Mechanisms for Jumping Microrobots

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***Abstract*—This paper presents two mechanisms to enable jumping microrobots. These small jumpers must store considerable mechanical energy and quickly release it. The first mechanism presented is a mechanical gain stage capable of amplifying the force generated by a standard inchworm motor by at least 10 times. This mechanism could be used with any style of inchworm motor. Secondly, a latching mechanism was designed and fabricated so that the microrobot could store its energy and remain in a high energy state for an arbitrarily long period of time. Finally, a prototype jumping microrobot was fabricated that includes this latching mechanism.**

I. Introduction

Microrobotics has been an active area of research in the MEMS community for decades. The dream of having an army of wirelessly enabled bug-like creatures that can cooperate to accomplish tasks is appealing for a variety of applications. While many researchers have been successful in designing and fabricating various microrobots, challenges to their fundamental operation still remain. One of the most pressing of which is developing efficient means of locomotion.

Jumping offers a promising solution to getting microrobots from place to place. Not only does it allow them to navigate over obstacles many times their size, but it can do so efficiently. Efficient locomotion is especially important when developing a truly autonomous microrobot due to the power limitations. An autonomous microrobot must either store its power on board or scavenge from its surroundings. Either requires all microrobot subsystems to operate at the lowest power possible.

Researchers study jumping robots at many different size scales. On the larger end of that spectrum, Haldane et al. [1] have created a 1 foot tall fully autonomous robot with the ability to hop across complicated terrain and jump off walls to increase its maximum achievable height. The design was inspired by one of nature's best jumpers, the galago. At smaller size scales researchers also look to biology for ideas. Churaman et al. [2] 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.

Due to the physical limitations of jumping at small size scales, much of the work in jumping microrobts has focused on the storage and rapid release of mechanical energy. This modality requires forces that are often greater than the capability of the motors and actuators that are commonly microfabricated [3]. In this work, we present a mechanism for amplifying the force from a traditional electrostatic inchworm motor to enable the energy storage required for jumping microrobots. Additionally, a mechanism is proposed to allow for the quick release of this stored energy.

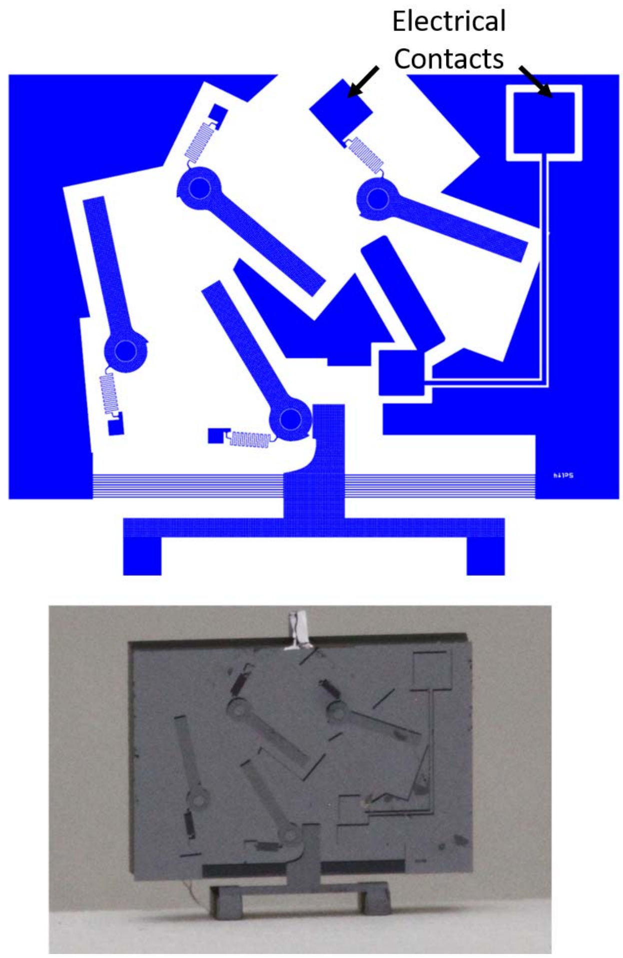

Fig. 1. A prototype jumping microrobot in layout (top) and as fabricated (bottom). The chip is 4x3 mm^2.

