FIRST LEAPS OF AN ELECTROSTATIC INCHWORM MOTOR-DRIVEN JUMPING MICROROBOT

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ABSTRACT

Here is presented the first MEMS microrobot capable of using onboard motors to store enough mechanical energy to jump. This 43 mg microrobot achieves this by utilizing an inchworm-of-inchworms motor topology, which allows the force from a standard electrostatic inchworm motor to be amplified by a factor of 10 while increasing its areal force density. An off-chip microcontroller has successfully run this motor through 14 steps, deflecting the main shuttle 560 µm and storing over 1 µJ of energy. The microrobot has jumped 1 mm using energy stored by its motors, and 6.5 mm when its springs were loaded externally.

INTRODUCTION

Researchers have been excited by the idea of creating, controlling, and manipulating objects at small scales since the mid-1900s [1]. From these early ideas evolved the dream of creating a fleet of tiny mobile robots that could operate autonomously, sense their surroundings, and communicate to accomplish group tasks. Today, these microrobots could be used in manufacturing, search and rescue, and medicine. However, as with many technological advances, their true niche may not be discovered until after their development. Even when microrobots were first proposed in the early 1980s, their development was likened to that of the computer and the hard-to-foresee creation of the video game market [2].

Although microrobots have been actively researched for decades, many challenges to their fundamental operation remain unsolved. Among these challenges is the basic ability to locomote. Researchers have had varying degrees of success creating walking, jumping, flying, and swimming microrobots. While all locomotion modalities have certain benefits and drawbacks, this work focuses on jumping microrobots. Jumping offers the ability to maneuver over obstacles many times the size of the microrobot which will be a crucial ability when navigating through most environments.

Although jumping microrobots have been built at many size scales, this work focuses on microrobots at the millimeter scale. At this scale it is common to store energy either chemically or mechanically and release that stored energy over a short period of time. Churaman et al. [3] designed a 4x4 mm^2 microrobot from silicon and an elastomer that could jump 32 cm into the air. The elastomer was chosen to mimic the protein that insects use to jump. This microrobot could jump many times, but had no motors on board, so it was primed and launched manually with tweezers. In the same paper, Churaman describes a jumping microrobot that is driven chemically. It used porous silicon infused with sodium perchlorate as its energy storage mechanism. When a light was shined on this microrobot, its onboard electronics would trigger the ignition of the sodium perchlorate and the microrobot jumped 8cm into the air. This microrobot, while not requiring any assistance to store energy, can only take a single jump.

The work described here is the first step towards creating an autonomous jumping microrobot capable of jumping 10s of centimeters at a rate of multiple times per minute. The microrobot uses large serpentine springs to store the mechanical energy used for the jump. These springs are loaded slowly over time using two electrostatic inchworm motors in tandem. In its current form, the microrobot is tethered with wires to provide power and control, however the long-term goal is to use a multi-chip solution. There will be a chip with high voltage relays and solar cells for power, as well as a custom CMOS chip with a microprocessor and radio [5] for the control and communication. Each chip will be connected through a MEMS zero insertion force socket [4].

