Microsyst Technol (2007) 13:883–890
DOI 10.1007/s00542-006-0294-9

TECHNICAL PAPER

Development of an underwater biomimetic microrobot with compact structure and flexible locomotion

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Received: 14 June 2006 / Accepted: 13 October 2006 / Published online: 16 November 2006

Abstract Compact structure and flexibility is normally considered as a pair of incompatible characteristics for legged microrobots. Most robots choose complex structure of multi-joint legs to attain the flexibility, while some microrobots have poor flexibility for miniaturization. To attain a microrobot with both compact structure and flexible locomotion, we designed a novel type of biomimetic locomotion employing ionic conducting polymer film (ICPF) actuators as one-DOF legs. We developed several prototype microrobots using this locomotion. In this paper, a microrobot using this biomimetic locomotion, named Walker-3, utilizing six ICPF actuators with two-DOF motion is developed. It is 30 mm in length, 55 mm in width and 8 mm in height (in static state). Experimental results indicate that Walker-3 can attain 6 mm/s of walking speed and 7.1 deg/s of rotating speed and climb on a 30° ascent at a speed of 0.5 mm/s with control signal of 10 V, 0.5 Hz. It is also suitable for uncertain terrain, such as climbing on a stairs less than 2 mm high and striding over a pit less than 5 mm wide. It has better flexibility, balance and load ability than its predecessors. We compared it with some legged microrobots and the result shows a microrobot with this biomimetic locomotion can have both compact structure and multi DOF locomotion.

1 Introduction

Because of wide applications, such as cleaning the micro pipeline in the radiate area, getting samples from the seabed for archeology or mining, scanning the blood vessel for medical holography and so on, research of underwater microrobots developed at a high speed in recent two decades. Some underwater robots with screw propellers have been developed, but limited by the electromagnetic of traditional motor, screw propellers are difficulty to be used in microrobots. So smart materials, such as ionic conducting polymer film (ICPF), piezoelectric elements, pneumatic actuator, shape memory alloy, which can be used as artificial muscles, paved the way for a large variety in microrobot design. Biomimetic microrobots using these smart actuators come to the focus.

It is normally considered that compact structure and flexibility are incompatible. Some robots choose complex structure for flexible locomotion, while some microrobots have poor flexibility for miniaturization. To attain a microrobot with both compact structure and flexible locomotion, we designed a novel type of biomimetic locomotion using ICPF actuators as one-DOF legs.

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We developed several microrobots using this biomimetic locomotion. In this paper, we introduced the recent one. It has a compact structure that it only employed six legs without joints. Compared with its predecessors, it is more stable, flexible and powerful. According to our experiments, it realized a walking speed of 6 mm/s, rotating speed of 7.1 deg/s and climbed at a speed of 0.5 mm/s on a 30° ascent. It also showed a good suitability for uncertain terrain, such as stairs and pits.

This paper is structured as the following. Firstly, we introduced the smart actuator, ICPF and the novel type of biomimetic locomotion. Secondly, we introduced the microrobot using this locomotion and analyzed its motion mechanism. Thirdly, we carried out the experiments and measured its walking and rotating speeds. Fourthly, we compared the microrobot with some legged microrobots. And the last is our conclusions.

2 The biomimetic locomotion with ICPF actuators

2.1 ICPF actuator

An ICPF actuator consists of a perfluorosulfonic acid membrane with chemically plated gold as electrodes on both sides. It bends when a voltage is applied between the electrodes (Hirose et al. 1992; Osada et al. 1992; Segalman et al. 1992; Oguro et al. 1993). The actuator is soft and can work in water or a wet environment. The ICPF actuator has several advantages. It works on low voltage (above 1V), bends silently, responds quickly, consumes little energy, is environmental friendly and has a long life. Its density is close to that of water. As an emerging technology, the weak propulsion and the muscle fatigue phenomenon limit its application.

Because of its quick response, ICPF actuator is widely used as oscillating or undulation fins in swimming microrobots. (Guo et al. 1998, 2000, 2002, 2003, 2004; Laurent and Piat 2001; Anton et al. 2004; Jung et al. 2003). ICPF actuators are used as artificial muscles to drive robots (Mojarrad and Shahinpoor 1997; Shahinpoor et al. 1998). ICPF actuators are also used in biped walking underwater robot (Guo et al. 2004; Kamamichi et al. 2003). An ICPF micro-leg with two DOF (degree of freedom) has been developed (Otis et al. 2003). A ciliary motion-based eight-legged walking microrobot has also been developed (Ryu et al. 2002; Kim et al. 2003).