II. Jumping Mechanics

Nature provides numerous and varied examples of jumpers at small size scales. While some continuously hop from place to place constantly loading and unloading their legs, others use their ability to jump more sparingly such as a flea escaping a

Material	E [Pa]	Maximum Strain [%]	Energy Density [mJ/mm^3]
Silicon	1.69x10^{11}	1.0	8.5
PDMS	7.5x10^5	293	3.4
Polyurethane	7.6x10^6	500	95
Resilin	2.0x10^6	190	4

TABLE I
MECHANICAL PROPERTIES OF ENERGY STORAGE MATERIALS [3], [4], [5].

predator. Constant hopping, which has been implemented in larger scale robots [1], requires more complicated control than the occasional jump. Thus, the later is the focus of this work.

To accelerate the robot upwards, the jumping mechanism can be designed like a motor or as an energy storage and release mechanism. To determine which to use, the physics of the system must be considered. The following equation relates the time the actuator must actively accelerate the robot with the desired initial velocity of the microrobot.

$$t_{acc} = \frac{2l_{leg}}{v_i} \tag{1}$$

Additionally, it was shown in [2] that the height a jumper will reach is related to its initial velocity by the following equation:

$$h = \frac{m_{robot}}{C_d A_{robot}\rho_{air}} ln\Big(1 + \frac{C_d A_{robot}\rho_{air}}{2m_{robot}g}v_i^2\Big) \tag{2}$$

In Equation 2, h is the final height of the robot, m_{robot} is the mass of the robot, C_d is the drag coefficient, A_{robot} is the frontal area of the robot, ρ_{air} is the density of air, g is gravity, and v_i is the initial velocity of the robot. Assuming the robot weighs 10 mg, and must clear an obstacle of 10 cm, it must have an initial velocity of 1 m/s. Using Equation 1 with an initial velocity of 1 m/s and a leg length of 1 mm yields an acceleration time of less than 10 ms [3]. Designing and fabricating a motor capable of this speed and power is exceedingly difficult. This leads jumping microrobot designers to use mechanical and chemical energy storage systems in place of motor-like actuators.

III. MECHANICAL ENERGY STORAGE

Mechanical energy storage is an attractive option for jumping microrobots because the energy can be stored over a long period of time and released quickly. This allows for the use of microfabricated motors which cannot operate on the timescales required to accelerate the microrobot body directly. The first challenge is to choose a material in which to store the mechanical energy.

A. Selecting a Material

When selecting an energy storage material, important things to consider are ease of process integration, maximum deflection, maximum force, and energy density. Additionally, the mechanical properties of the material should be well matched to the output characteristics of the motor. The maximum energy that can be stored in a beam can be written as:

$$U_{max} = \frac{1}{2}AlE\epsilon_{max}^2 \tag{3}$$

Where A is the beam cross-sectional area, l is the beam length, E is the Young's Modulus, and ϵ_{max} is the maximum strain before fracture. Using Equation 3, table I was generated to show the mechanical properties of various materials. The fracture strain for silicon varies in the literature from 0.6% all the way up to 6.0% [5]. Here we use a value of 1.0% strain, which is consistent with previous work [6]. This table helps enlighten the design choices available for energy storage mechanisms. Resilin, the bio-material that fleas use to store mechanical energy, is given for reference. Polyurethane is the clear choice to maximize energy density. However, integrating this material into a process is difficult. This leaves PDMS and silicon. PDMS is advantageous because of its high maximum strain. PDMS beams can operate comfortably below their fracture strain and still displace a significant amount. Silicon beams on the other hand must operate very close to their fracture limit to achieve a usable displacement. Integrating PDMS into a standard silicon process has been done successfully for the creation of jumping microrobots [2], however it is a non-standard processing step and requires development. In this work, silicon was chosen as the energy storage material for its high energy density and ease of integration. Furthermore, using silicon allows for these devices to be fabricated in a standard process, SOIMUMPs from MEMSCAP.

