MANIPULATING THE MOVING TRAJECTORY OF INSECT-SCALE PIEZOELECTRIC SOFT ROBOTS BY FREQUENCY

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ABSTRACT

This paper reports the control and manipulation of the moving trajectories of insect-scale soft robots by the applied driving electrical voltage frequency utilizing the asymmetric structural design of the actuating mechanism. Three distinctive advancements have been achieved: (1) a simple asymmetric structural design to create uneven responses on the legs of artificial insects to realize motion controls; (2) the capability of moving forward, leftward and rightward by adjusting the applied driving frequency; and (3) a demonstration of recording the ethanol concentration map around an area in real time by carrying a gas sensor on top of the robot on a controlled path bypassing the existing obstacles. As such, this work can advance the state-of-art technologies on wirelessly controlled, unmanned robots for various potential applications.

INTRODUCTION

Over the past two decades, insect-scale robots have been studied for potential applications such as hazardous environment explorations as well as search and rescue operations [1]. The micro-robots based on rigid structures and materials have achieved considerable progress in recent past years. For example, controllable locomotion of shape morphing [2], jumping [3], flying [4] has been realized. Despite the decent performance of rigid insect scale-robots, there are still constraints coming from the inherent properties of the rigid materials or stiff structures.

The rigid materials utilized in micro-robots such as lead zirconate titanate (PZT) [5] and carbon fibers [6] are brittle and fragile so that these robots can be easily damaged to lose their functions [7]. In order to realize reasonable maneuverability and safe interaction with the external environment, sophisticated structures and control systems are commonly used.

Inspired by biology, researchers have developed soft insect-robots with naturally compliant materials. Several works have demonstrated soft-robots based on different driving mechanisms with decent controllability [8] and many attempts have been made based on specific materials, such as magnetic composite [9], carbon nanotubes [10]-[11], light sensitive materials [12], ionic polymers [13], electroactive materials [14], and soft piezoelectric materials [15], etc.

Among the soft actuating materials, piezoelectric polyvinylidene fluoride (PVDF) is popular for advantages in flexibility, lightweight and fast responses. Although a relatively low driving voltage is realized in our previous work by using a pre-curved structure design, only forward movement have been accomplished [16]. In order to achieve controllable tuning, an insect-scale soft robot with the asymmetry structure is designed, fabricated and tested in this paper. The experimental and simulation results show that the soft robot we have designed can realize the motion trajectory control via the superposition of various vibration modes under different driving frequencies.

Figure 1: (A) The design of the insect-scale soft robot made of polymer layers, including an optical photo. (B) Cross sectional view of the robot showing the unimorph piezoelectric actuator (PVDF) with front and back legs (PET). (C) Simulation results of the asymmetric structure under different driving frequencies to have straightforward, counter-clockwise and clockwise motion trajectories at different frequencies.
CONCEPT AND PRINCIPLE

The soft-robot consists of three layers as shown in Figures 1A and 1B: two PET films (polyethylene terephthalate) and one PVDF film (d31=-27 pC/N, PolyK Technologies) to form a sandwich structure. The PVDF layer serves as an active layer while the PET layer serves as the inactive layer. When a voltage is applied on the PVDF layer, it can transition from polar to nonpolar states to produce the lattice strain and dimensional changes. The elongation will occur by applying a negative electrical field on the PVDF layer along the direction of polarization and the deformation will recover after the electric field is removed. The top and bottom PET layers with legs are bonded on both sides of the PVDF as the passive structures. As the unimorph PVDF structure deforms under the excitation of the AC driving voltage (Figure 1B), the whole robot can vibrate. The two front legs and rear legs made of PET are connected to the top and bottom PET flat layers, respectively. Each leg is folded around 41° relative to the ground to provide a ground reaction force during the movements. In general, there are two reaction cases. (1) The leg kicks the ground in the forward direction such that the reaction force will be in the backward direction. Due to the inclined angle design of the legs, the legs will absorb the backward force and turn into an elastic potential energy. (2) The leg kicks the ground in the backward direction and the ground exerts a forward force on the robot, which will result in the forward motion of the robot.