2.2 Biomimetic locomotion

Each leg of the stick insect is composed of the coxa, the femur, the tibiae and the tarsus. The tarsus is also called foot and does not contribute to the movements. The coxa offers the foot one DOF motion in the direction of movement. The femur and the tibiae offer the foot a two-DOF motion to enable it to find a reliable foothold together in the swing-search phase and touch the ground and support the body while moving in the stance phase, as shown in Fig. 1 (Dean 1989; Cruse 1985a, b).

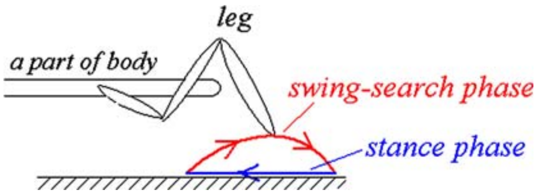

Fig. 1 The two main phases in stick insect walking

A stick insect inspired biomimetic locomotion prototype using two ICPF actuators is developed, as shown in Fig. 2. The actuator in vertical direction is called the driver. The actuator in the horizontal direction is called the supporter. The free end of the driver is the foot. The driver and supporter are controlled by two channels of AC signals, which are the same frequency, so that they bend along Tra.2 and Tra.1. The phase of supporter is 90° delayed than that of driver, so that driver and supporter collaborate as shown in Fig. 3, where the swing-search phase is from (a) to (d) and the stance phase is from (d) to (e).

3 A microrobot with biomimetic locomotion

3.1 Review of the predecessor microrobots

We had previously developed two microrobots using this locomotion, named Walker-1 and Walker-2, as shown in Figs. 4, 5 (Zhang et al. 2006, 2006a, 2006b).

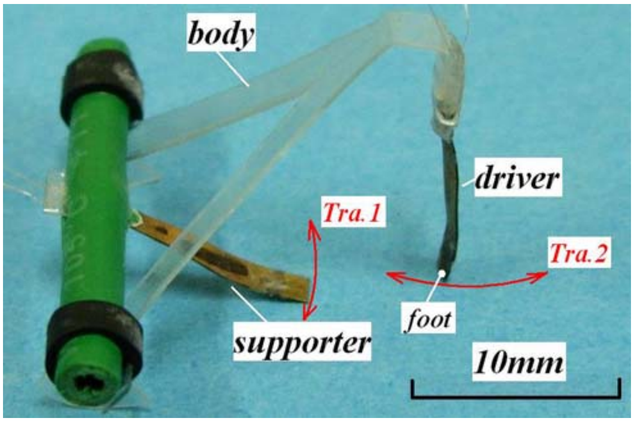

Fig. 2 The prototype of the biomimetic locomotion

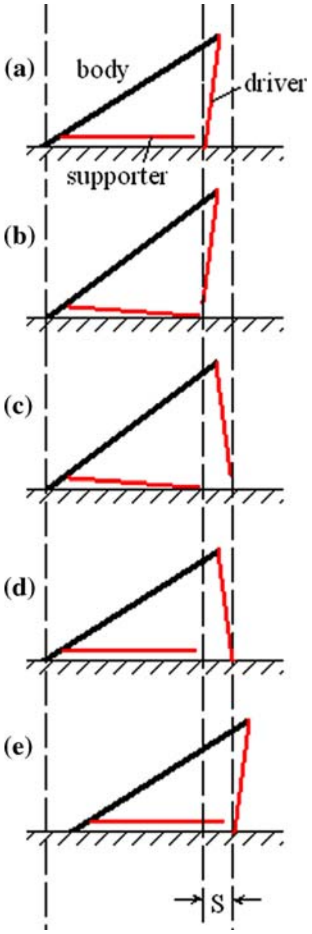

Fig. 3 One step cycle of the biomimetic locomotion

Both of them have six ICPF actuators on plastic film body, which are divided into two groups, the drivers are from A to C, and the supporters are the others.

