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Development of a Biomimetic Quadruped Robot

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Abstract

This paper presents the design and prototype of a small quadruped robot whose walking motion is realized by two piezocomposite actuators. In the design, biomimetic ideas are employed to obtain the agility of motions and sustainability of a heavy load. The design of the robot legs is inspired by the leg configuration of insects, two joints (hip and knee) of the leg enable two basic motions, lifting and stepping. The robot frame is designed to have a slope relative to the horizontal plane, which makes the robot move forward. In addition, the bounding locomotion of quadruped animals is implemented in the robot. Experiments show that the robot can carry an additional load of about 100 g and run with a fairly high velocity. The quadruped prototype can be an important step towards the goal of building an autonomous mobile robot actuated by piezocomposite actuators.

Keywords: quadruped robot, piezocomposite actuator, bounding locomotion

1 Introduction

In recent times, robot designs often import ideas from the structures and functions of natural systems. However, direct application of natural locomotion methods to robots is extremely difficult due to several reasons: an enormous complexity in the mechanical structure of biological systems, many degrees of freedom in each leg, far more efficient energy storage system and muscular system than artificial ones. Therefore, in order to overcome those difficulties, ideas of simplification should be considered. In the design of legged robots, reducing the number of legs or degrees of freedom can be an example.

As an effort to simplify the robot mechanism and to mimic biological muscles, unconventional actuators have been considered. In particular, piezoelectrical actuators have been used in several designs of small legged robots[1–3]. De Ambroggi *et al.* introduced a piezoelectrically actuated flea robot with three legs[1]. The robot inspired from fleas possesses a small size (approximately 2 cm by 2 cm) and light weight, but has shortcomings in the ability of carrying a load, and hence the controller board must be separated from the robot.

Goldfarb and his coworkers developed a piezoelectrically actuated mesoscale quadruped robot with the length of 9 cm, width of 6.5 cm, height of 5 cm, and the weight of 51 g[2]. The robot has the capabilities of self-powered operation and maneuverability on rough surfaces. Though the robot shows promising results towards building autonomous mobile robots actuated by smart materials, it lacks agility of motions and sustainability of a heavy load, which may be augmented by adopting biomimetic ideas from legged animals or insects.

A recent example of biomimetic legged robot is a self-contained hexapod robot with 35 mm length and 3 g weight[3]. The robot is designed to move in the alternating tripod gait driven by two piezoelectric actuators. It shows the advantage in the size of biomimetic robot, but the experimental results have not shown a successful locomotion yet.

The work presented here is for the development of mesoscale, legged robots that are actuated by piezoelectrical actuators. Compared to the piezoelectrically actuated legged robots above, more biomimetic ideas are

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applied to the design and locomotion of robot. The structures and functions of insect leg are considered and the most common locomotion type of quadruped animals is also employed in the robot.

In this work, a piezocomposite actuator named Lightweight Piezoceramic Composite Curve Actuator (LIPCA) is used. LIPCA is used to generate two kinds of locomotion gaits of the robots. LIPCA is made of a piezoelectric ceramic layer and other layers of glass/epoxy and carbon/epoxy (see Fig. 1). Among several versions of LIPCA, LIPCA C2 is used for our robots, because experimental results show that LIPCA C2 can produce the largest displacement among other series[4].

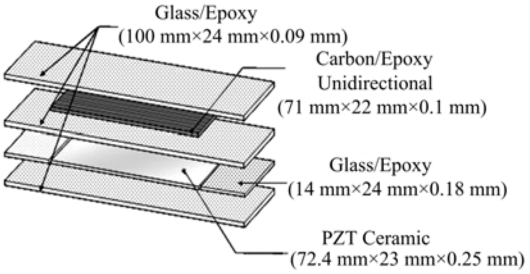

Fig. 1 Structure of LIPCA-C2: layers of PZT ceramic, carbon/epoxy, and glass/epoxy.

LIPCA possesses several advantages as the actuator for mesoscale legged robots. First, LIPCA is a linear actuator, and so well-suited for legged robot mechanisms[5]. Second LIPCA is a lightweight actuator, which is a desirable attribute for mesoscale robots. Third, LIPCA has a higher force and a larger displacement than other types of piezocomposite actuators.

