NANOENERGETIC SILICON AS A THRUST ACTUATOR FOR JUMPING MICROROBOTS

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ABSTRACT

The first reported jumps of an untethered, sub-cm scale microrobot are reported. The microrobot weighs 300 mg, is 8 mm long, and uses nanoporous energetic silicon to create thrust for jumping. A polymer hexapod skeleton was used, with the energetic silicon chip placed on the underside of the skeleton facing down to provide upward thrust. Experiments were first conducted with off-board circuitry and power, and then the circuitry and power were integrated onto the robot to obtain fully autonomous untethered jumps. Tethered jump heights (with offboard power and control) are estimated at 40 cm, while a 6 cm maximum height was measured for untethered jumps (fully autonomous robot with on-board power and control).

INTRODUCTION

While microrobots have long been of interest, they are only recently becoming a reality. The majority of the work to date on small scale robotics consists of centimeter-scale systems assembled from conventional components. Crawling, flying, and jumping robots have been demonstrated on the centimeter scale [1-3]. Microfabricated crawling robots on the sub-cm scale have been demonstrated [4,5], but mobility remains a major challenge. Microfabricated actuators generally have very limited force or range of motion. While jumping is a common type of mobility in insects at these size scales, is a particularly difficult type of motion to achieve in MEMS because of the high power required for takeoff. The primary challenge is a high density energy storage mechanism which can release its energy on a millisecond timescale. Bergbreiter et al. proposed an elastomer to store energy as elastic strain in [6]. We propose energy storage in an energetic material which provides thrust when the energy is released through rapid combustion. The system can be designed with several discrete pockets of energetic material so multiple jumps can be taken over the course of a mission. We also provide an on-board sensor that provides intelligence, instructing the robot to jump when a specific change in the environment is sensed. This is the first time a sub-cm robot has been demonstrated with the intelligence to decide when to move based on a change in its environment.

MICROROBOT DESIGN AND CONSTRUCTION

Overall Design

While there are many definitions for microrobots, we stipulate that a microrobot requires these features at a minimum: a form/skeleton of some sort, a means for mobility, some level of intelligence or decision-making, and a power supply for the mobility and decision making. Our microrobot provides each of these aspects, and while its intelligence and mobility are certainly rudimentary, these can be improved with future iterations.

The overall design of the microrobot is pictured in Figure 1. The skeleton used in our design is a hexapod made from a polymer. While four legs would be sufficient for stability in a jumping-only platform, we elected to use 6 legs to allow for future integration of crawling-type actuation in an alternate-tripod gait. The polymer provides durability, flexibility, and low mass. In addition, electronic elements may be enclosed inside the polymer

Figure 1. Computer modeled rendering of jumping microrobot, with 1) photodefined polymer skeleton, 2) nanoporous energetic silicon thruster, and 3) control circuit including light sensor and power supply.

for protection in lieu of traditional packaging approaches that may add unnecessary mass.

The mobility is provided by a nanoporous energetic silicon microthruster. This material is attractive because it can be initiated at low voltage and energy levels (as low as 3 V, 0.25 mJ [7,8]) compatible with the limited power supply available on a small robotic platform. It can also be batch-fabricated in very precise, controllable quantities as small as 100 µg using MEMS fabrication processes. Upon initiation, the material burns and gas is produced, which is ejected from the chip to produce thrust.

Because of power, size and weight considerations, we took the approach of providing the most basic level of intelligence in this first iteration of the jumping microrobot. This consists of a sensor that, upon detecting a specific environmental change, outputs a signal to tell the energetic thruster to initiate and cause the robot to jump.

Skeleton

A UV-cure polymer process for rapid prototyping [9] was used to create the microrobot platform shown in Figure 2. The process uses photolithography and Loctite® photopatternable adhesives. For this platform, Loctite® 3525, an acrylic, was deposited on a transparency substrate between microscope slides to achieve the desired thickness. The polymer was then patterned in plane using an ink-jet printed mask and a hand held UV lamp (Spectroline®, EN-180, 365nm).

After curing, the mask was removed and excess polymer was washed away with acetone. At this point, the robot was released from the substrate and an additional thin layer of polymer was coated on the underside of the robot. The legs were then manually folded out of plane and constrained in this position before the robot was again exposed to the UV light for additional curing. After

Figure 2. Polymer hexapod microrobot skeleton, with dummy embedded microcontroller.

removing the constraints, the robot had assumed this new form. This resulted in the three dimensional robot skeleton used in this work.