Walker-1 can walk only in a straight line and its speed is 4.7 mm/s when control signal is 10 V, 5 Hz.

Walker-2 can not only walk in three straight lines, but also rotate around its symmetric axis. As a successor of Walker-1, Walker-2 has some advantages, such as stability, flexibility, upload ability, less water resistance and so on. But its disadvantage is that its moving motion is inefficient because one driver always resists forward moving limited by its structure.

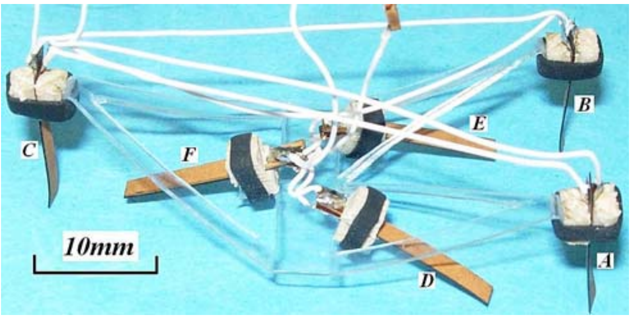

Fig. 4 A photo of Walker-1

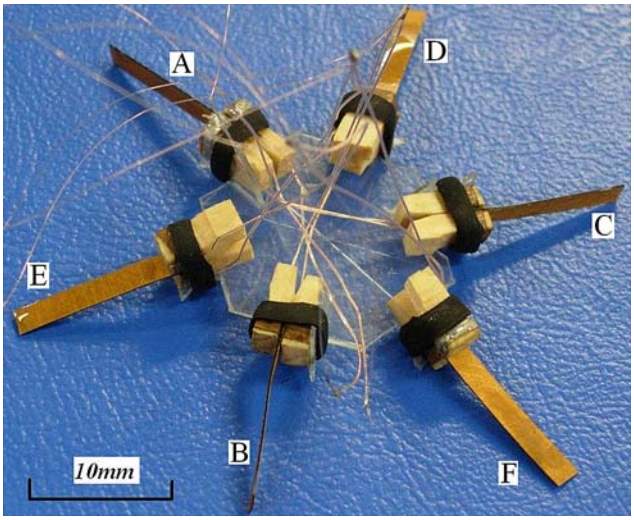

Fig. 5 A photo of Walker-2

3.2 The structure of the improved microrobot

To inherit the advantages of Walker-2 and overcome its disadvantage, an improved microrobot, named Walker-3, has been developed, as shown in Figs. 6, 7.

Walker-3 is 30 mm in length, 55 mm in width and 8 mm in height. It has also six ICPF actuators, with dimensions of 11 × 3 × 0.2 mm, which are divided into three drivers and three supporters. The drivers and the supporters are on both sides of a rectangle film body. Although they are asymmetric, adjusting the centers of

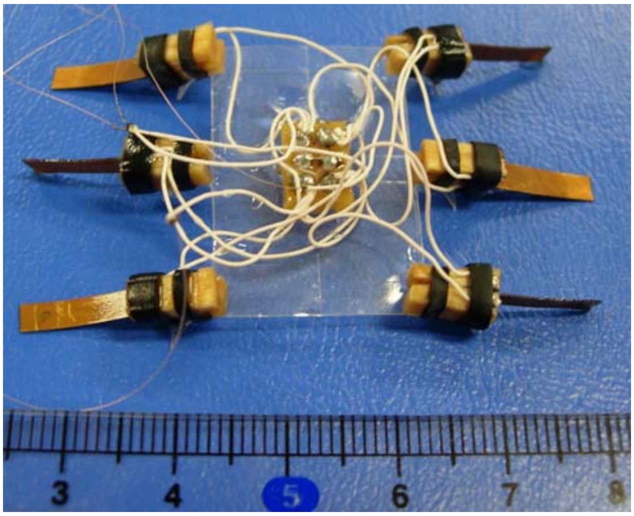

Fig. 6 A photo of Walker-3

drivers and supporters to the weight center, the asymmetric effect can be ignored.

Walker-3 is proposed to walk and rotate. The control strategies are shown in Table 1.

3.3 Motion mechanism and speed model

Figure 8 represents one step cycle of walking forward. It is divided into four periods.