B. Energy Storage in Silicon Beams

The most efficient way to store energy in a beam is through axial compression or tension, as described in Equation 3. In this energy storage modality, each part of the beam stores an equal amount of energy. In a bent beam, the strain energy is concentrated in specific areas of the beam, namely at the surfaces where the radius of curvature is the smallest. Using pure axial tension poses a problem because the strain limit of silicon necessitates that the beam is not stretched by more than 1.0%. This means the beams would need to be 100 times longer than the target displacement. However, if the beams are used in a way in which they are both bent and stretched axially, this requirement is relaxed. It was shown in previous work [6] that the displacement for a centrally loaded clamped-clamped beam is given by:

$$F(x) = 16\frac{Ew^3t}{l^3}x + 8\frac{Ewt}{l^3}x^3 \tag{4}$$

The first term in this equation corresponds to beam bending and the second term corresponds to the axial loading. This equation can be integrated to give the potential energy stored in the silicon beams as a function of their displacement.

$$U(x) = 8\frac{Ew^3t}{l^3}x^2 + 2\frac{Ewt}{l^3}x^4 \tag{5}$$

Equations 4 and 5, allow the microrobot designer to choose a target initial stored energy, and determine how much force

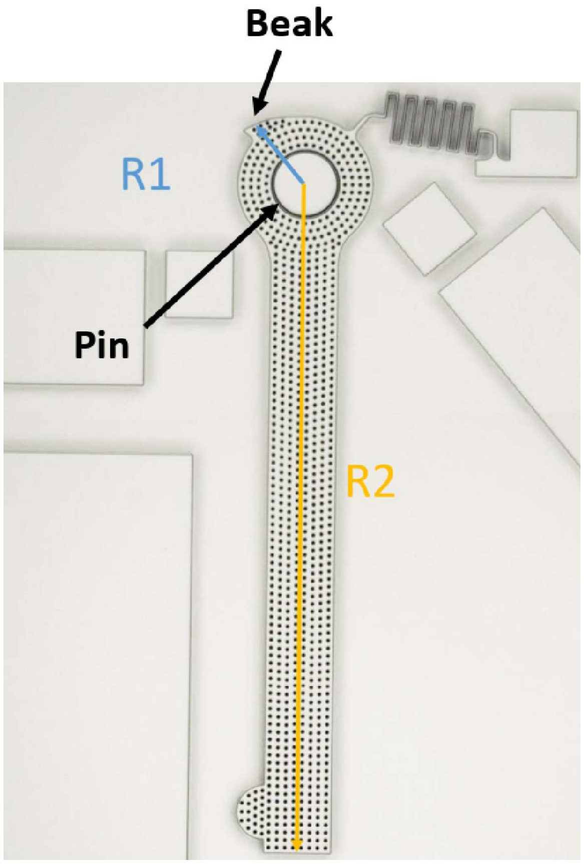

Fig. 2. A lever arm used to obtain the mechanical advantage. R1 is 100 μm. and R2 is 1 mm.