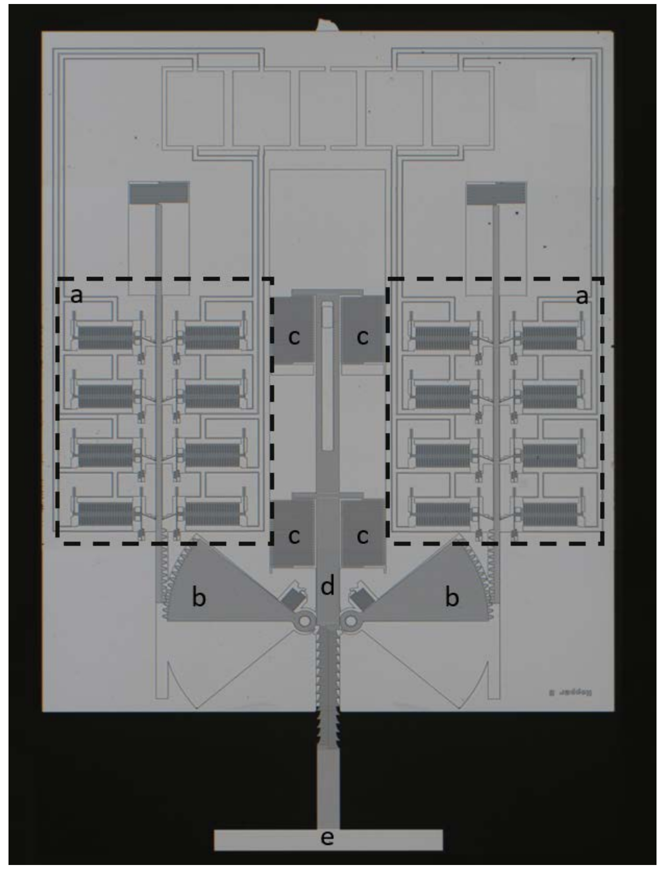

Figure 1: The 5.0 x 6.4 mm^2 jumping microrobot. (a) Electrostatic inchworm motors. (b) Pinions. (c) Energy storing serpentine springs. (d) Main shuttle. (e) Foot.

MICROROBOT OVERVIEW

The individual components required to create a fully autonomous jumping microrobot have been around for well over a decade, however no such microrobot has been developed. The integration of the motors, mechanisms, control, power, and energy storage has proven to be a challenging road block. This integration problem was a main driving force in many of the design choices for this jumping microrobot.

The entire microrobot is microfabricated using a two-mask silicon-on-insulator (SOI) process. This process is relatively simple to run in an academic cleanroom and exists as a standard process in industry, which would allow these microrobots to be made in large volumes. More importantly, this process allows for the creation of

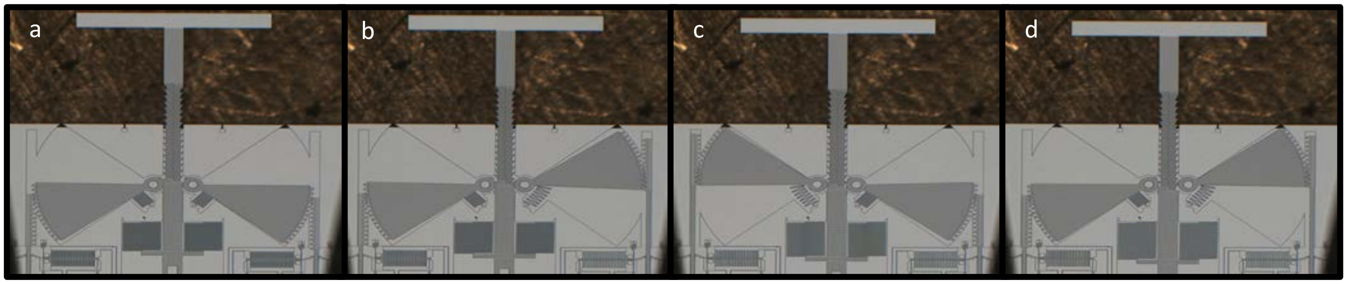

Figure 2: The inchworm of inchworms taking three macro steps. a) the jumping microrobot as fabricated, b) the right-side inchworm shuttle engages with the pinion and moves main shuttle 40 µm, c) the left-side inchworm shuttle engages with the pinion and moves the main shuttle 40 µm, allowing the right-side pinion to release, d) the process continues until the main shuttle is fully deflected. The foot is 2 mm long.

a wide variety of structures. Silicon is a versatile material that can be machined into a sensor, motor, and energy storage element all within the same process. So, where other jumping microrobots have required manual assembly of the energy storage materials [6], this process allows for the energy storage mechanisms to be fabricated next to the motors that will drive them. Figure 1 shows the jumping microrobot chip and its salient components.