1. In period A (from d to a), supporters lift the body up and drivers are lifted away from the ground.
2. In period B (from a to b), drivers bend forward.
3. In period C (from b to c), supporters bend upward enough so that supporters are away from the ground and drivers hold the ground.
4. In period D (from c to d), drivers bend backward as the propulsion stroke and the body is pushed forward.

The swing-search phase is the periods A,B and C. During this phase, the drivers are lifted away from the ground to find another foothold with the help of supporters. The stance phase is period D. In this phase, the drivers push the body forward while moving. The experimental video samples can be seen at http://www.weizhang.info.

The speed of the walking motion is decided by the displacement of the drivers and the frequency of the control signals, as shown in Fig. 9. Assume that the displacement of the actuator is d and the microrobot moves forward l in one step cycle,(1) shows the relationship between d and l. Equation (2) represents a speed model, where v is the speed and f is the frequency of the drivers' control signal.

$$l = d \tag{1}$$

$$v = df \tag{2}$$

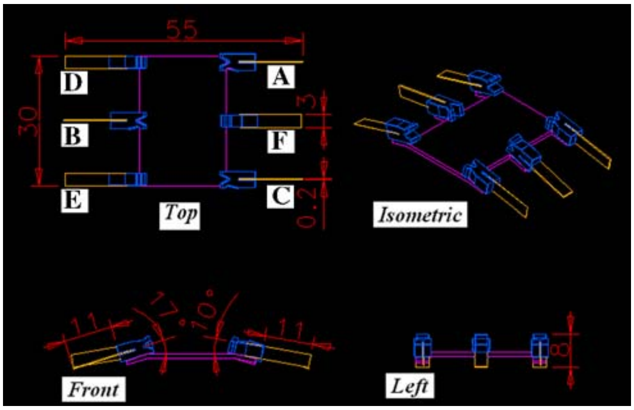

Fig. 7 Dimensions of Walker-3

Table 1 The control strategies of the Walker-3

	A	B	C
Walking forward	-	-	-
Walking backward	+	+	+
Rotating in clockwise	+	+	-
Rotating in counter clockwise	-	-	+

A, B and C stand for the three drivers, as shown in Fig. 7. " + " and " - " mean the drivers bending forward and backward respectively in stance phase

Rotating motion in counter clockwise is shown in Fig. 10. As an abbreviated description, in the stance phase (c to d), drivers push the body rotating. In the swing-search phase, drivers prepare for the stroke with the help of supporters. The microrobot can rotate θ in one cycle described as (3), as shown in Fig. 11a. From (4) and (5), θ can also be described as (6), where d is the displacement of drivers. And the rotating speed is (7), where ω and f stand by the rotating speed and the frequency respectively.

The structure also provides flexibility to Walker-3 during rotating motion. A rotating cycle is also divided into four periods. In brief, the swing-search phase is from state (d) to (a) to (c). In this period, the drivers prepare for the stroke with the help of supporters. The stance phase is from state (c) to (d). In this phase, the drivers push the rotating body.

The speed of rotation is decided by the displacement of the driver in the stance phase and the frequency of the step cycle, as shown in Fig. 11b. The microrobot can rotate to an angle of θ in one step cycle. So it can be described by (3), where α and β can be calculated by (4) and (5), d is the displacement of the driver. Equation (7) represents the speed model, where ω and f are the rotating speed and frequency, respectively.

$$\theta = \pi + \alpha - 2\beta \tag{3}$$

$$\alpha = \alpha_1 + \alpha_2 = \arctan\frac{15+d}{55} + \arctan\frac{15-d}{55} \tag{4}$$

$$\beta = \frac{\pi}{2} + \alpha_2 = \frac{\pi}{2} + \arctan\frac{15-d}{55} \tag{5}$$

$$\theta = \alpha_1 - \alpha_2 = \arctan\frac{15+d}{55} - \arctan\frac{15-d}{55} \tag{6}$$

$$\omega = \theta * f = \left(\arctan\frac{15+d}{55} - \arctan\frac{15-d}{55}\right)f \tag{7}$$