In order to control the moving trajectories of the robot, the top PET layer has asymmetric holes on the top of the PET layer as shown in Figure 1A. The asymmetric distributions of the holes result in the asymmetric distributions of the weight and stiffness of the robot, which cause and the asymmetric deformations under excitations. Since the movements of the robot come from the reaction force as the leg hits the ground, more hitting events can generally result in larger advancements. A large structural vibration amplitude at the leg can result in the leg to stay in the air with more time with less ground-striking events. This results in less frequency to induce robot movements. On the other hand, a leg with a smaller vibration amplitude can result in more hitting events with the ground to have more ground-striking events which results high frequency in terms of robot movements. By adjusting the applied frequency, we can control the leg ground-hitting frequency and vibration mode of the robot for asymmetric motions. It is observed in the tests that the ground-hitting frequency is the dominate factor for the forward robot movements. As such, the robot turns rightward when the left leg hitting frequency is higher than that of the right leg. In the contrary, it will turn leftwards when the right leg hitting frequency is higher than that of the left leg. If the hitting frequency of the left and right legs is the same, the robot will have straight forward movements.

To validate these, Abaqus finite element (FEM) analysis is utilized as shown in Figure 1C. Since the four legs of the robot are relatively stiffer than that of the body, the structure of the robot is simplified as a flexible unimorph plate supported by four rigid legs. In order to form an asymmetrical structure, we constructed a circular hole (2 mm in diameter) on one side of the top layer in the simulation model. The physical properties of PET and PVDF layers used in the simulation are listed in Table 1. An equivalent peak to peak 300 V sinusoidal wave is applied to the PVDF layer as the driving signal. The ground is defined as an incompressible structure for the contact with the four legs and a friction coefficient of 0.5 is used between the ground and the leg. The vibration states of the structure at different frequencies under AC excitation are shown in Figure 1C in one driving cycle. The color shows the vertical vibration amplitude of the structure; with red area indicating larger vertical vibration amplitudes and blue area indicating smaller magnitudes. The direction of the gray arrow indicates the direction of the robot head. At 100 Hz, the first vibration mode is dominant such that the vertical vibration amplitudes of the legs on the left and right sides are about the same, resulting in the straight forward moving direction of the robot. At 500 Hz, the high order vibration mode dominates. The vertical vibration amplitude of the two legs on the left side is larger than that of the two legs on the right side with less hitting frequency to the ground to cause the counterclockwise rotational movement of the robot. Similarly, the other high-order vibration modes at 800 Hz result in the clockwise.

<table>
<thead>
<tr>
<th>Material</th>
<th>PET</th>
<th>PVDF</th>
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<tbody>
<tr>
<td>Density (t/mm³)</td>
<td>1.38e-009</td>
<td>1.78e-009</td>
</tr>
<tr>
<td>Young’s Modulus (Mpa)</td>
<td>2500</td>
<td>3000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>d31(pC/N)</td>
<td>None</td>
<td>27</td>
</tr>
<tr>
<td>d33(pC/N)</td>
<td>None</td>
<td>-33</td>
</tr>
</tbody>
</table>

Table 1: Materials properties used in simulations

![Fabrication process of the soft robot. PET layer with substrate is patterned by a paper cutting machine. Gold electrode on PVDF is deposited through e-beam evaporation. The three layers are aligned and laminated and the legs are folded.](Image)
movement direction of the robot. These simulation results show that one can control the vibration amplitude on each leg by different frequencies which can be used as a motion direction control method.

**FABRICATION**

In order to fabricate the triple-layer unimorph structure for the robot, a lamination-cut-release fabrication method is utilized [17] as shown in Figure 2. First, the double-layer PET film is patterned by a programmable cutting machine. Afterwards, a 62.5 μm-thick sticky PET structure is peeled off from the substrate. Two 50 nm-thick Au electrodes are deposited by electron beam evaporation on the top and bottom of a commercial 18 μm-thick PVDF film. Two 25 μm-in-diameter Si/Al alloy wires are carefully attached on the sticky side of the two PET layers. Afterwards, the PVDF layer is laminated with the bottom PET structure and top PET structure. A gas sensor (Sensirion, Inc.) together with a small flexible printed circuit board is mounted at the rear top surface of the robot using the sticky surface of the PET film. Finally, the legs are folded along the cut to an angle of 41°. The as-fabricated soft robot has a total weight of 106 mg without the sensor and the length is 3 cm with the width of 1.5 cm.