ENERGY STORAGE

Mechanical energy storage is core to the operation of this microrobot. The more mechanical energy that can be stored, the higher the microrobot can jump and the more maneuverable it will be. When storing mechanical energy in a material, the maximum energy stored can be written as follows:

$$U_{max} = \frac{1}{2} AlE\epsilon_{max}^2 \quad (1)$$

Where *A* is the cross-sectional area, *l* is the length, *E* is the Young's Modulus, and ϵ_{max} is the maximum strain that the material can undergo before fracturing. The reported fracture strain of silicon ranges from 0.6% to 6.0% [7]. These microrobots were designed with a fracture strain of 0.8%.

As Churaman showed [3], the height that a jumping microrobot can achieve is related to the energy it stores by the following equation:

$$h = \frac{m_{robot}}{C_d A_{robot} \rho_{air}} ln\left(1 + \frac{C_d A_{robot} \rho_{air}}{m_{robot}^2 g} U_{stored}\right) \quad (2)$$

Here, *h* is the achieved height, *m* is the robot mass, *A* is the cross-sectional area of the robot, C_d is the drag coefficient, ρ is the density of air, *g* is the gravitational constant, and *U* is the initial stored energy. For the microrobot presented here, the mass is 43 mg, the cross-sectional area is 2.8 mm^2, and a value of 1.5 is used for C_d. To achieve a jump height of 10 mm, a microrobot of this size would theoretically need to store 4.3 µJ of mechanical energy and successfully convert all that mechanical energy into potential energy. This corresponds to only 0.004 % of the total volume of the microrobot needing to be strained to this limit of 0.8%. If even one tenth of a percent of the total microrobot volume is strained to this strain limit, it would be able to jump over 20 cm.

When designing this microrobot, a decision had to be made on the nature of the energy storage elements. A previously developed energy storage device, the MEMS Hammer, used beams in axial tension. This maximizes the stored energy in a given area by operating the beams in the cubic region of their force deflection curves [11]. Although this is an attractive option from an energy storage standpoint, the nonlinear nature of these beams requires much larger forces than those required for a linear serpentine spring to store the same amount of energy. Therefore, the energy storage

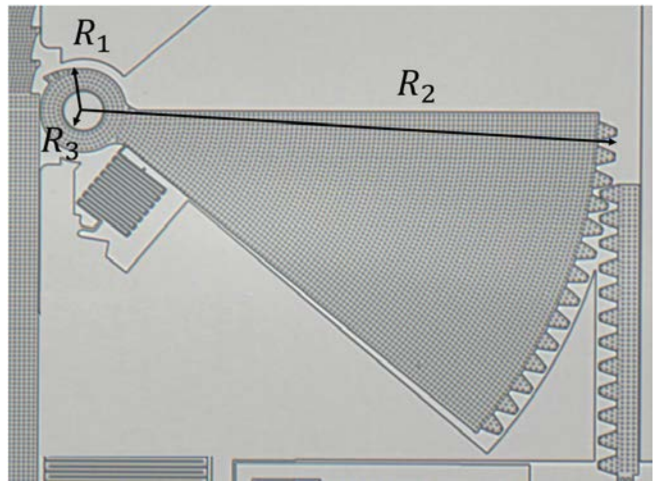

Figure 3: The pinion responsible for transferring and amplifying the force from the inchworm shuttle (rack) to the main shuttle. The latch on the pinion interfaces with the cutout holds on the main shuttle. The mechanical gain is roughly R2/R1. R2 is 1200 µm.

elements on this microrobot are four serpentine springs found in the center of the device, shown in Figure 1. These springs have a theoretical spring constant given by:

$$k = \frac{Ew^3 t}{NL^3} \quad (3)$$

Here *w*, *L*, and *t* are the width, length, and thickness of the beams respectively, E is the Young's modulus of silicon, and *N* is the total number of beams in the serpentine structure. For this design, the beam width is 10 µm, length is 369 µm, thickness is 40 µm, and the number of beams per serpentine spring is 50. This gives a theoretical spring constant of 2.68 N/m per serpentine spring, and a total stiffness of 10.7 N/m for the whole structure. The spring constant is related to the energy stored in the spring by the following equation:

$$U_{stored} = \frac{1}{2} k\Delta x^2 \quad (3)$$

The deflection of these springs is variable, and will be discussed later, but the maximum possible deflection is 1120 µm. This gives a total theoretical stored energy of 6.5 µJ and a theoretical jump height of 15 mm. In order to store this energy, a force of 11.8 mN needs to be applied to the springs.