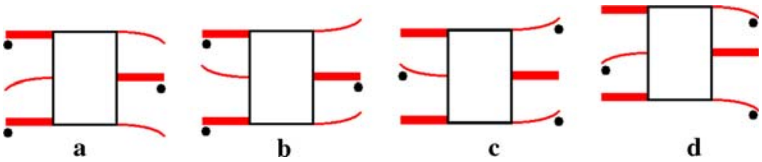

Fig. 8 One step cycle of walking straight. (The marks, •, indicate which legs contact the ground)

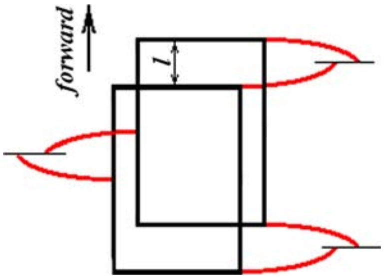

Fig. 9 The efficiency of walking straight. (Supporters are not drawn out)

4 Experimental results

The walking and rotating speeds experiments are carried out on an underwater plastic surface. Figure 12 shows an experimental scene of walking motion. Applied signals of different voltages and frequencies, we recorded the time and the distance and calculated out the walking speeds, as shown in Fig. 13. In the same way, the rotating speeds are also calculated out, as shown in Fig. 14. The results indicate that speeds are direct proportion to the voltage.

We carried out the experiments of the climbing ability on ascent. Figure 15 represents an experimental scene when Walker-3 climbing on a 15° ascent. Applied signals of (10 V, 0.5 Hz) and (10 V, 1 Hz) respectively, we recorded the speeds on ascents during 0° and 35° with step of 5°, as shown in Fig. 16. The result shows that speeds decrease as the degree of ascent increasing.

We also carried out experiment of climbing and striding and Walker-3 climbed on a 2 mm-high stair and strode over a 5 mm-wide pit, with 0.5 Hz, 8 V.

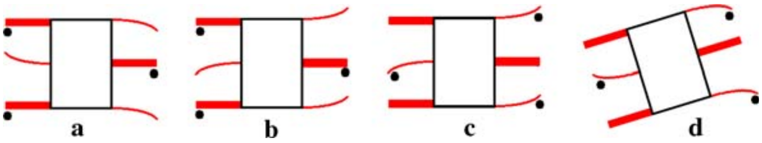

Fig. 10 One step cycle o fthe rotating motion. (The marks, •, indicate which legs contact the ground)

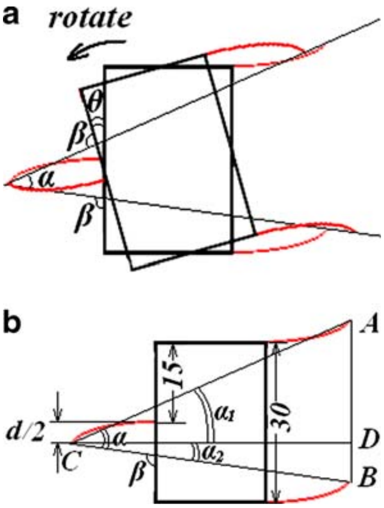

Fig. 11 **(a)** The rotate angle in one step. **(b)** To calculate the rotating angle. The efficiency of the driver in rotating motion. (Supporters are not drawn out.)

