OPTIMIZATION OF MEMS-SCALE JUMPING MICROROBOT

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ABSTRACT

Insects are capable of surpassing many body lengths in the height of a single bound. Despite being such a small package, they can accomplish these great feats through the build-up and storage of energy, which is then released nearly instantaneously via a latch mechanism. In this project we wish to design a jumping microrobot which utilizes the same type of energy build up and release – though, not through a literal musculature-controlled spring compression and physical latch mechanism. Instead, the focus of the project is to construct a MEMS robot composed of conductive materials for the main structure, which can be brought together via electrostatic force, stretching silicone polymers to store energy. Upon discharge of the voltages between each part, the polymers will then pull the robot into the air. This paper will investigate the changes in dynamics of this type of robot based on varying a few parameters; These include the number of springs, strength of springs, and electrostatic force strength.

Keywords: MEMS, Jumping Microrobots, LaMSA, Bio-inspired, Nonlinear optimization.

NOMENCLATURE

F_{comb}^{L}	Force generated by the lower comb drives.
F_{comb}^{U}	Force generated by the upper comb drives.
g	Acceleration due to gravity
a	Initial acceleration of the MEMS Jumping robot
M_{tot}	Total mass of the robot
$F_{SprVert}$	Force of the Spring in vertical direction
h	Displacement of the frame relative to body
x_{12}	Number of Springs
x_{13}	Width of Spring
x_{14}	Length of the Spring
x_{15}	Number of Upper Fingers
x_{16}	Number of Lower Fingers
x_{17}	Width of the Upper Finger
x_{18}	Width of the Lower Finger
x_{19}	Voltage
x_{20}	Elongation/proportion of the spring
MW	Minimum width
t	Thickness
ε_0	Vacuum permittivity
F_l	Finger length

1. INTRODUCTION

There are few robots created at the micro-scale. Some examples include those fabricated by Wayne A. et al, who have created two microrobots; one which stores energy mechanically through springs' arrangement and another by stored chemical energy which generates thrust force by exhausting gas from a chemical reaction. Most make use of the benefits of the scaling laws relating to spring forces. They are built from having pieces which stretch springs, to store energy, and a 'latch' which can rapidly release this energy. This mimics the type of mechanism in many biological systems, called "LaMSA" or Latch-Mediated-Spring-Actuation systems.

These systems are limited in the methods by which they can be fabricated at the micro-scale. They often are not resilient to continued use, as was the case with the MEMS robot in [1]. Many often include shape memory alloys as an actuation mechanism, to serve as the latch. This requires outside thermal heat transfer, as well as a need to re-load the robot every jump [2]. The design for this paper utilizes a highly compliant elastomer in order to store large amounts of energy, while allowing for repeated and simple-to-execute jumps.

Our design builds off of the general jumping microrobot from the work done by Aaron P Geratt and Sarah Bergbreiter [3]. In the original paper, this robot consists of primarily a body and frame, both made from silicon, and six elastomeric (silicone) springs connecting these two main parts. The fabrication of the robot is done mainly through cutting into a silicon layer, incorporating elastomeric materials (which will serve as springs) and cutting out the remainder of the robot via DRIE. The robot is said to be capable of storing 100μJ of energy.

However, this robot is hardly optimized. The dimensions were chosen, seemingly arbitrarily, for both the main robot and the springs. The tests for jump heights were performed via manual human manipulation. compression through tweezers. This led to, not only unstable jump height, but also wavering jump direction.

The project's motivation is to maximize the possible initial acceleration of this robot through mechanical design as well as implement changes to allow for variation of control, in addition to altering the design for a more effective use of the already-existing stored energy itself. We chose to frame this problem as a maximization of the force stored in the springs (which contribute to vertical movement) per total mass of the robot itself. This ensures maximum initial acceleration.