Unfortunately LIPCA has some drawbacks, too. For a fully autonomous locomotion, a robot needs to carry an additional load that typically includes a control circuit and a battery, which requires an actuator to produce a stronger force. However the active force of LIPCA is not strong enough. In addition the displacement is not so large either, which forces to build a large mechanical amplifier. As a result, the mechanism becomes more complicated and heavier. Finally, like other piezoelectric actuators, LIPCA requires a high drive voltage for operation. Therefore, using LIPCA as actuator for legged robots, in spite of the weakness, entails a clever design of locomotion mechanism, which leads to the employment of biomimetic ideas.

2 Robot design

2.1 Locomotion of quadrupeds

Many locomotion types in nature can be applied for quadruped robots, among which walking and bounding are the most general locomotions (see Fig. 2). In the walking, the front leg on one side and the rear leg on the opposite side make a pair, and they move in the same phase when the robot moves. On the contrary, in the bounding locomotion, two front legs make a pair and two rear legs make another one, and two pairs move in the opposite phases. The bounding locomotion is employed in our four-legged prototype robot that is described in the next section.

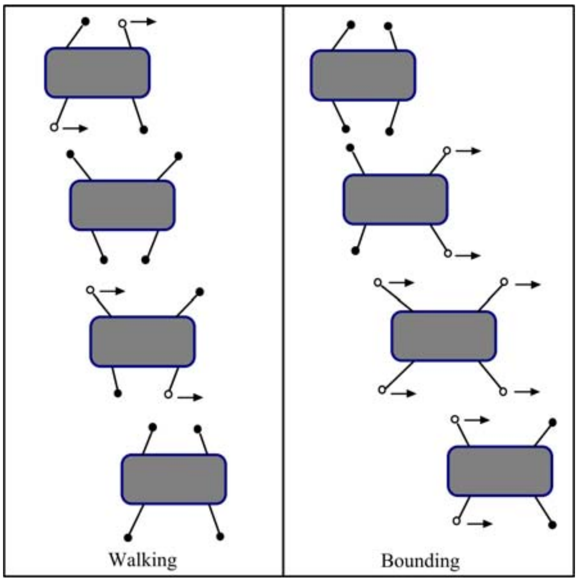

Fig. 2 Walking and bounding locomotions of quadrupeds (top view).

2.2 Leg design

In the design of a mesoscale, legged robot, the most important factors can be the stability and simplicity of mechanism. A variety of leg configurations are found in biological systems. Insects have six or more legs, while mammals have four and humans have two legs. In fact, the less the number of legs of a robot has, the more attempts we have to do to control the locomotion while maintaining the balance.

Robots with six or more legs have a significant advantage in stability. In such robots, the statically stable gait design is possible because six legs can make two tripod gaits. One set of legs stands on the ground while the other set swings above the ground. For example, insects and spiders are able to walk immediately after the birth[6]. However, the configuration requires a higher complicacy of mechanism, so it is not suitable for mesoscale robots. On the contrary, four-legged configurations are much simpler than six-legged ones, but they still have a sufficient stability. Therefore, four-legged configurations can be a more reasonable choice for our robots. Note that two pieces of LIPCA are placed up and down and each leg has only one joint.

Usually each leg of walking robots has one to four degrees of freedom (DOF) and each DOF can be realized by one actuator[6]. In general, the maneuverability of legged robots is proportional to the number of DOF of robot legs. For a legged robot to show complex and agile maneuvers, three or four DOF may be necessary for each leg, which entails several actuators per leg, a large amount of energy consumption, and a high complexity of control.

Numerous experiments with legged robots that we conducted previously led to a conclusion that at least two DOF is necessary in order for the robot leg to perform the most basic motions, lifting and stepping. Such motions can be generated by a variety of arrangements of joints in an individual leg (see Fig. 3 for example). Compared with the arrangements of other animals such as mammals, insect legs generate a less thrusting force, and so the power of actuators can be used more effectively.

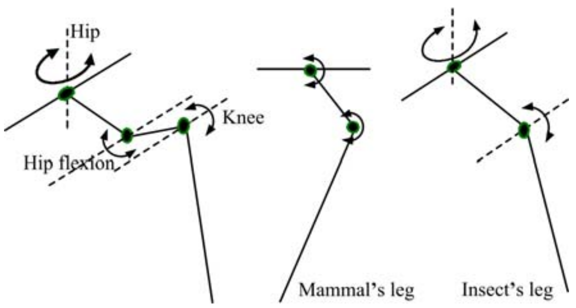

Fig. 3 Legs with two or three degrees of freedom.

