Crawling and Jumping Soft Robot KOHARO

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Abstract

We describe crawling and jumping by a deformable soft robot. Locomotion over rough terrain has been achieved mainly by rigid body systems including crawlers and leg mechanisms. This paper presents an alternative method of moving over rough terrain, one that employs deformation. First, we describe the principle of crawling and jumping as performed through deformation of a robot body. Second, we show two prototypes of a spherical robot. Then, we describe three prototypes in the Expo demonstration to show their performance.

Keywords: deformation, locomotion, crawl, jump

I. Introduction

We have demonstrated the performance of crawling and jumping soft robots "KOHARO" at the Prototype Robot Exhibition, Expo 2005 Aichi, Japan. This paper describes the developed crawling and jumping soft robots and their demonstration in the Expo.

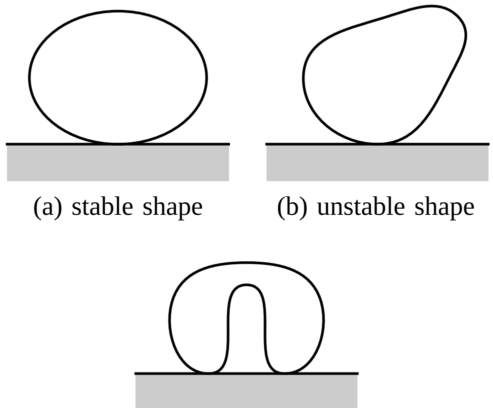
Rough terrain locomotion has mainly relied on rigid body systems, such as crawlers and leg mechanisms. Locomotion mechanisms consisting of rigid body systems have drawbacks: large weight that may cause impact to humans and difficulty in recovery from their overturning. Recently, mechanisms that can recover from their overturning have been studied [1], [2], but these mechanisms tend to be complicated. An alternative approach to light-weighted and simple mechanisms is thus required. Recent researches on soft actuators such as shape memory alloy (SMA) wires and polymer gel actuators has yielded impressive results [3]–[5]. Soft actuators have been used to drive leg mechanisms and soft body robots [6]. Locomotion mechanisms consisting of soft actuators can be light-weighted. Unfortunately, soft actuators still have drawbacks. They tend to generate a small force, and those that generate a large force need either a high driving voltage over 1,000V, making it difficult to build self-supporting robots, or a wet environment.

To overcome this problem, we have employed soft actuators to controllably deform a robot body, enabling it to crawl over and jump on rough terrain. Crawling and jumping using deformation can cope with rougher terrain than rigid body systems can. Additionally, soft body deformation reduces the damage in collision with humans. We have developed circular soft robots [8] and the prototypes of spherical soft robots [9]. For the demonstration in the Expo, we have developed three prototypes: 1) jumping and crawling prototype, 2) crawling prototype, and 3) slope-climbing prototype. These crawling and jumping soft robots are referred to as "KOHARO", acronym of crawling and jumping robot in Japanese. In this paper, we introduce the prototypes of "KOHARO" and show their performance in the expo demonstration. First, we describe the principle of crawling and jumping as performed through deformation of a robot body. Second, we show two prototypes of a spherical robot. Then, we describe three prototypes in the Expo demonstration to show their performance.

II. Principle of Crawling and Jumping by Deformation

Suppose a robot is in stable on the ground, as illustrated in Figure 1-(a). Self-deformation of the robot body generates a moment by a gravitational force around the area the robot is in contact with the ground. The moment causes the robot to move on the ground. If the robot deforms from a stable shape into an unstable shape described in Figure 1-(b), it rotates clockwise and moves towards the right. Successive deformation of the robot body, which can be generated by actuators, enables a continuous crawling motion along the ground. Thus, the proposed crawling approach uses gravitational potential energy.