The spring constant of these serpentine springs was measured with a Dage 4000 Multipurpose Bondtester. The spring constant per serpentine spring was measured to be 1.62 ± 0.22 N/m. This leads to a total stored energy of 4.0 µJ, a maximum spring force of 7.1

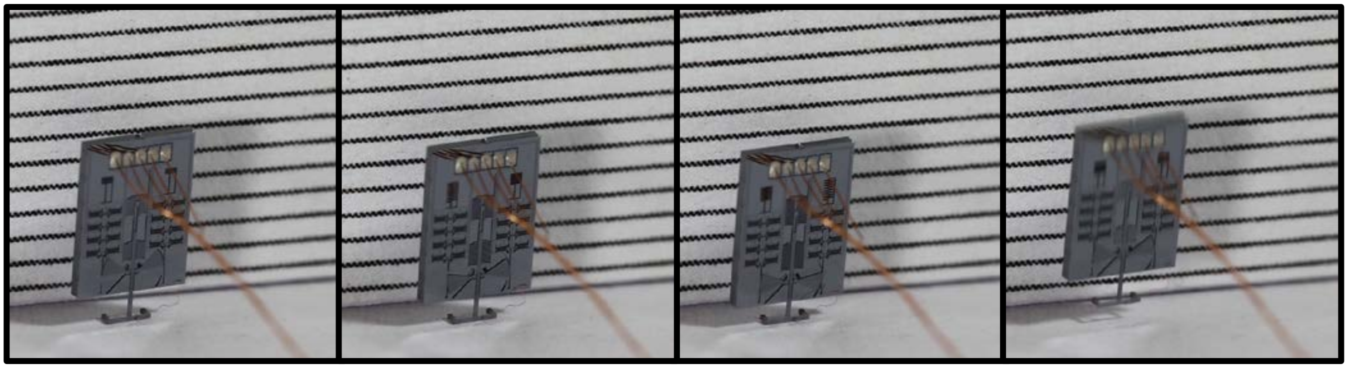

Figure 4: Stills from a 60-fps video of the jumping microrobot taking its first self-powered leap. It took 14 macro steps, storing 1.05 uJ of mechanical energy, before releasing that stored energy and jumping 1 mm. The line spacing is 1 mm.

mN, and a maximum jump height of 9.4 mm. The discrepancy between the measured and theoretical value is likely due to the rotational degree of freedom at the intersection between each beam and the perpendicular truss that connects it to the next beam. When the beams rotate like this, their strain is reduced which causes the spring constant of the entire structure to be lower than expected.

HIGH-FORCE INCHROWM MOTORS

For a jumping microrobot to be autonomous it must have a means of actively loading its energy storage elements. The electrostatic inchworm motor is an active area of research [8] and an ideal motor for an SOI process. These motors run at voltages ranging from 60–120 V and can apply forces on the order of a few millinewtons over a distance of 1 mm. A common figure of merit for an inchworm motor is the areal force density given in millinewtons per square millimeter. These values are, in the best case, between 1 and 2 mN/mm^2 for electrostatic inchworm motors running at 100 V. Additionally the maximum forces reported by electrostatic inchworm motors are typically under 2 mN [10]. The required forces to load this microrobot are well-above these values, so a new motor topology was designed and implemented.

The basic building block of an electrostatic inchworm motor is the gap closing actuator (GCA) array. This array can apply large electrostatic forces over distances of a few microns. By combining multiple correctly phased GCAs with a central shuttle, the electrostatic inchworm motor can apply this large force over a much longer distance. In this work, the entire inchworm motor is used as the basic building block for a motor, hereafter referred to as an inchworm-of-inchworms (IoI).