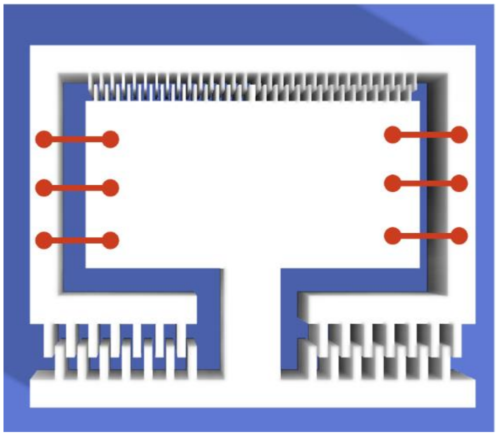

FIGURE 1: General shape of the modified design, with overhang and interdigitated fingers

Other changes we made, which would assist in maximizing jump height overall, include designing an overhang between the frame and the body, so they will catch when the jump occurs, so the energy lost in the air through a 'wobble' of the springs is as low as it can functionally be made. The method of control is also altered. As opposed to manual deformation via tweezers, the design in this paper instead utilizes electrostatic force to compress the robot. By implementing interdigitated fingers at select sections where large surfaces of the upper and lower parts of the body meet, capacitance can be employed. The robot will now need an additional coating of a dielectric material. The lower section will need a voltage, for the interdigitated fingers to produce the required electrostatic force. The variables we sought to test against optimal initial acceleration include the number of interdigitated fingers on both the lower and upper sections, the width of these fingers, the number of springs, the spring dimensions (and thereby the spring stiffness), and all of the following geometric dimensions which can enable these values.

2. METHODOLOGY

A model was created for the initial acceleration using the physics principles. In the modelling, the elastomer material connecting the body and frame is considered to have a spring like behavior.

$$a = \frac{F_{SprVert}}{M_{tot}} - g \tag{1}$$

As shown in Equation number (1) acceleration (a) depends on the vertical component of the spring force ($F_{sprVert}$) and the total mass (M_{tot}) of the body. The horizontal spring component of the force each other out in the process. The total mass includes the mass of the body, frame, springs, and interdigitated fingers. Gravity is considered, negative 'g' in the equation is the acceleration due to gravity.

2.1 Objective Function

The goal of the optimization is to maximize the initial acceleration. The problem comes into the category of Relaxed nonlinear optimization problem. For solving a nonlinear maximization problem using sequential quadratic programming in MATLAB using 'fmincon'. It should be converted to a minimization problem. Equation numbered show the minimized form of the objective function.

$$Minimize \;\; a = -\left(\frac{F_{SprVert}}{M_{tot}} - g\right) \tag{2}$$

2.2 Constraints

The primary constraints for optimization are the geometric and manufacturing limitations. Figure (1), Figure (2) and Figure (3). shows the design variables for the body, frame and spring which are set according to the minimum width that can be made or fabricated using Deep Reactive Ion Etching (DRIE). The minimum width depends on the RIE ratio of the fabrication unit and the thickness of the Robot itself. The figure length for the Upper and Lower interdigitated fingers are same. The distance between the interdigitated figure depends on the elongation of the spring and the distance 'h' between the body and the frame in its compressed state. There is a tolerance gap given in between the figure which is half of the h.

For the comb drives combined should generate more force than the force required for the displacement of the frame by h meter which is shown in Equation (5). The h is dependent on the elongation of the spring which is one of the design variables. Equation (3) (4) describe the equation for calculating the total comb drive force produced by the upper and lower fingers.

$$F^{L}_{comb} = \frac{1}{2}\frac{\varepsilon_0 \cdot t}{MW} x_{19}^2\big(2 \cdot (x_{18} - 1)\big) \tag{3}$$

$$F^{U}_{comb} = \frac{1}{2}\frac{\varepsilon_0 \cdot t}{MW} x_{19}^2 (x_{19} - 1) \tag{4}$$

$$F^{U}_{comb} + F^{L}_{comb} \geq F_{spring\ Vertical} \tag{5}$$

Here V is the voltage given to the figures to generate the electrostatic force. MW is the minimum width that can be produced by RIE machine. MW is thickness (200×10^{-2}) divided by the RIE ratio of 10. x_8 , x_8 and x_{10} are set such that springs can be accommodated with enough tolerance.