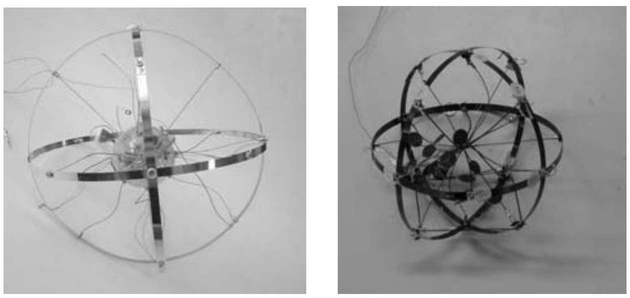
Deformation allows elastic potential energy to be stored which, if released rapidly enough, can generate a force large enough to make the robot jump. Now suppose the robot deforms from one stable shape into another, which has large high potential energy as illustrated in Figure 1-(c). If the potential energy is released rapidly enough, the robot will jump. The high-energy shape shown in Figure 1-(c) turns, with a small disturbance, into the stable shape shown in Figure 1-(a), generating the force required for the jump. Thus, the proposed approach uses elastic potential energy. Actuators inside the robot body can be used to store this elastic energy. The forces required to store the elastic



(a) stable shape (b) unstable shape

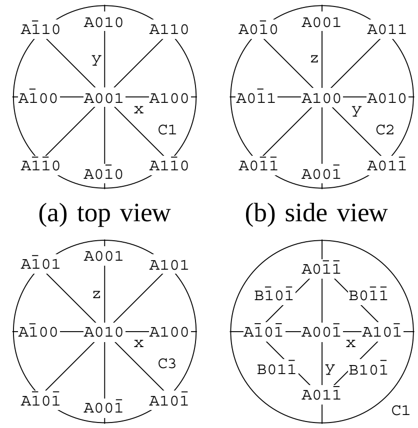
(c) stable shape with high potential energy

Fig. 1. Principle of crawling and jumping



(a) (b)

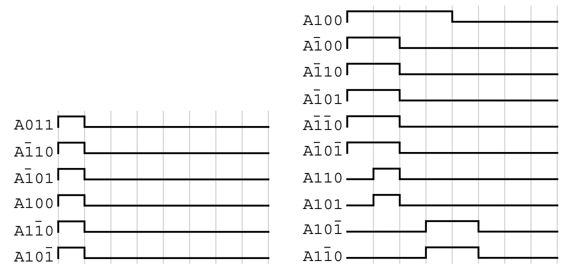
Fig. 2. Prototypes of spherical soft robot



(a) top view (b) side view

(c) front view (d) bottom view

Fig. 3. SMA coils attached to spherical prototype



(a) S111 to S$\bar{1}$11 (b) S111 to S1$\bar{1}\bar{1}$

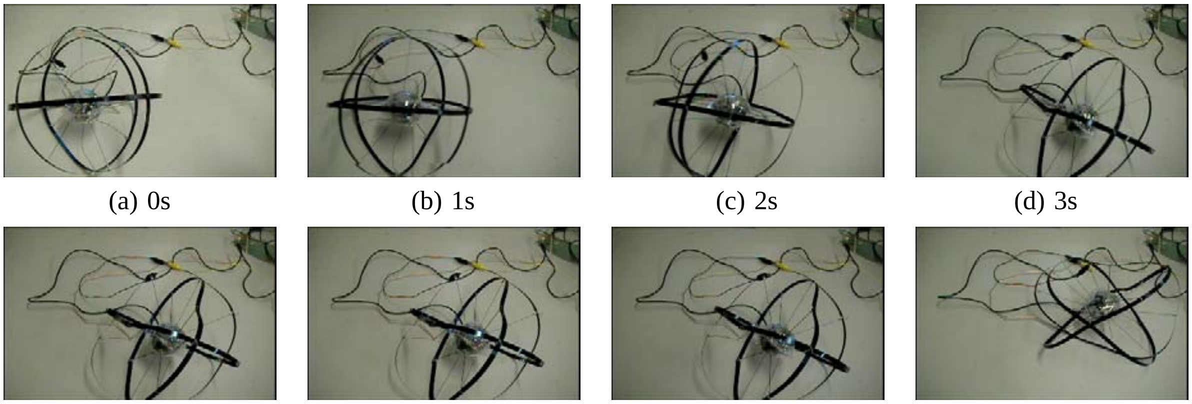
Fig. 4. Voltage patterns for a crawling spherical prototype

energy is generally much smaller than those required to perform a jump.