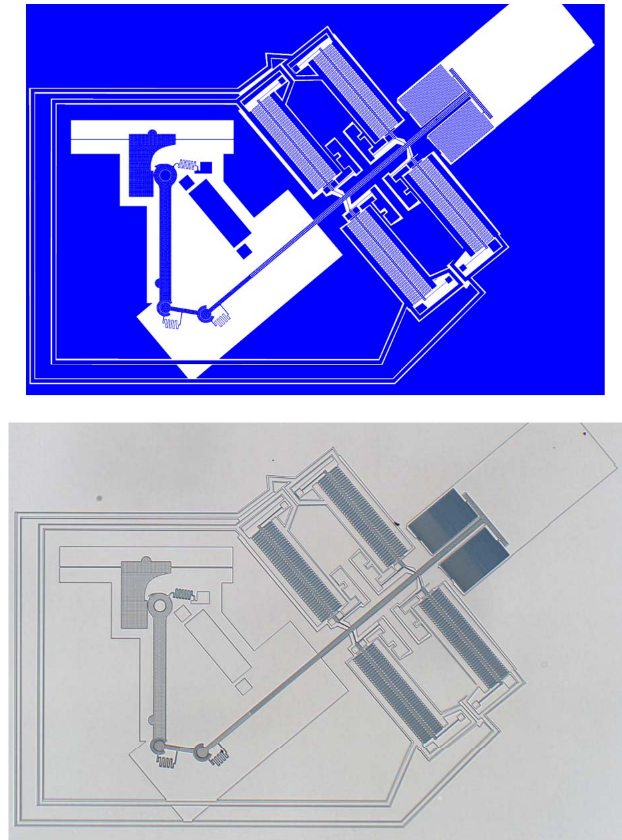

Fig. 3. An inchworm motor attached to the end of a lever arm in layout (top) and as fabricated (bottom). The lever arm in 1 mm long.

across what distance will need to be loaded into the springs. This informs the design of the motor that loads these springs. However, for appreciable stored energies these forces are considerably higher than the capability of even the most robust motors.

Since their creation over 15 years ago, much progress has been made in improving electrostatic inchworm motors. The layout area has been drastically reduced and the areal force density has increased significantly. Today, the best electrostatic motors can achieve a force density of 1.38 mN/mm^2 [7]. A 10 mg microrobot storing 10 μJ of potential energy, enough to clear a 7 cm obstacle, would require a force of 180 mN and a deflection of 200 μm. The aforementioned motor could easily produce this deflection, but it would require over 130 mm^2 of actuator area to achieve that force.

C. Fabrication

All devices presented in this paper are fabricated in a two-mask sinicon-on-insulator (SOI) process. The SOI wafers used have a 40 μm device layer, 2 μm buried oxide, and 550 μm handle wafer. The device layer silicon is patterned and etched using a deep reactive ion etcher (DRIE). Then the backside is aligned, patterned, and etched again using DRIE. The devices are then released using a vapor hydrofluoric acid (HF) etch.

IV. Force Amplification Mechanism

Inchworm motors are a reliable and efficient means of producing linear force, however as previously stated, their force characteristics fall shy of the requirements for silicon based jumping microrobots. This could be remedied in two ways: creating higher force motors or adding an amplification stage to take advantage of the long throw of these motors. While designing new motors with increased output force might seem to be the simpler solution to enabling jumping microrobots, there is no obvious path to creating such a motor. Therefore, a mechanical gain stage was developed to accomplish the task.

Figure 2 depicts a main sub-component of the mechanical gain mechanism. This structure is free to rotate about the pin, and in doing so produces a large mechanical advantage at the tip of the beak. The force applied at the bottom of the lever is magnified by the ratio of $\frac{R2}{R1}$, which is a factor of 10 in this case. The main failure mechanism of this structure is the pin anchor shearing off the handle wafer. This device relies on the ability of the pin to supply the reaction force at the interface of the lever arm. The pin stays anchored as long as the stress in the oxide is kept below its fracture limit of 54 MPa [6].

The goal is to attach an inchworm motor at the bottom end of the lever arm to amplify the force output of the motor. Figure 3 shows this first design of this interface both in layout and as fabricated. This inchworm motor, designed using