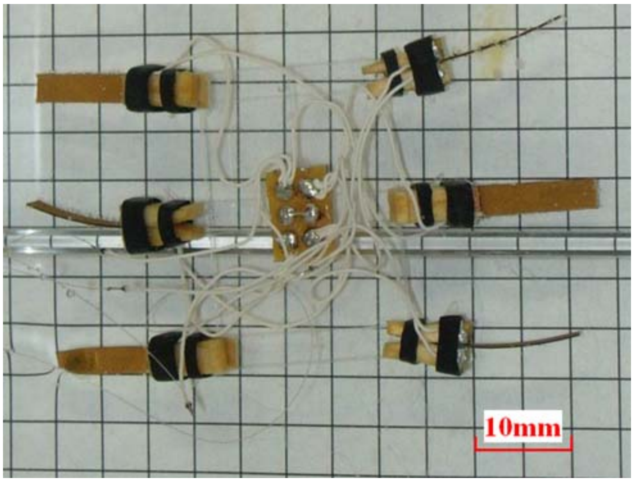

Fig. 12 An experimental scene of walking motion

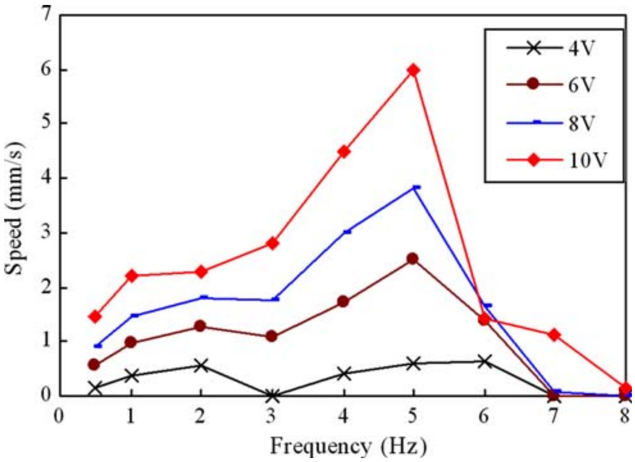

Fig. 13 The speeds in walking motion

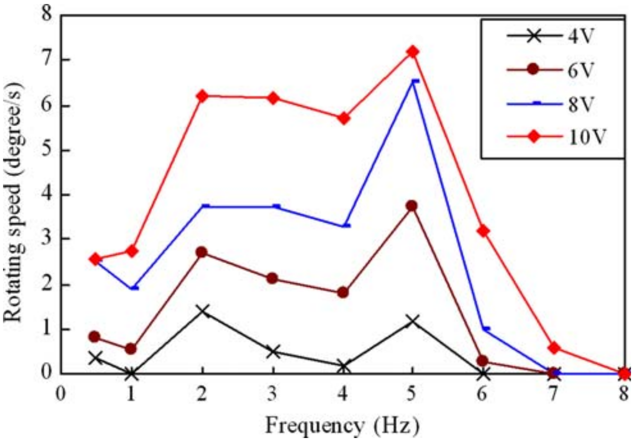

Fig. 14 The angular speeds in rotating motion

5 The characteristics of Walker-3

5.1 Compare with its predecessors

As an improved prototype, Walker-3 has some advantages over Walker-1, Walker-2.

5.1.1 Stable structure

Because of the structures, their centers of gravity lie on the symmetric axial or center. The stability of the robots is decided by the base area and the height of the center of gravity. The larger the base area, more stable is the robot. The lower the center of gravity, more stable is the robot. On the basis of Table 2, we draw the conclusion that Walker-3 is more stable than Walker-1 and Walker-2, which is also proved by our experiment.

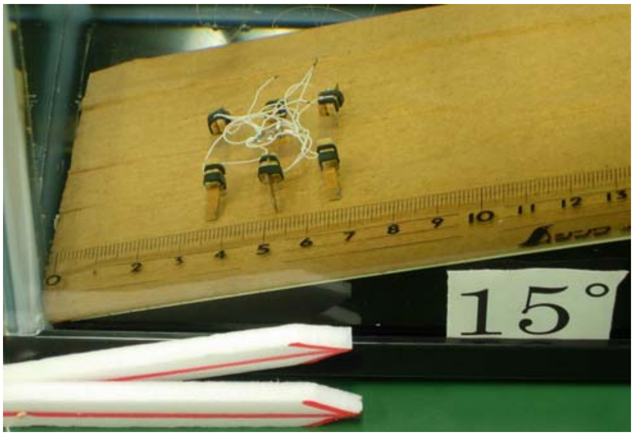

Fig. 15 An experimental scene of climbing on a 15-degree ascent

5.1.2 Flexible motion

The DOF of the robots is shown in Table 3. Although Walker-2 can move with 3-DOF motion, it is flexible during rotating, but its one driver resists forward moving, while Walker-3 is flexible during both walking forward and rotating motion, which is in common use.

5.1.3 Rigid leg state

The rigidity of ICPF actuators in standing state (used in Walker-1) and lying state (used in Walker-2 and Walker-3) has been measured.

A driver is fixed at one end as a cantilever in water. Floating upload is clamped at its free end. Without applied signals, we measured the displacement by changing the floating uploads. Figure 17 describes the experimental result. With the same upload, the actuator in lying state has less displacement than in standing state. The result indicates that the drivers of Walker-2 and Walker-3 are in rigid state.