III. Experimental Results

We build two prototypes of a spherical soft robot to assess experimentally the feasibility of a deformable robot crawling and jumping. The prototypes are shown in Figure 2. The body of a prototype consists of three circular shells intersecting orthogonally. Prototype shown in Figure 2-(a), which is referred to as prototype A, is for crawling. This prototype consists of 18 SMA coils and shells made of spring steel. The diameter of the the spherical body is 200mm and the prototype weighs 137g. The core inside the spherical body includes circuits to drive SMA coils, a microprocessor, and a serial communication circuit. The core weighs 75g. Prototype shown in Fig.2-(b), which is referred to as prototype B, is for both crawling and jumping. This prototype consists of 22 SMA coils - 18 for crawling and jumping and 4 for jumping. The diameter of the spherical body is 90mm and the prototype weighs 5g. Circuits to drive SMA coils and a microcomputer are outside of the prototype.

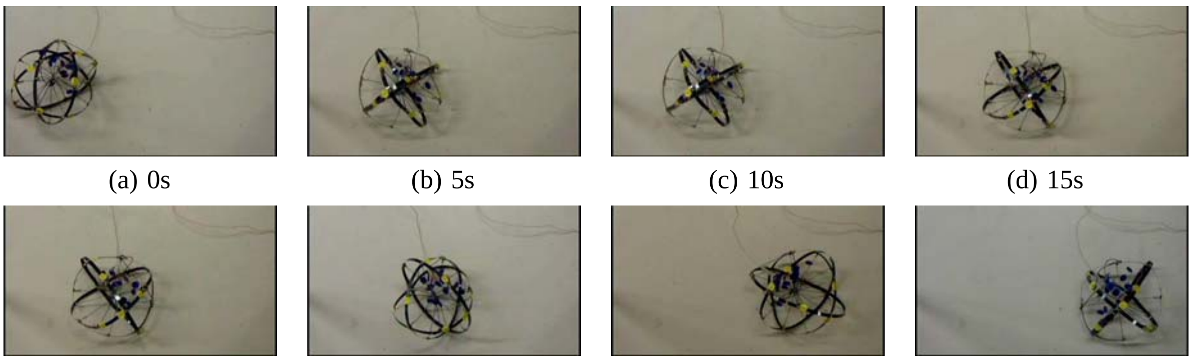
Figure 3 shows SMA coils attached to a spherical prototype. Figure 3-(a), (b), and (c) show the top, side, and front view of the prototype, respectively. All the SMA coils used for crawling are illustrated in these figures. As can be seen in the figures, the SMA coils for crawling are attached between the center of the sphere and the three circular shells labelled C1, C2, and C3. Let us suppose that C1 lies on the x-y plane, as shown in Figure 3-(a). Two coils are along x-axis from the center to the circular shell in the positive and negative directions, which are denoted to as A100 and A$\bar{1}$00. The two coils along the y-axis are denoted by A010 and A0$\bar{1}$0. Four additional SMA coils, A110, A1$\bar{1}$0, A101, and A10$\bar{1}$, are attached to the circular shell. Coil A110 is located between A100 and A010. Note that coil A110 is described by the *digital sum* of A100 and A010. Thus, there are eight SMA coils involved in deforming circular shell C1. Circular shells C2 and C3 lie on the z-x and y-z planes, as shown in Figure 3-(b) and (c), respectively. The coils along the z-axis will be referred to as A001 and A00$\bar{1}$. Circular shells C2 and C3 also contain eight SMA coils, as illustrated in the figures. Thus, the 18 SMA coils used for crawling are labelled A100 and A$\bar{1}$00 through A001 and A00$\bar{1}$ as well as the digital sum of each adjacent pair. Figure 3-(d) shows the bottom of the prototype. SMA coils for jumping are attached along a square formed by the terminal points of the four SMA coils for crawling, A10$\bar{1}$, A01$\bar{1}$, A$\bar{1}$0$\bar{1}$, and