The IoI can be seen in operation in Figure 2. The images in this figure were taken at a probe station with the microrobot on its back. To begin loading the main shuttle, the inchworm motor on the right side of the microrobot takes 450 micro steps of 2 µm, which advances the rack by 900 µm. As the rack moves, it rotates the pinion by 80 degrees, moving the latch (shown on the top left side of the pinion in Figure 3) by 90 µm. During the end of this deflection, the latch engages with the main shuttle and deflects it 40 µm, defining a macro step. The latch holds on the main shuttle have a pitch of 80 µm and are offset by 40 µm on the left side versus the right side.

From here the right-side inchworm motor engages and holds its GCAs to keep the main shuttle in place while the left-side inchworm motor starts to actuate. After 180 micro steps of the left-side inchworm motor, the left-side pinion has just engaged with the main shuttle, the right-side inchworm motor GCAs release and the restoring spring snaps the right-side shuttle to its original location. The left-side inchworm motor continues to take an additional 270 micro steps, bringing the microrobot into the state shown in Figure 2c. The two pinions can take up to 28 macro steps of 40 µm each to generate a total main shuttle displacement of 1120 µm. The main shuttle spring energy is released when both inchworm motors disengage all their GCAs.

Electrostatic inchworm motors are attractive for their ease of integration and low power operation. The motors take micro steps at a rate of 80 hz and operate at 100 V. The total capacitance that must be driven during each micro step is 21 pF, which corresponds to an energy of 0.21 µJ per micro step. The energy required per macro step is then 94.5 µJ. If all 28 macro steps are taken, 2646 µJ of electrical input energy are required to store 4.0 µJ of mechanical energy. Currently it takes the microrobot 5.6 seconds for each macro step, meaning it can jump once every 2.5 minutes. These electrostatic inchworm motors have been shown to move at speeds up to 3.4 cm/s [9], which could theoretically lead to a jump rate of 1.3 jumps per second!

This IoI topology is advantageous because it allows the force from the inchworm motor to be amplified when it gets to the main shuttle. Figure 3 shows a detailed view of the pinion. When the inchworm motor shuttle applies a force at the right side of the pinion, it applies a moment, which in turn must be balanced by the moment applied by the R_1 lever and the main shuttle. This effectively amplifies the inchworm motor force by a factor of R_2/R_1. The serpentine spring that attaches the pinion to the field SOI decreases this amplification factor by less than 1%. R_2 and R_1 in this design are 1200 µm and 120 µm respectively so the mechanical gain we calculate for is 10. R_3 is bounded by the shear limit of the buried oxide that anchors the central pin to the substrate. Previous work has shown the fracture stress of this oxide is 54 MPa [11], so R_3 was chosen to be 47 µm to ensure this anchor remains fixed to the substrate.

The inchworm motors were measured to have a force density of 0.83 mN/mm^2 on their own, with no mechanical gain. Sizing this pinion correctly can greatly increase this areal force density. The theoretical force density with the mechanical gain stage is 6.1 mN/mm^2 but has yet to be experimentally verified.

TESTING AND RESULTS

It is complicated to test a mobile (non-autonomous) MEMS device because power and control are typically provided through probes under a microscope. Here, the power and control are provided through 60 µm copper wires that are bonded to the microrobot using a conductive epoxy. These wires, while allowing the microrobot to move, are exceedingly difficult to deal with due to their relatively large stiffness (~10 N/m). Braiding the wires together and removing any kinks before bonding proved critical to keeping the microrobot from being pulled around by the wires.

