PCB-BOT: THE FIRST STEPS OF A 4 MG LEGGED MICROROBOT

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ABSTRACT

The design, fabrication, and system integration of insect-scale robots are still significant challenges in the field of small-scale robotics. In this work, we present the 4 mg PCB-bot, the lightest legged microrobot actuated without an external field (e.g., magnetic field). The PCB-bot has 3D printed leg mechanisms directly integrated onto a flexible printed circuit board (FPCB). The 4.4 mm long PCB-bot has four legs which can be controlled to drive an inchworm-like crawling gait. The PCB-bot took its first steps and achieved a maximum velocity of 1.2 mm/s (0.27 body lengths per second) when powered by 250 V, 50 Hz square waves applied via wire tethers.

KEYWORDS

Microrobotics, 3D Printing, Two-Photon Polymerization

INTRODUCTION

Microrobots at the scale of small insects have great potential for search and rescue, surveillance, and inspection missions as they can easily access spaces where humans and larger-scale robots cannot go [1, 2]. However, creating small scale robots that can navigate and interact with complex 3D environments like their insect counterparts (e.g., ants, termites) is a significant challenge due to limited 3D fabrication and integration methods at the sub-millimeter scale. Although the recent advent of 3D printing at the microscale with two-photon polymerization (TPP) has enabled rapid prototyping of 3D actuated mechanisms [3] and microrobots [4], they still lack a capability to be integrated with essential electronic components for autonomous robots such as wires, batteries, and microcontrollers.

In this work, we demonstrate PCB-bot, a 4 mg legged microrobot fabricated by 3D printing with TPP on a flexible printed circuit board (FPCB). The robot has four legs that are driven by 3D torsional comb-drive actuators [5]. The actuators with legs are directly 3D printed on the FPCB followed by a subsequent metal sputtering process to achieve electrical conductivity. Since the robot body is the FPCB, electronic components can be easily integrated onto the robot. As a demonstration, the PCB-bot was directly soldered to copper wires to test tethered locomotion on its feet and took its first steps.

ROBOT DESIGN AND FABRICATION

A robot was designed with a flexible printed circuit board (FPCB) as the main body and four 3D printed electrostatic torsional actuators with legs. The isometric view of the robot is shown from the ventral side in Fig. 1(a). The design of the actuator which drives the legs is based on the 3D torsional comb-drive actuator in [5]. A false-colored SEM image of the actuator is shown in Fig. 1(b). The actuator consists of 3D round comb-drives with torsional springs at both ends of the moving comb. When voltage is applied to the actuator, the moving comb rotates around the torsional spring axis due to electrostatic force generated between the moving and static combs (Fig. 1(c)).

The robot moves forward by taking advantage of anisotropic friction of the angled feet; the feet are designed to slide forward on the ground while remaining fixed when moving in the opposite direction. The two sets of actuators at the front and the back of the robot are designed to rotate in opposite directions but the legs are angled in the same direction (Fig. 2). When the robot is actuated, an electrostatic torque swings the legs. The hind legs swing backward but the rear feet hold their position on the ground due to high friction. The fore legs swing forward and can slide on the surface (Fig. 2(b)). When the actuators are powered off, the torsional actuators return to their original position due to a spring torque at the hip. During this phase, the fore legs hold their position on the surface while the hind legs slide forward (Fig. 2(c)).

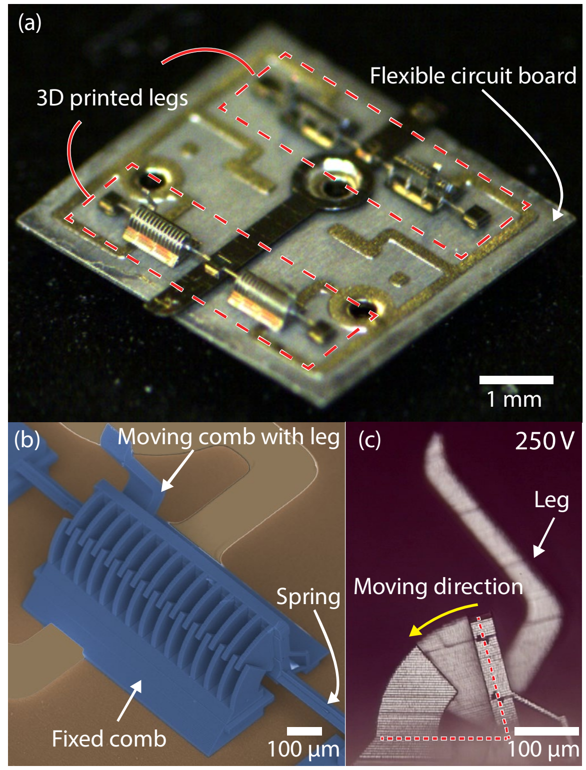

Figure 1: (a) The fabricated robot shown from the ventral side. (b) An SEM image of the actuator with a leg. The leg is directly 3D printed on the flexible printed circuit board. (c) The side view of the leg mechanism when actuated.

The robot was fabricated by directly 3D printing legs with actuators on a 100 µm thick double-sided FPCB (4.4 X 4.8 mm^2). The FPCB was cleaned and heat-pressed prior to printing to flatten the board. The FPCB was attached to a glass substrate using gel-like photoresist (IP-G, Nanoscribe GmbH) which successfully held the FPCB flat during printing. Desired 3D structures including the microactuators and legs were directly printed on the FPCB by TPP (Nanoscribe Photonic Professional GT +, Nanoscribe GmbH) with IP-S photoresist (Nanoscribe GmbH). The printed structures were developed in propylene glycol methyl ether acetate (PGMEA, Sigma-Aldrich) for 2.5 h and immersed in isopropyl alcohol (IPA, VWR) for 5 min. During this process, both IP-S and IP-G were developed, and the robot was released from the glass substrate. 60 nm of aluminum was sputter deposited over the robot (Perkin Elmer, 2400-8L) to add a conductive surface to the 3D printed actuators. Finally, 50 AWG copper wires (SP155, MWS Wire Industries) were hand-soldered to copper pads on the opposite side of the FPCB with solder paste (SMDLTLFP10T5, CHIPQUIK) to power the robot.