5.2 Compare with some legged robots and microrobots

Most biomimetic robots use multi-DOF legs (Birch et al. 2000, 2001, 2002; Clark et al. 2001; Klaassen et al. 2002; Bachmann et al. 2002). These robots are flexible in unlimited space, but their multi-DOF legs are not suitable for a compact microrobot, because of some problems, such as the complex control strategy, too many wires for control signal or energy supply to each actuator and complexity manufacturing.

As the development of micro manufacturing technology, microrobots with one-DOF legs are been developed. A microrobot prototype and a solar pow-

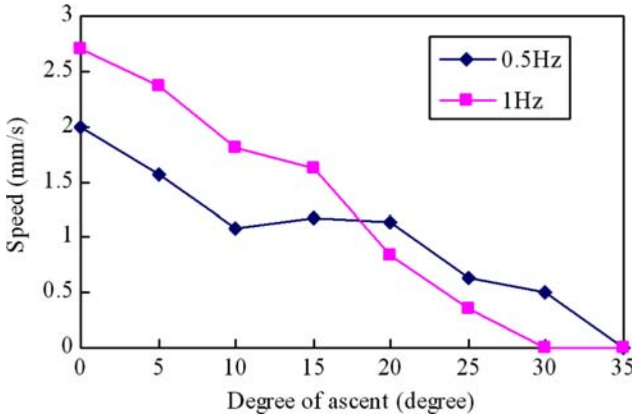

Fig. 16 The speeds in climbing on different ascents (10v)

Table 2 The parameters for stability

	Walker-1	Walker-2	Walker-3
Area among drivers (mm^2)	440	717	825
Area among supporters (mm^2)	340	717	825
Height of gravity center (mm)	10	4	4

Table 3 The DOFs of the robots

	Walker-1	Walker-2	Walker-3
The DOFs on flat	1	3	2

ered silicon robot with one-DOF legs are developed (Kladitis et al. 1999; Hollar et al. 2003). It seems that they use dissymmetrical friction to move in a single direction, but the contrary friction produces a big resistance. A microrobot with eight one-DOF ICPF legs and a walking silicon microrobot have been developed using the same principle (Ryu et al. 2002; Kim et al. 2003; Ebefors et al. 1999). The one-DOF legs are divided into two groups to avoid friction. But because of its mechanical structure they can only realize one-DOF motion. An obstacle or a low stair is a big problem and multi-DOF motion is also a difficult mission for them. While, Walker-3 with one-DOF legs can walk, rotate and climb on ascent. It is also suitable for uncertain terrain, such as stairs or pits.

6 Conclusions

To deal with the incompatibility of compact structure and flexibility in legged microrobot, in this paper, we proposed a novel type of biomimetic locomotion using one-DOF legs. We developed a microrobot named Walker-3. The experimental results show that Walker-3 can attain the walking speed of 6 mm/s and the rotating speed of 7.1 deg/s, and climb on a 30° ascent at speed of 0.5 mm/s. Walker-3 can also climb on a 2 mm high stair and stride over a 5 mm width pit. It is stable, flexible and powerful than its predecessors. And comparison results shows Walker-3 with one-DOF legs realized 2-DOF motions, it is flexible than some microrobots with one-DOF legs. The results indicate a microrobot using this novel type of biomimetic locomotion can have both compact structure and flexibility.

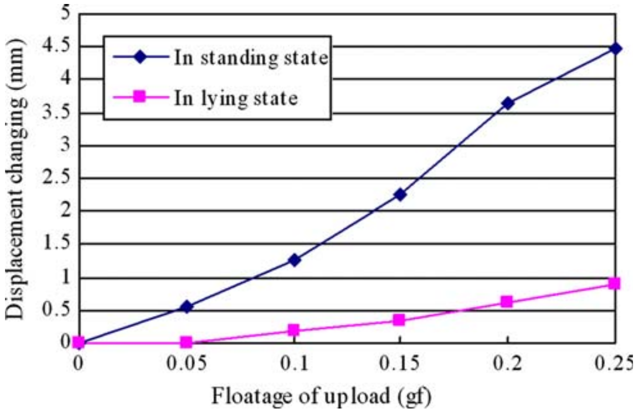

Fig. 17 The flexibility of the static actuator

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