Nanoporous Energetic Silicon Microthruster

The nanoporous silicon energetic chip is created in a $\langle 100 \rangle$ p-type silicon wafer via an electrochemical etching process in hydrofluoric acid and ethanol described in detail in [7]. The desired porous silicon regions are defined using an LPCVD silicon nitride as a masking layer, and an integrated thin-film Cr/Pt/Au resistor is deposited on top of the porous silicon to provide a low-power initiator. The pores are filled with oxidizer by dissolving sodium perchlorate (NaClO_4) in methanol and applying a drop to the porous silicon surface with a syringe [10]. Capillary forces pull the solution into the pores, and the sodium perchlorate precipitates onto the surface of the pores as the methanol evaporates away. This leaves a very densely packed mixture of silicon (which acts as the fuel) and an oxidizer. The energetic reaction can be initiated by rapidly heating to 225°C , achieved via joule heating of the integrated resistive initiator. The reaction produces water vapor due to hydrogen surface termination of the nanoporous silicon [11]. While nanoporous energetic silicon is not an ideal propellant, the volume of gas produced per gram of energetic is larger than that for black powder. This evolved gas is the mechanism for thrust generation.

The porous silicon chip was attached to the underside of the microrobot skeleton with double-sided tape, with the active side facing away from the hexapod body, as shown in Figure 3. No confinement cavity or expansion nozzle was used for this initial version of the microrobot. Electrical connections between the initiator and the off-board DC power supply or the on-board control circuit were made by wirebonding with 5 mil or 12 mil diameter aluminum wire.

Control Circuit and Power Supply

The control circuit was designed using discrete, surface-mount parts. Integration of the electronic controls for sensing and actuation is limited to a $8\text{ mm} \times 5\text{ mm}$ area, since this is the overall footprint of the microrobot. The control circuit is shown schematically in Figure 4. To minimize size and weight, we kept the number of parts to a bare minimum of only 5 parts. Together the $100\text{ }\mu\text{F}$ and $10\text{ }\mu\text{F}$ capacitors comprise the power supply for the microrobot, the SFH3710 phototransistor provides sensing, and the 2N7002 n-channel enhancement mode field effect transistor (FET) provides the logic. The $10\text{ k}\Omega$ resistor ensures the bias applied from the phototransistor is high enough to open the FET gate. The

Figure 3. Nanoporous silicon microthruster positioned on underside of microrobot.

Figure 4. Schematic of control circuit, which supplies power, sensing, and logic to microrobot.

circuit is assembled by attaching the parts with solder onto pre-patterned gold traces on a silicon chip. A picture of the assembled circuit connected with wirebonds to the porous silicon chip and attached to the top of the microrobot is shown in Figure 5.

When charged to 5 V , the $100\text{ }\mu\text{F}$ capacitor provides the operating voltage to power the phototransistor. The spectral sensitivity of the phototransistor is $350\text{--}950\text{ nm}$, with a maximum sensitivity wavelength of 570 nm . When the phototransistor senses light in this range, the 5 V from the $100\text{ }\mu\text{F}$ capacitor is also applied to the gate of the FET. At this 5 V gate-source voltage, the source-drain resistance of the FET is on the order of $15\text{ }\Omega$. This causes the $10\text{ }\mu\text{F}$ capacitor (also charged to 5 V) to discharge through the initiator (pictured in Figure 4 as a $3\text{ }\Omega$ resistor).

RESULTS

Tethered Jumps

The nanoporous silicon energetic was patterned in a 2 mm diameter active area for these experiments. For the tethered jumps, the control circuit was not included on the back of the robot. The wirebonding wires were bonded to the initiator on the silicon chip, then clipped about 6 inches long and the ends left hanging. These wires were connected to a DC power supply. Initiation was achieved by turning on the power supply to 3 V . The total weight

Figure 5. Picture of assembled control circuit, a) attached to porous silicon chip with wirebonds, and b) assembled onto top of microrobot.

of the robot with energetic silicon chip and the electrical leads in this configuration was 100 mg.

Two tethered jumps were made, one with a 40 μ m deep porous layer and 12-mil wires to supply power, the second with a 60 μ m deep porous layer and 5-mil wires. The depth of the porous silicon corresponds roughly to the volume of the energetic material. The resulting jumps were captured using a high speed camera recording at 1000 frames per second (Figure 6). A scale with 1-cm gradations was positioned behind the launch platform to allow measurement of the vertical position. A simple MATLAB routine was used to analyze each frame and record the position of the microrobot with the user pointing and clicking at the approximate location of the microrobot. The routine stores the pixel locations selected for each

Figure 6. Images from high speed video for jump with 12-mil wire tethers. Images are spaced 10 frames (10ms) apart. A piece of the nanoporous silicon chip that detached from the robot can be seen in frames 1-3.

frame. The same procedure was used to determine the conversion factor from pixels to centimeters. There were 46 pixels/cm in one video and 38 pixels/cm in the other. Therefore, the precision of the measurement is much better than 1 cm. The error in position is estimated at 5 pixels, around 0.1 cm.