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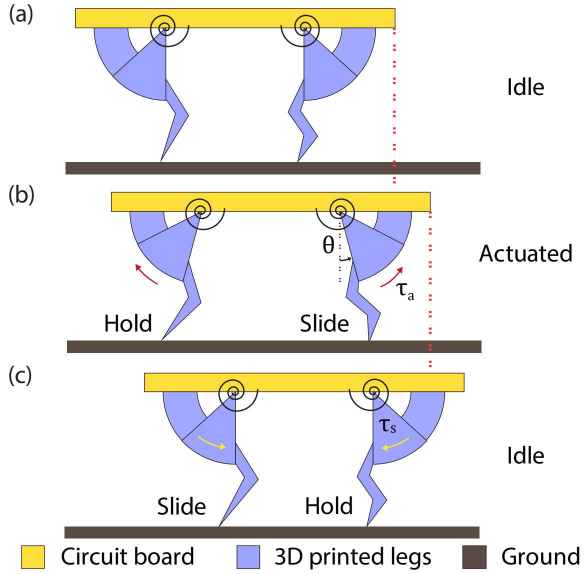

Figure 2: The working principle of the robot locomotion. The schematic of the robot is shown from the side view. (a) The robot in its idle state. (b) The robot in its actuated state. The actuation torque (τ_a) swings the legs and generates an angular displacement (θ). (c) The robot at its idle state. The spring torque (τ_s) at the hips swings the legs back to the original position.

RESULTS AND DISCUSSIONS

Both quasi-static and dynamic behavior of the legs are characterized as shown in Fig. 3. The error bars show the standard deviation between data points. We observe that the 3D comb drive's angular displacement is linearly proportional to V^2 as expected from the model in [5]. A maximum angular displacement of 9° was achieved at 250 V. In Fig. 3(b), the angular displacement of the actuator with varying frequency is plotted. The voltage was kept to 250 V. The frequency was swept from 1 Hz to 100 Hz. Although the angular displacement decreases as the frequency goes higher, the

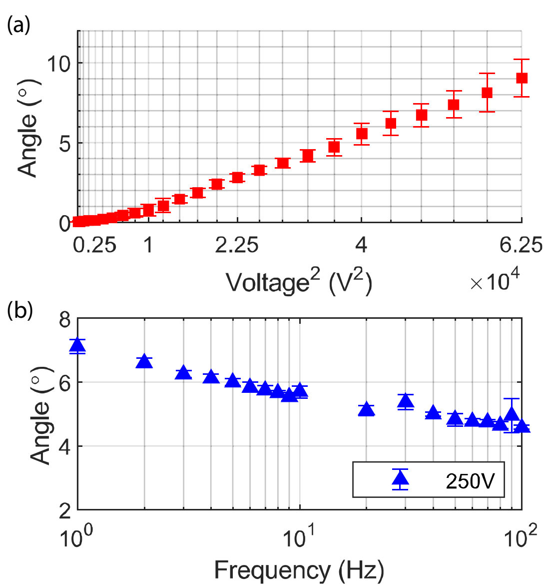

Figure 3: Actuator characterization results. (a) A quasi-static angular displacement of the actuator with varying voltage. (N = 9) (b) A dynamic characterization result with varying frequency. The applied voltage is fixed to 250 V. (N = 3)

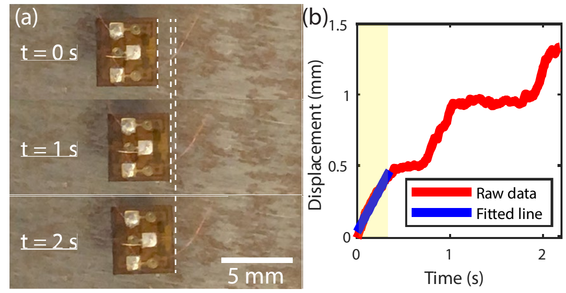

Figure 4: Walking robot characterization results. (a) Three sequential images with 1 s interval from the top view. The robot is shown from the dorsal side. The inset shows the waveform shape that is applied to the robot. (b) The displacement of the robot with respect to time. A linear function was fitted to calculate the velocity of the robot (1.2 mm/s).

actuator could stably generate displacement up to 100 Hz.

The 4.4 X 4.8 X 0.7 mm^3 tethered robot was placed on a flat acrylic plate and was connected to a power supply (2400, Keithley) which generated a 250 V square wave at 50 Hz. Three captured images taken at 1 s intervals clearly show that the tethered robot can take steps and move forward (Fig. 4(a)). From the video, the position of the robot was tracked and plotted in Fig. 4(b). Due to external forces applied to the robot from soldered copper wires and friction from the acrylic plate, the displacement of the robot was not linear. From the plot, the maximum velocity of the robot was fitted which was 1.2 mm/s, or 0.27 body lengths per second.

3D printing on FPCBs opens up significant design space for insect-scale robots. By taking advantage of extremely fast design and fabrication cycles with the capability to create complex 3D structures, the mobility of the robot can be improved. For example, the locomotion can be optimized for non-smooth terrain by adjusting foot geometries and leg movements. In addition, improved actuation torque can increase robot's payload capacity which then enables an integration of small, low-power controllers and power electronics with the FPCB framework to further increase robot autonomy.

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