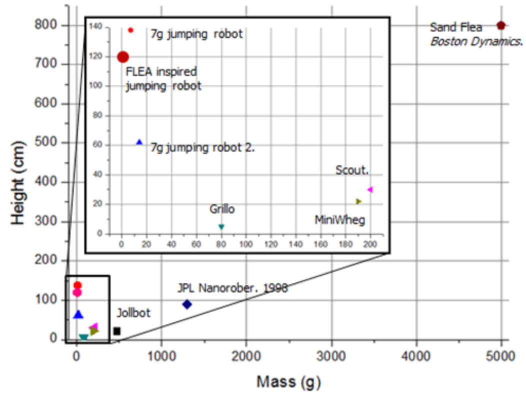


Fig. 11 Comparison of jumping robots in terms of mass and jumping height.

0.055 J and that of the 20-mm one is 0.014 J. The conversion efficiencies are 82% and 42%, respectively. This large difference in the conversion efficiencies of the two prototypes could be ascribed to differing structural compliances resulting from different structure lengths and the non-qualified manual assembly process.

As shown in Fig. 10, the jumping height is controlled by the electric current input. This is one advantage of the active storage mechanism over the passive one, in which it is difficult to vary the jumping height when using a single elastic material.

VII. Discussion and Future Work

The flea-inspired jumping mechanism is one of the many catapult mechanisms for energy storage and rapid release. Elastic energy is stored by increasing actuator stiffness and is released by torque reversal. Many types of jumping robots use various escapement cam mechanisms such as the ones with an abrupt cam diameter drop and toothless gears. The energy storage and release submechanisms are coupled in these mechanisms. However, the flea-inspired catapult mechanism separates these submechanisms, and replaces them with active energy storage and release submechanisms.

Fig. 11 shows a comparison of many types of jumping robots in terms of their weights and jumping heights. This comparison might not be accurate considering that the experiments might have been conducted under different conditions, for example, tethered or untethered system, the presence or absence of embedded sensors, and repeatability of jumping. However, we can approximate the same considering the mechanisms' efficiencies and performance levels. The flea-inspired jumping mechanism is indicated by a solid red-colored circle. It is the lightest jumping mechanism despite being tethered to the power supply. If the 2.5 g Li-polymer battery is embedded, the mechanism weight increases but remains under 5 g and the jumping height decreases to 60 cm. The SMA coil spring actuator has high power density and the fiber-reinforced composite structure has high strength and low density. It can be considered that the flea-inspired jumping mechanism has the potential to be the lightest jumping robot.

To develop an autonomously powered jumping robot inspired by the flea's catapult mechanism, a Li-polymer battery, which has a high power-weight ratio, should be used as the embedded power source. Furthermore, under the application of a current, the SMA converts electrical energy to thermal energy via Joule heating; however, this process has a very low efficiency. Therefore, the SMA coil spring design should be optimized for maximum thermal energy efficiency by changing the transition temperature and the geometrical thermal characteristics. Moreover, the planar structure design should be optimized for reducing air drag, enhancing robustness, and decreasing weight.

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