In order to simplify the mechanism, each leg is designed to have only one joint, the hip joint. One LIPCA piece actuates two legs in which the motion of LIPCA is transferred to the legs by means of a crank. By this simplification, only two pieces of LIPCA are required to actuate four legs of the robot such that the energy consumption and total mass are reduced. The structure of individual leg of our robots is illustrated in Fig. 4.

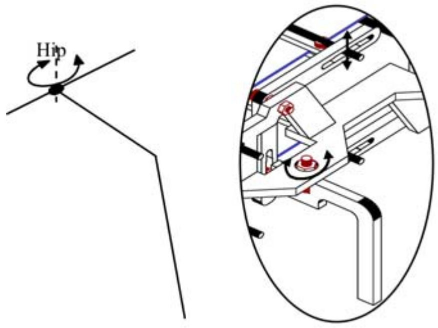

Fig. 4 Hip joint of a leg (Each leg is designed to have only one joint for simplicity).

Using one DOF per leg can lead to a simple design, but more careful considerations are necessary for driving the robot to move forward. As discussed above, at least two DOF are required for each leg in order to implement both lifting and swinging. For example, one DOF is for swinging the leg but it cannot lift up the leg from the ground at the same time. However, this problem could be solved in our robots by making a difference of the lengths of front and rear legs. Fig. 5 shows how the angle α can contribute effectively to the forward movement.

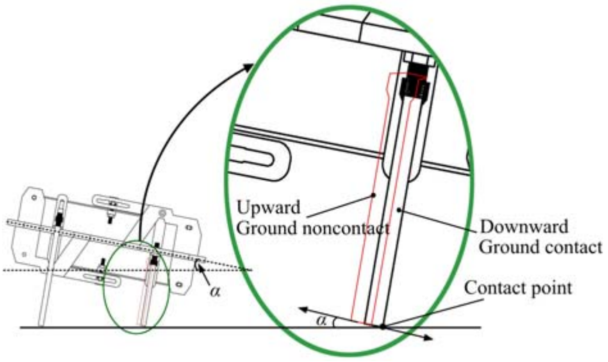

Fig. 5 Robot frame angle (α) and the tip of the leg. The angle is created by the difference of leg lengths.

The principle is as follows. The moving direction of the leg is set to be parallel to the robot frame direction. Hence, when the leg moves upward, the tip does not contact the ground. This behavior is similar to lifting the leg up from the ground. When the leg moves downward, the end point contacts the ground and forms a pushing force, which enables the robot to move forward.

2.3 Simulation of locomotion

Using the ADAMS software, we built an equivalent model of the robot for the mechanism simulation. In the simulation, the effect of several design factors, such as the working frequency, friction of the floor, and the body frame angle, were examined. In all simulations, the basic design variables, such as the robot mass, and the leg rotation angle, were kept constants. A computer model of the robot is shown in Fig. 6.

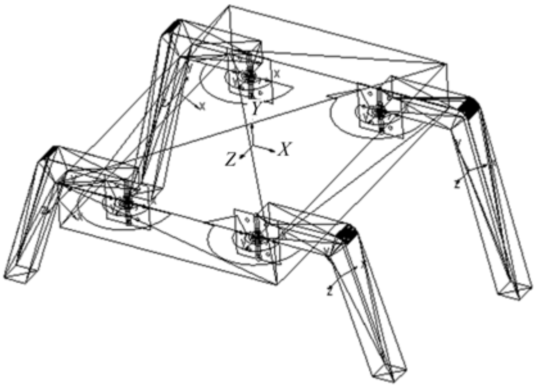

Fig. 6 Equivalent model of the robot for computer simulation in ADAMS software.

In the simulation work, when the working frequency varies from 10 Hz to 60 Hz, the robot model moved properly in bounding gait. The simulation results also show that though each leg has only one joint the robot still obtains a stable locomotion. Fig. 7 displays four states of the bounding mode from the simulation work. Comparing Fig. 2 with Fig. 7, a similar pattern can be found.