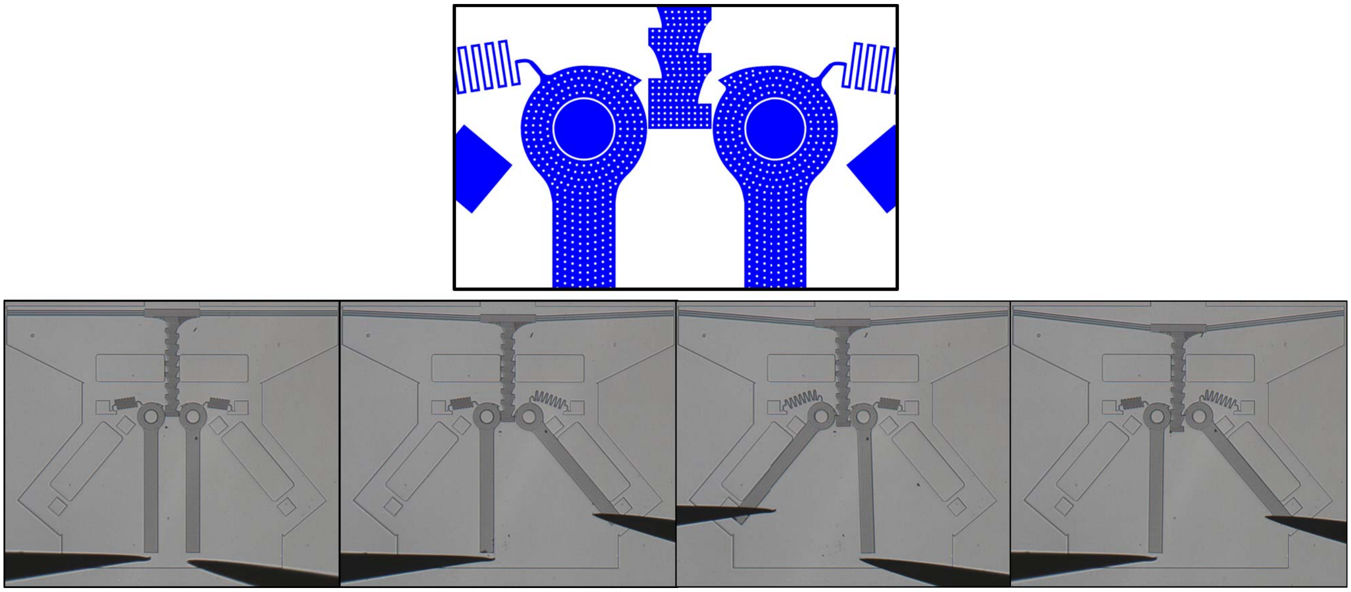

Fig. 4. (top) Layout view of the shuttle and two out-of-phase lever arms. (bottom) Two probe tips are used to simulate the forces of an inchworm motor. The mechanical gain mechanism is depicted at four different displacements. From left to right, 0 μm, 40 μm, 80 μm, and 120 μm. Note the stretching of the silicon springs along the top of the structure.

[7], can theoretically output 1.9 mN of force at an operating voltage of 90 V and displace 1.0 mm. This would load the energy storage mechanism on the left side with 0.23 μJ of mechanical energy. The device could not fully load the energy storage mechanism due to a miscalculation in one of the serpentine spring stiffnesses. However, the mechanics of the pin joints, designed from [8], and shuttle movement worked as expected. With a minor redesign, the actuator should be fully operational.

The last challenge in creating this mechanical gain mechanism is to determine how to use these small rotations about the pin to move a shuttle an arbitrarily far distance. To do this the inchworm motor was used as motivation. This motor utilizes two isolated sections of actuator that are operated out of phase. While one side is holding onto the shuttle, the other side engages and pushes the shuttle forward one step. Now that motor holds on while the other side engages and pushes the shuttle forward one step. Figure 4 shows this phased operation in action. From left to right the device starts in its as-fabricated state. The right probe trip pushes the right lever arm engaging the shuttle with the beak and displacing it 40 μm downwards. The left probe tip then engages with the left lever arm until the left beak makes contact with the shuttle. The right arm lets go, and the left lever arm continues pulling the shuttle down an additional 40 μm. This process can theoretically continue forever, however in this case the silicon beams will eventually hit their strain limit and fracture.

V. Rapid Release Mechanism

Once the energy has been stored in the beams, the energy must be release quickly. Ideally this release should be triggerable with an electrical signal. In the past this problem has been solved by using manual actuation. Churaman et al. [2] used elastomer beams and a pair of tweezers to launch their jumping microrobots over 30 cm in the air. The small deflections used in this work make manual actuation exceedingly difficult without fracturing the devices, so an electrical release was developed.

This latching and release mechanism builds on previous work [6] with the goal of significantly lowering the voltage required to keep the device in its high energy state. There are a few additional process steps added to allow the latching to operate at a low voltage. After the first DRIE, the wafers are sent through a high temperature pure hydrogen anneal for 10 minutes. This serves to smooth out the scallops from the DRIE process. After the second DRIE and HF release, the chips are coated with 55 nm of atomic layer deposition (ALD) alumina. The alumina is etched from the top surfaces using a chlorine based reactive ion etch (RIE). The alumina that coated the sidewalls remains.