**EXPERIMENT RESULTS**

We use a frequency-tunable function generator to provide sinusoidal waves as driving signals. Afterwards, the driving signal is boosted up through a piezoelectric amplifier to amplify the voltage up to a peak to peak value of 300 Volts. All the experiments are conducted on a paper substrate. The relationships between the velocity and angular velocity with respect to the driving frequencies are shown in Figure 3. The red dots indicate the velocity while the blue line indicates the angular velocity in the turning directions. The positive value of angular velocity shows the clockwise turning movements while the negative value shows the counterclockwise turning movements. From Figure 3, we can conclude that the robot basically runs straight forward when the driving frequencies are below 220 Hz. In this range, the forward speed increases with the driving frequencies. When the driving frequencies are in the range of 230 Hz to 260 Hz, the robot turns counterclockwise, and the angular velocity increases with the driving frequencies. This indicates that the difference in the ground hitting frequency between the right and left legs has gradually reach the maximum so that the robot has the largest counterclockwise angular velocity. It is also noted that the forward moving velocity also increases and reaches about 7 cm/s a 270 Hz. When the driving frequencies are in the range of 280 Hz to 330 Hz, the ground hitting frequency of the right leg is higher than that of the left leg. The angular velocity is clockwise and reaches the largest value of 1.8 rad/s at 300 Hz. In the

![Figure 3: Experimental results of the forward velocity in cm/s (red) and turning speed in rad/s (blue) under different input frequencies. cm/s. Below 200 Hz, the moving direction is straightforward. At around 250 Hz, a high negative angular velocity is observed. At 300 Hz, a positive angular velocity is achieved.](image3.png)

![Figure 4: (A) The trajectory of the soft robot including the avoidance the obstacles on the ground. (B) The ethanol concentration mapping recorded on the path. (C) The recorded responses of the gas sensor versus time. (D) The real-time control frequency signals.](image4.png)
range above 330 Hz, the velocity dramatically decreases as the driving frequency increases. The reason is that the vibration amplitude usually attenuates in higher vibration modes in a mechanical system such that the reaction force from the ground is also reduced. Noticeably, the robot can achieve a straight speed of 7 cm/s at the driving frequency of 270 Hz, which suggests that there are the superposition effects between different moving directions.

By tuning the driving frequency, different moving directions of the robot can be achieved. In a prototype demonstration, the insect-scale robot is able to carry an onboard, 550 mg gas sensor (Sensirion, Inc.) to detect the gas concentrations along the moving path as shown in Figure 4a. Our robot can also avoid the randomly placed physical obstacles by only tuning the frequencies. The soft robot can record the ethanol concentration distribution with reasonable accuracy as shown in real-time as it travels (Figures 4b & 4c). The sequence of the control frequencies is shown in Figure 4d, indicating the straightforward, left-turn and right-turn locomotion under 120 Hz, 250 Hz, and 300 Hz of driving frequency, respectively.

CONCLUSIONS
This paper presents a miniature soft robot with its motions controlled by the driving frequency by means of the asymmetrical structural design. Simulation results obtained by the FEM method show that the asymmetric deformation of the robot can be induced by the asymmetric design of the body structure. Furthermore, the resulting asymmetric deformation can cause different ground hitting frequency which can affect the moving speed and direction of the robot. The simulation results are qualitatively verified by the experimental results as different motion trajectories are achieved under different input driving frequencies. Furthermore, a prototype robot has been demonstrated to avoid the ground obstacles and record the gas concentrations along the traveling path by carrying a commercial gas sensor on top. As such, the moving robot and the proposed motion control mechanism of the robot by the driving frequency have the potential for various applications such as identifying gases in a confined space.

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