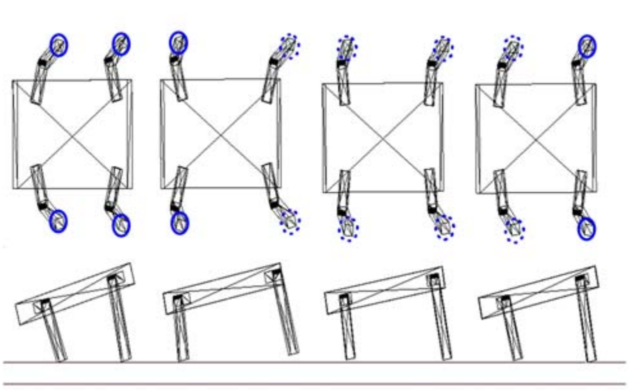

Fig. 7 Bounding gait of the robot in the simulation.

3 Robot prototype

3.1 Bounding prototype

In the current prototype, only bounding locomotion is employed because the natural frequency of LIPCA actuator is fairly high, so it can drive the robot to run with a high velocity. The bounding prototype uses two pieces of LIPCA to realize locomotion. The upper LIPCA is connected to both rear legs, which forms one group, and the lower LIPCA and front legs constitute the other group. The LIPCA is connected to the legs by means of a crank. When a LIPCA moves, the crank rotates, and the legs move as a result. Fig. 8 describes the overall design of bounding prototype.

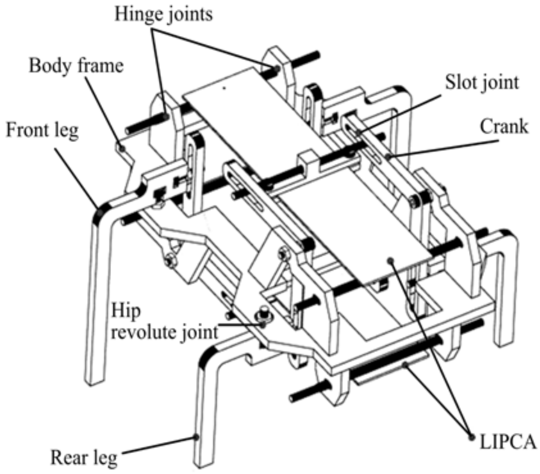

Fig. 8 Overall design of bounding prototype.

3.2 Fabrication

Robots were built from the CAD work of all the components. For the fabrication, acrylic material was used because a light and rigid body was desired. Each part of the robots was fabricated first, and then they were assembled by using bolts, nuts, carbon rods and carbon pipes. As the final step, two LIPCA pieces were attached to the robot body frame.

The weight of the prototype is about 50 g and the length, width, and height are 120 mm, 115 mm, 75 mm, respectively. Fig. 9 shows the bounding prototype. The displacement of LIPCA has the following relation with that of robot leg: the maximum displacement of LIPCA at the resonant frequency is about 3 mm, which is increased to 5 mm with 10° rotation range by means of amplification mechanism (see Fig. 10).