(a) 0s (b) 1s (c) 2s (d) 3s

(e) 4s (f) 5s (g) 8s (h) 16s

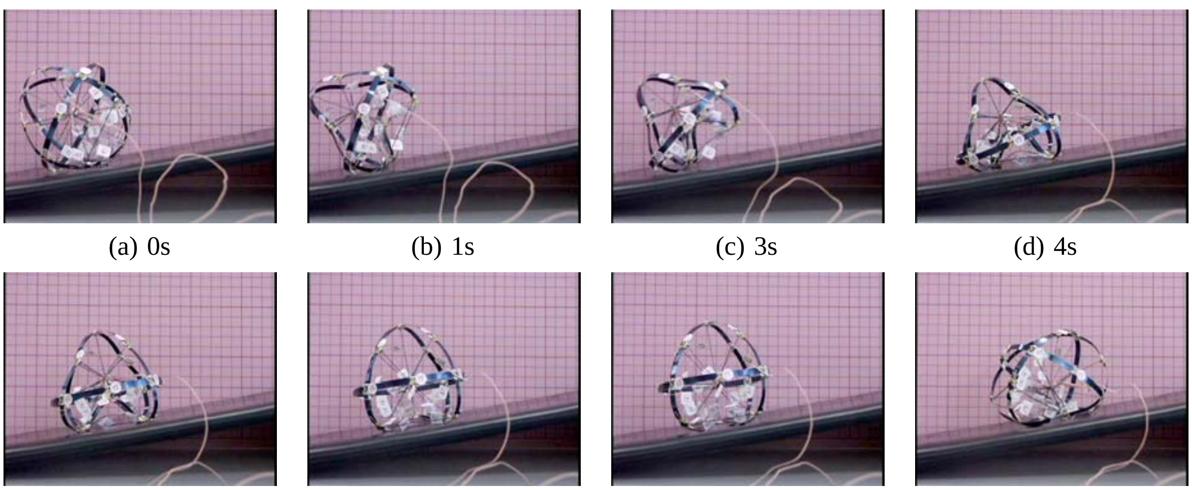
Fig. 5. Spherical soft robot crawling (prototype A)



(a) 0s (b) 5s (c) 10s (d) 15s

(e) 20s (f) 30s (g) 40s (h) 50s

Fig. 6. Spherical soft robot crawling (prototype B)



(a) 0s (b) 1s (c) 3s (d) 4s

(e) 9s (f) 12s (g) 15s (h) 18s

Fig. 7. Spherical prototype climbing a slope (prototype B)

$\mathrm{A}0\bar{1}\bar{1}$, which neighbor $\mathrm{A}00\bar{1}$. The SMA coils for jumping are labelled $\mathrm{B}10\bar{1}$, $\mathrm{B}01\bar{1}$, $\mathrm{B}\bar{1}0\bar{1}$, and $\mathrm{B}0\bar{1}\bar{1}$. Note that coil $\mathrm{B}10\bar{1}$, for example, starts from the terminal point of $\mathrm{A}10\bar{1}$, considering the rotation around $\mathrm{A}00\bar{1}$ along the square.

a) Crawling: Figure 4-(a) describes the voltage pattern used to perform the transition from $\mathrm{S}111$ to $\mathrm{S}\bar{1}11$ across arc $\mathrm{A}011$. The specified SMA coils are activated during the first time step and released during the second time step. Figure 4-(b) describes the voltage pattern used