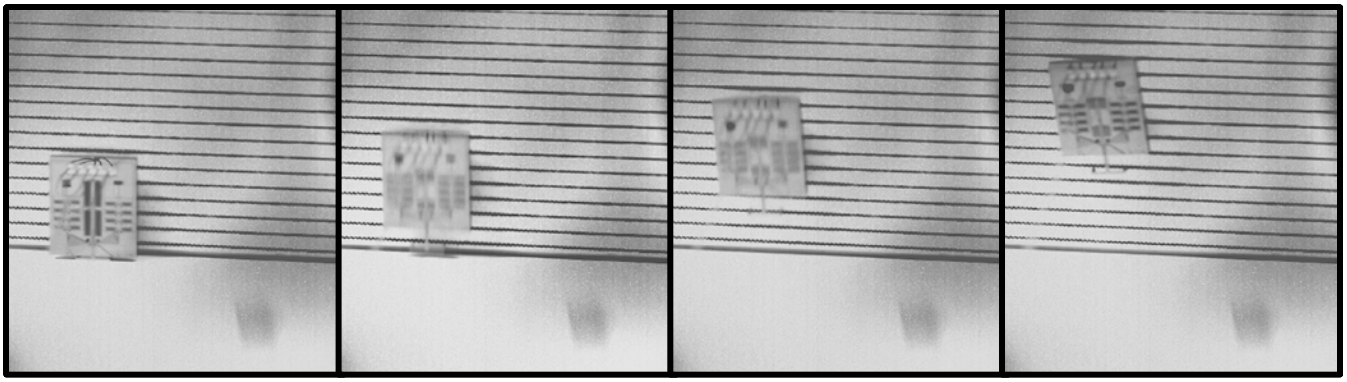

Figure 5: Stills from a 500-fps video of the jumping microrobot taking its largest leap to date, 6.5 mm. The robot leg was manually depressed but held in place by the GCAs. The microrobot jumped when the GCA voltage was released. The line spacing is 1 mm.

Once the microrobot was wired up, it was stood up on its foot with tweezers. The stills in Figure 4 show that there are small pieces of substrate silicon attached to the back of the foot. These protrusions allow the microrobot to stand up even when there are no wires bonded to it. The braided copper wires are taped down to the table to limit the torque applied to the microrobot during testing. Two different tests were performed. In the first test, the microrobot was only allowed to use its IoI to store mechanical energy. The result of this test is shown in Figure 4. The microrobot took 14 macro steps and eventually jumped 1 mm. The pinions sometimes had trouble resetting to their original positions, which limited the total number of macro steps to 14. It seems that something during the epoxy curing process led to an increase in stiction between the pinion and the substrate. In the second test, the serpentine springs were loaded manually with a probe tip. Once fully deflected, one side of the IoI was actuated to lock the main shuttle in place. When a button on the microcontroller was pressed, the IoI would release the main shuttle and the microrobot jumped. The results of this test are shown in Figure 5. The microrobot, while theoretically capable of jumping 9.4 mm only reaches a height of 6.5 mm. These loses can be due to several things including friction in the mechanisms, stiffness from the copper wires, and loses in the silicon springs themselves.

MATLAB MICROROBOT LIBRARY

The layout for this microrobot was generated entirely using a MATLAB library developed by the Pister group. This library contains high level functions that range in complexity from creating a circle, to a motor, to a full jumping microrobot. The repository can be found at the end of this paper under the contact information.

CONCLUSION AND FUTURE WORK

A jumping microrobot capable of storing and releasing mechanical energy was designed, fabricated, and tested. The IoI was the enabling advancement that made this microrobot possible by amplifying the force output of a standard inchworm motor. In the future, the stored energy and therefore the output force of the IoI will need to be increased to reach jump heights of 10s of cm. This can be accomplished in part by moving the energy storage components to the substrate layer. This would be beneficial because wider and thus more energy dense springs can be fabricated in the substrate. Additionally, this move makes more device side area available to be used as additional motor area. To create a truly autonomous microrobot, the copper wires that proved power and control must be eliminated. Using onboard solar cells and high voltage relays for power, and a bare die microcontroller and radio chip, the dream of an autonomous army of jumping microrobots could become a reality.

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https://github.com/pinxisimitu/MEMS_Microrobot_Library