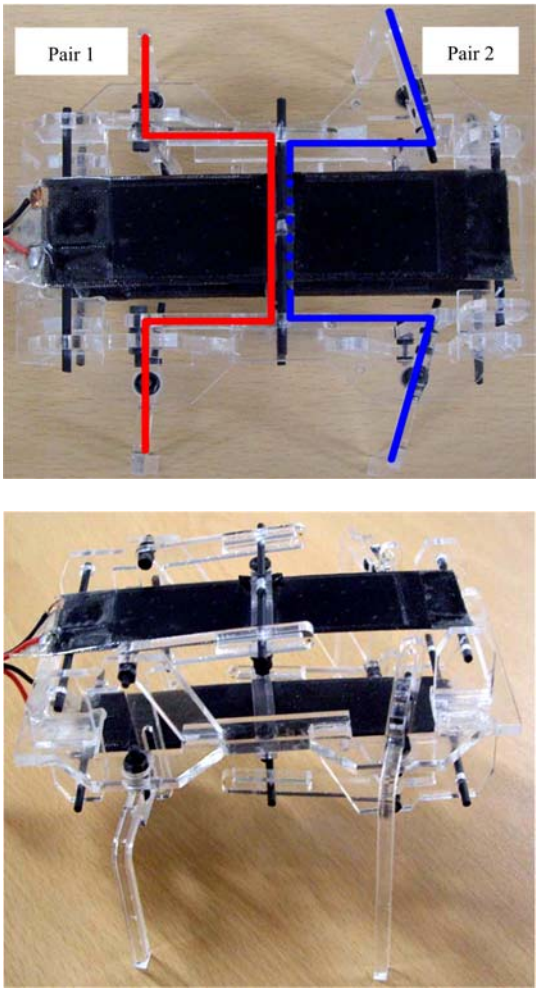

Fig. 9 **Bounding robot prototype.**

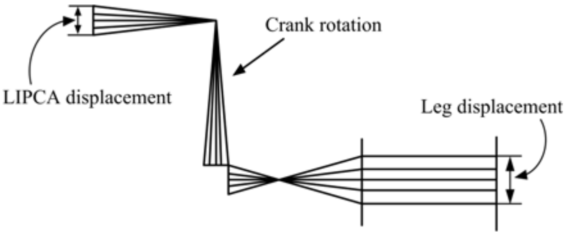

Fig. 10 **Relations of LIPCA displacement and leg displacement.**

4 Experiment

4.1 Effect of frequency on the velocity

Numerous experiments were conducted on a flat plywood panel to evaluate the performance of the prototype. A power supply and an oscilloscope were used to supply a high voltage and measure the frequency of AC voltage.

A square signal voltage was used because it could produce more power and larger displacement of LIPCA than ramp or sign signals. LIPCA was actuated by about 370 Vpp signal with frequency in the range of 5 to 80 Hz, beyond which the prototype cannot move properly. The experimental apparatus is shown in Fig. 11.

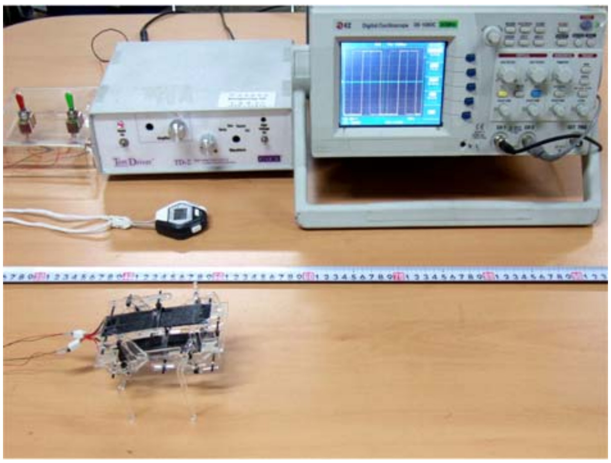

Fig. 11 **Experimental apparatus composed of a locomotion track, a power supply and an oscilloscope.**

The first set of experiments was to measure the locomotion velocity of the robot at different frequencies. We excited the LIPCA pieces and measured the time for the robot to move to the end on the track. By changing the frequency, we could get the velocity data of the robot at various frequencies (see Table 1). Fig. 12 shows the velocity data for various frequencies of the bounding prototype. It is shown that when no additional load is applied, the maximum velocity, 470 mm·s^{-1}, of the bounding prototype can be obtained at 50 Hz frequency.

Table 1 **Velocity data for different frequencies**

Frequency (Hz)	v (mm·s^{-1})					
	1 trial	2 trial	3 trial	4 trial	5 trial	average
10	26.4	32.0	30.1	29.7	28.3	29.3
20	111.1	125.0	117.6	142.0	135.1	126.2
40	432.9	500.0	444.4	469.5	500.0	469.4
50	432.9	478.5	485.4	483.1	485.4	473.1
60	202.4	194.9	185.9	189.4	195.3	193.6
70	230.4	179.9	183.8	173.0	170.4	187.5
80	141.6	145.6	147.5	153.8	183.8	154.5

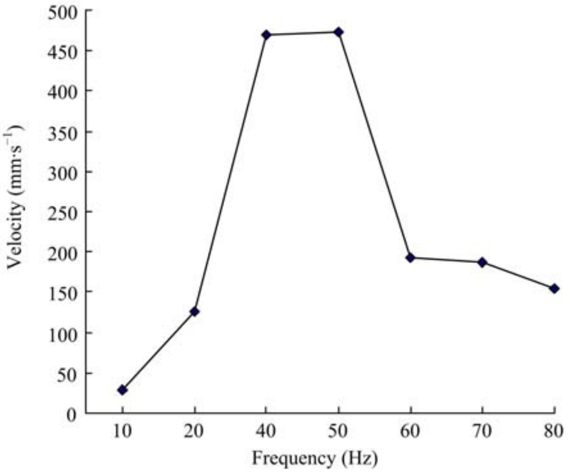

Fig. 12 Velocity for different frequency (no additional weight).