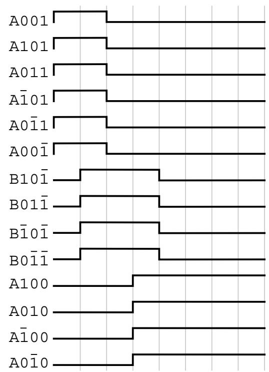


Fig. 8. Voltage pattern for spherical prototype jumping

to perform the transition from $\mathrm{S}111$ to $\mathrm{S}\bar{1}\bar{1}1$ via vertex $\mathrm{A}001$. Two opposing coils, $\mathrm{A}100$ and $\bar{1}00$, and four coils adjacent to $\mathrm{A}\bar{1}00$ are activated at the first time step. Coils $\mathrm{A}110$ and $\mathrm{A}10\bar{1}$ are activated and then released. Coils $\mathrm{A}1\bar{1}0$ and $\mathrm{A}101$ are activated before releasing the six coils activated during the first step and then relaxing the latter two coils. Alternating between a transition across an arc and a transition via a vertex enables the spherical prototype to crawl along a straight line. Figure 5 describes the crawling of a prototype A on a flat ground. Fig.6 describes the crawling of a prototype B on a flat ground. As shown in the figures, the spherical robots can crawl on a flat ground.

b) Slope-climbing: Figure 7 describes the slope-climbing of a prototype B by transition via a vertex. The prototype can climb up a slope of 10°.

c) Jumping: By applying the voltage patterns plotted in Figure 8, the spherical prototype can jump. Figure 9 shows the jump of a prototype B. The prototype can jump 180mm, which is twice of the diameter of the prototype.

IV. Demonstration at Prototype Exhibition

We have demonstrated the performance of our crawling and jumping soft robots at the Prototype Robot Exhibition, Expo 2005 Aichi, Japan. This section describes the demonstration at the exhibition. Since the two prototypes of a spherical soft robot cannot climb a slope fast, we have built a prototype of a cylindrical soft robot in addition to the two prototypes for the demonstration of climbing a slope. Figure 10 shows three prototypes on the demonstration field.

Figure 11 shows a demonstration of prototype A jumping. We have applied four robots for this jumping demonstration since it takes about one minutes for a robot to jump. Figure 12 shows a demonstration of a cylindrical prototype climbing a slope. We have applied two robots for this slope-climbing demonstration. One is climbing up and the other is going down a slope. Figure 13 shows a demonstration of prototype B crawling. We have applied

Fig. 10. Three prototypes for demonstration

a visual feedback in this demonstration. Each robot has six LEDs at the crossing points of circular shells. Six LEDs light up one by one. Detecting the position of each LED using a CCD camera above the demonstration stage, we can determine the position and orientation of a robot. Feedbacking the detected position and orientation to the robot, it can determine which SMA coils should be activated to move toward its goal position. As shown in the above figures, KOHARO prototypes have shown good performance. Figure 14 shows a snapshot in the demonstration. Many audience have visited to and been interested in our demonstration.

V. Concluding Remarks

We described the demonstration of our crawling and jumping soft robots “KOHARO” at the Prototype Robot Exhibition, Expo 2005 Aichi, Japan. First, we explained the principle of crawling and jumping as performed through deformation of a robot body. Second, we introduced two prototypes of a spherical robot and evaluated their performance experimentally. Next, we described three prototypes in the Expo demonstration to show their performance. The demonstration was successful with many audience in eleven days.

We are applying linear object modeling [7] to analyze and optimize the motion of a circular robot. We will evaluate the potential energy of a circular soft robot during crawling and jumping in order to get a better understanding of the system. We are going to build a power source inside a robot to realize autonomous locomotion of “KOHARO”.