The trajectory for both jumps is plotted in Figure 7. The first jump used 12-mil wire to supply DC power to the initiator to ignite the porous silicon, but the wire was too stiff and constrained the motion to a maximum height of 10cm. The experiment was repeated with 5-mil wire and the starting trajectory was similar, but the robot continued upwards out of the ~11cm field of view. If drag effects are neglected and the initial velocity of approximately 2.8m/s is used, the projectile motion equation predicts a maximum height of 40cm, which is 50 times larger than the maximum dimension of the robot (8mm long x 4.7mm high x 5mm wide). If a drag coefficient of 1 is used, the maximum projected height is 36.6cm. The robot did land on its feet in both experiments, although it is unclear if this was due to the location of the center of mass, the stiffness of the wires, or pure chance.

Figure 7. Trajectory for each of two jumps, along with the projected unconstrained trajectory for the 5-mil wire jump with and without drag.

As noted above, we did not include a confinement chamber or expansion nozzle for this initial demonstration. Therefore the efficiency of the chemical to kinetic energy conversion is expected to be very low. Based on bomb calorimetry measurements, the energy density of our nanoporous silicon energetic material has been reported as 5.74 kJ/g [7]. The estimated mass of the energetic material in our jumping experiments is 150-200 μ g, for a net chemical energy content of 0.86-1.1 J. For the test with 5-mil tether wires, the total mass of the microrobot was 99.5mg and the takeoff velocity approximately 2.8 m/s. The kinetic energy is therefore 0.39 mJ, for a chemical to mechanical conversion efficiency of less than 0.01%. Microthrusters made by Rossi et al [12] with and without chambers and expansion nozzles showed up to a 100x increase in force generated when the chamber and nozzle were added, so there is room for vastly improved performance.

Untethered Jump

The full circuit was attached to the top of the microrobot with double-sided tape for untethered experiments. The nanoporous energetic silicon was attached to the underside of the microrobot in the same manner, with 5-mil aluminum wirebonding wire connecting the circuit to the energetic silicon chip (see Figure 1

and Figure 5). The mass including the circuit was 300 mg, with the 100 μ F capacitor accounting for almost half of the total mass (see Table 1).

Table 1. Mass breakdown of microrobot by component. Note the 100 μ F capacitor is by far the largest piece of the overall mass.

Component	Mass (mg)
Si substrate	74
10 μ F capacitor	8.7
100 μ F capacitor	131.3
2N7002 FET	8.4
SFH3710	3.3
10k Ω resistor	4.5
Hexapod	69.8
Total Mass	300

The untethered experiments were set up and the capacitors charged in a darkened room to prevent the phototransistor from triggering. Once charged, the jumps were triggered by turning on a set of 3 high-intensity LEDs, which also provided the light source for the high speed video capture of the jump.

The first successful untethered jump is shown in Figure 8, with a maximum height of 6 cm achieved. The expected jump height based on the estimated 40 cm from the tethered experiments is approximately 13 cm given the 3x increase in mass. One possible reason for the lower than expected jump height is that the microrobot flipped end-over-end at about 29 revolutions per second during the jump. This is primarily due to the massive 100 μ F capacitor positioned at the extreme end of the microrobot (see Figure 1), so the thrust was not directed through the overall center of mass. Using rough estimates for rotation axis and moment of inertia, the rotational energy calculated from the video only accounts for about 15% of the total energy, however. Variations in the nanoporous silicon properties or oxidizer deposition may account for the additional 30% discrepancy.

Figure 8. Sequence of frames from high speed video of second untethered jump. Interval between depicted frames is 5 ms, with dashed line indicating an omitted interval of 60 ms. The final pictured frame shows the maximum height achieved (~6 cm).

CONCLUSION

We have presented the first sub-cm scale jumping microrobot, using nanoporous energetic silicon as a thrust actuator. The maximum untethered jump height was 6 cm, over 7 times the body

length. Tethered experiments suggest that even larger jumps should be possible. Jumping is a promising new mode of mobility for microrobots, and nanoporous energetic materials provide a convenient mechanism for achieving large jumps with minimal input energy. The jump performance may be improved in future iterations through integration of confinement and expansion nozzles into the microthruster, and the circuit and actuators can be expanded to allow for multiple jumps.

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