4.2 Effect of angle on the velocity

As described in previous section, the angle of the body frame affects the motion of robot. In order to determine the optimal value of this angle, several experiments were performed. By using legs which have different length, the angle can be changed. Fig. 13 shows the velocities of robot measured at several values of α angle. The results show that 8° may be the most efficient value of α of the bounding prototype.

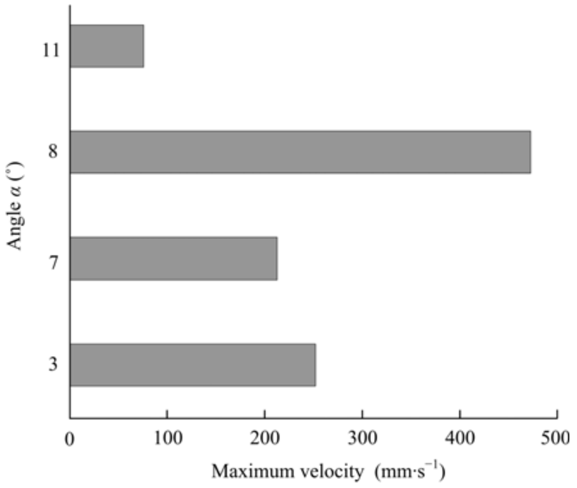

Fig. 13 Velocity for different angle α (no additional weight).

4.3 Payload experiments

The third set of experiments was applied to the robot prototype only in order to find out how much load it can carry. After attaching an additional payload to the robot, we had it run the whole track and measured the time. From these experiments, the maximum payload of the bounding prototype was found. The experimental results are summarized in Fig. 14. If a load is attached, the velocity drops, but the robot can still run at 67 mm·s^{-1} with the payload of 100 g. However, the weakness of the bounding prototype is that it does not have the ability of turning motion due to the symmetric configuration.

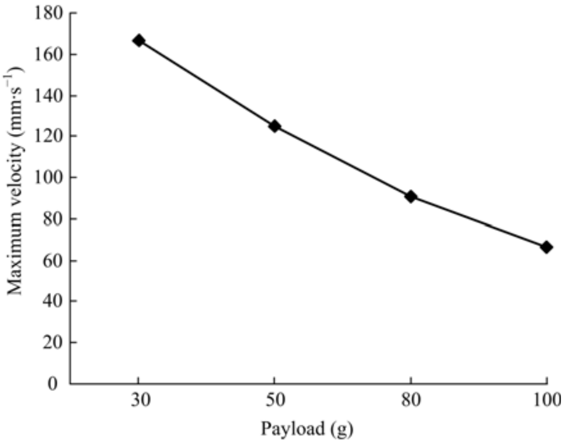

Fig. 14 Velocity for different payloads.

5 Discussion and conclusion

In this paper we reported a mesoscale, light, fast, four-legged robot, which is actuated by two pieces of a smart material, LIPCA. The leg configuration of robots is inspired by the structure of biological systems. Though the robot has a simpler mechanism it still has a sufficient stability. The configuration of insect legs is applied to the robot design and the power of actuators is used efficiently. Among several locomotion types of quadrupeds, the bounding motion is employed. A bounding prototype was fabricated and several simulations and experiments were conducted. Experimental results show that the bounding robot has a superior ability in terms of the locomotion velocity and the payload. In fact, the maximum speed of the bounding prototype, 470 mm·s^{-1}, is quite remarkable, since it means that the robot can move about four times its body length per second.

Experiments with different body frame angles α clarify how this angle contributes to the movement of the robot and by far the optimal value of α is 8°. Experiments also show that the robot prototype can attain more efficient motion with the optimal value of α.

Since the robot prototypes are made of acrylic, they are relatively rigid and easy to assemble and disassemble. There are several aspects to improve the performance of the robot. First of all, a small and light power supply circuit is currently under development such that the robot could be able to carry the circuit and battery. The total weight of the circuit and battery is expected to be less than 100 g. We also consider more application of biomimetic ideas to the robot and change of the material into lightweight and strong composites. Though the prototypes are yet to be improved, they are considered as an important step in building autonomous mobile robots actuated by smart materials.

Acknowledgement

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