Acknowledgment

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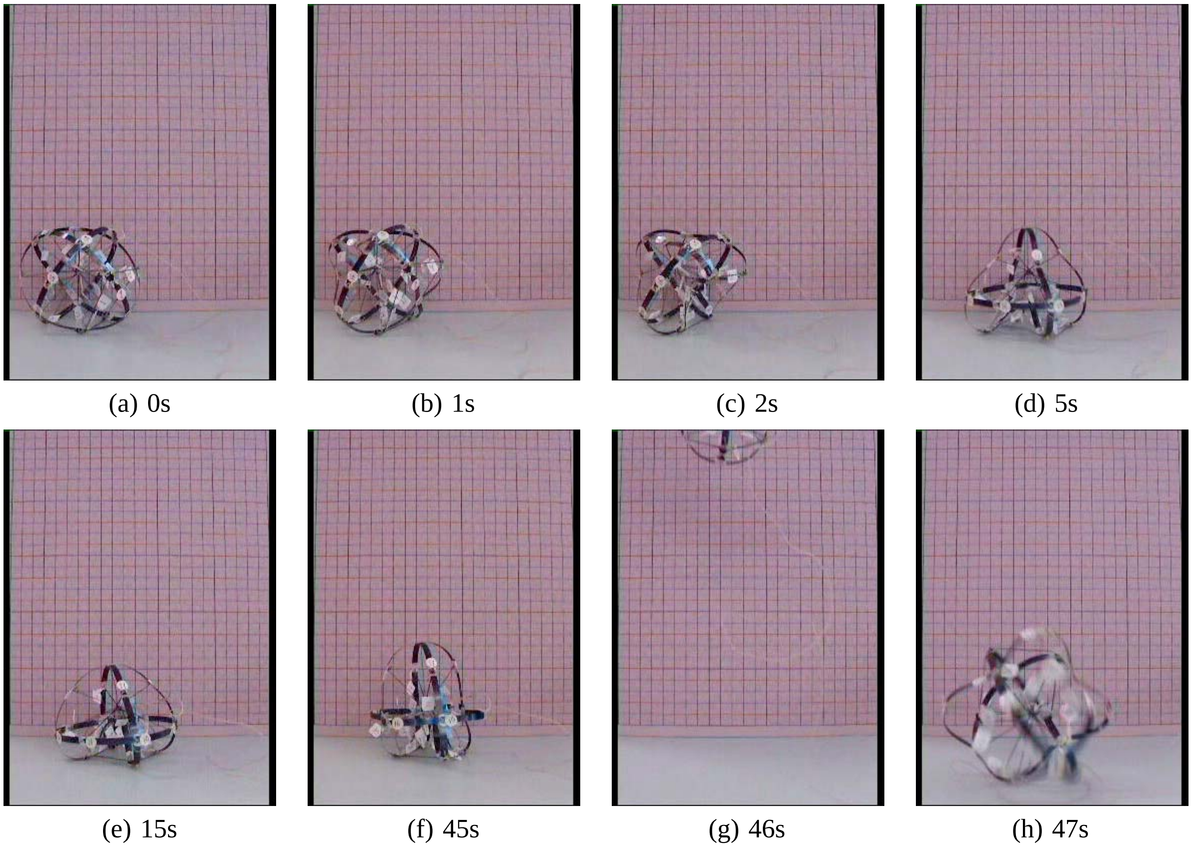
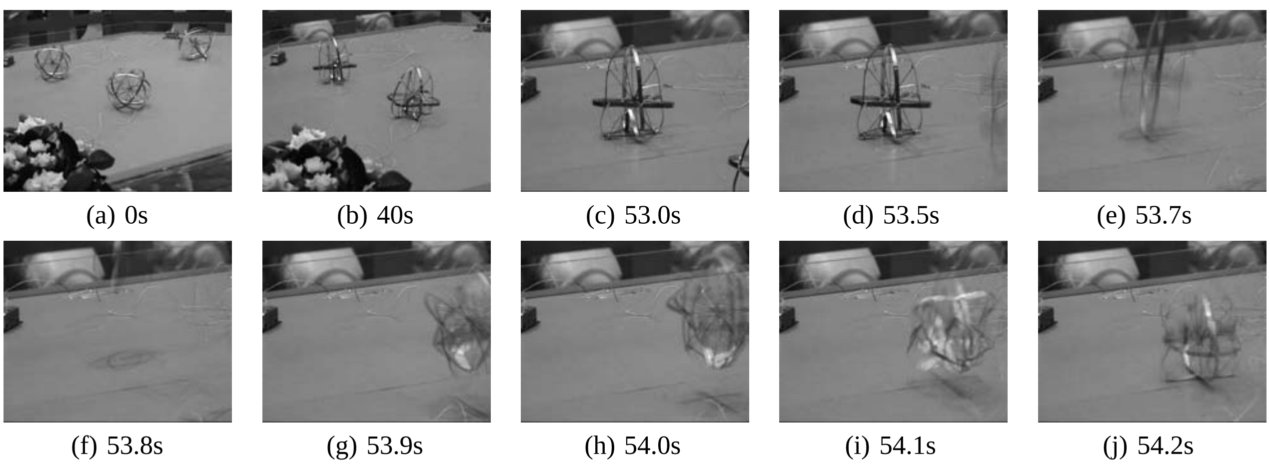