These additional processing steps were performed on the jumping microrobot shown in Figure 1. During operation, the energy storing beams are loaded manually using a probe tip, the lever arms are rotated to engage with each other, and finally everything is latched into place by applying a voltage across the electrical contacts. The purpose of the hydrogen smoothing and the alumina coating should now be clear. A capacitor is formed across the two electrical contacts shown in Figure 1. As long as there is a sufficient voltage across this structure, the device will remain in its high energy state. These latches can restrain forces of over 200 mN with a voltage as low as 35 V. To release the latch and make the robot hop, this voltage is removed and the energy stored in the beams accelerates the robot upwards without any manual input. Figure 5 shows the latching mechanism before and after release. More details on

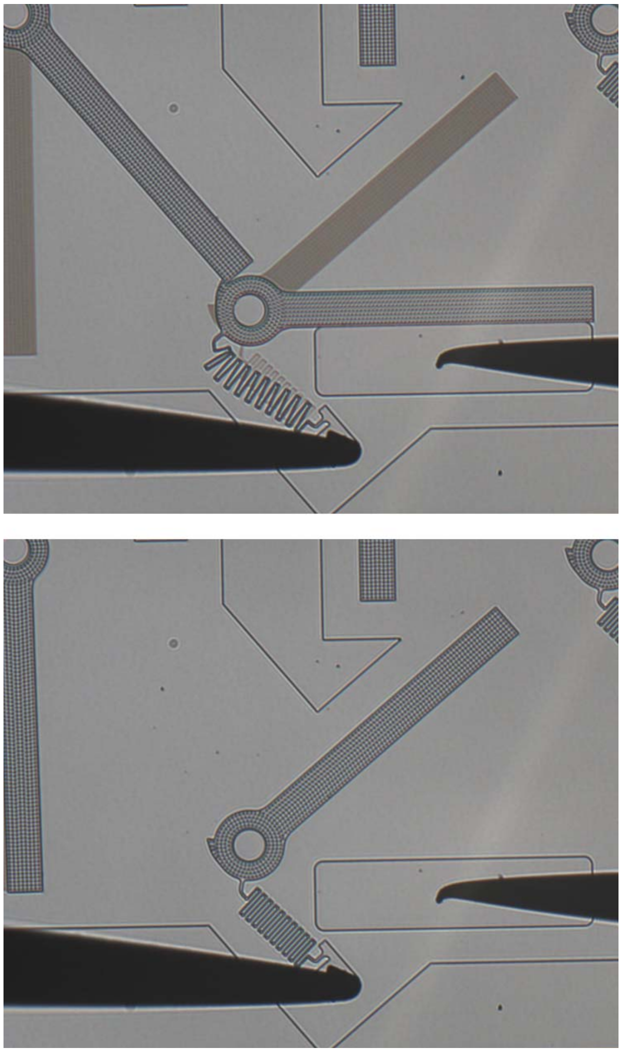

Fig. 5. Rapid release mechanism for the jumping microrobot. A voltage is applied across the lever arm and the contact to maintain the stored energy (top). The voltage is shorted to ground and the latch releases its mechanical energy (bottom).

the voltage characteristics of this latching mechanism can be found in perviously published work [9].

VI. Conclusion and Future Work

In summary, two different mechanisms have been proposed to enable autonomous jumping microrobots. A latching mechanism was proposed and fabricated to allow any high force actuator to remain in its high energy state so long as the latching voltage is still applied. Additionally, a force amplification system was designed and fabricated to allow current generation inchworm motors to apply at least 10 times more force than they could otherwise. By attaching two inchworm motors at the ends of two lever arms, a microrobot could theoretically load its energy storing beams and leap many cm into the air all without manual interaction. In the future, solar cells and high voltage buffers will be incorporated into the process allowing for a fully autonomous jumping microrobot.

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