(a) 0s (b) 1s (c) 2s (d) 5s

(e) 15s (f) 45s (g) 46s (h) 47s

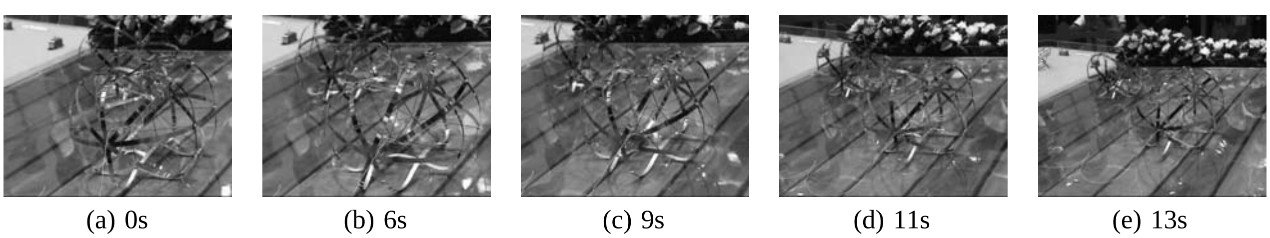
Fig. 9. Spherical soft robot jumping (prototype B)



(a) 0s (b) 40s (c) 53.0s (d) 53.5s (e) 53.7s

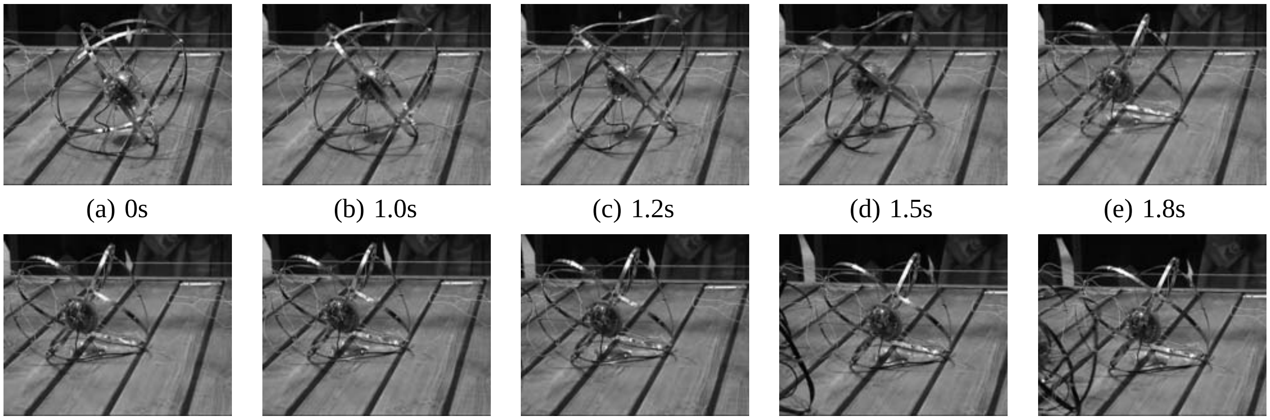
(f) 53.8s (g) 53.9s (h) 54.0s (i) 54.1s (j) 54.2s

Fig. 11. Demonstration of KOHARO jumping



(a) 0s (b) 6s (c) 9s (d) 11s (e) 13s

Fig. 12. Demonstration of KOHARO climbing a slope



(a) 0s (b) 1.0s (c) 1.2s (d) 1.5s (e) 1.8s

(f) 2.0s (g) 3.0s (h) 44s (i) 45s (j) 46s

Fig. 13. Demonstration of KOHARO crawling

Fig. 14. Demonstration at exhibition

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