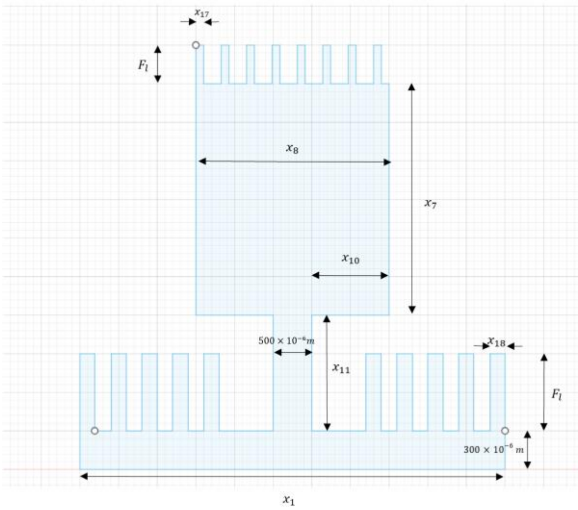

FIGURE 2: Design variables for the Body

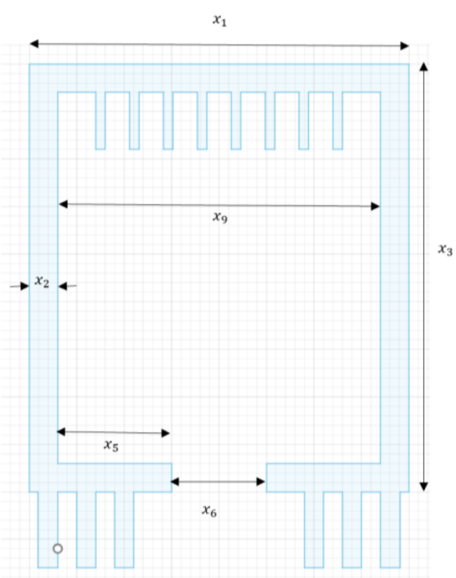

FIGURE 3: Design variables for the Frame

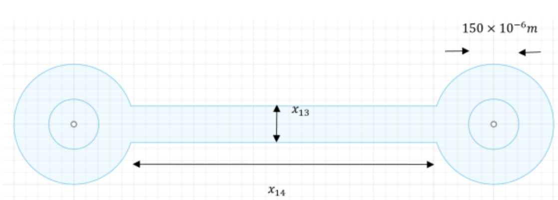

FIGURE 4: Design variables for the Spring elastomer

3. RESULTS AND DISCUSSION

Our optimization techniques resulted in feasible solutions, which could be used to manufacture a robot of this type, with either use of RIE or DRIE, and implementation of control over its maximum jump height through variation in voltage.

With a voltage of 120 volts, the optimizer resulted in an acceleration upwards of 9.4 meters per second squared. This value was the same for the relaxed problem, as well as for setting the values for number of upper and lower fingers to the nearest integer values. The resultant number of upper fingers and lower fingers are 72 and 66, respectively. The entire robot is just under 8mm in height.

TABLE 1. Optimized design variables

Design Variables	Value
x_1	$0.008\ m$
x_2	$9.711 \times 10^{-4} m$
x_3	$0.0012\ m$
x_4	$2 \times 10^{-4} m$
x_5	$0.0028\ m$
x_6	$5.4 \times 10^{-4} m$
x_7	$8.7116 \times 10^{-4} m$
x_8	$0.0041 m$
x_9	$0.0061\ m$
x_{10}	$0.0018\ m$
x_{11}	$5.2683 \times 10^{-4} m$
x_{12}	2
x_{13}	$1.605 \times 10^{-4} m$
x_{14}	$1 \times 10^{-3} m$
x_{15}	72
x_{16}	66
x_{17}	$3.6819 \times 10^{-5} m$
x_{18}	$3.6819 \times 10^{-5} m$
x_{19}	$120\ V$
x_{20}	1.0075

3.1 Future Research

There are a number of limitations and imperfections which can be the subject of potential future research.

1. The current geometric design has a mass distribution which is not ideal for the current optimized robot. It has ended up quite wide, leaving thick walls on either end. This can be minimized with changes to structural mass
2. Many robots have cumbersome methods by which to reload their mechanisms for follow-up jumps. They often need either external manipulation or pointed radiation. Our design is unique in that it can continually jump with just an on/off voltage control, but **only if** the robot is capable of reliably landing on its base. Geometric edits could potentially make this viable.
3. Experimental validation of our spring constant would be of great value, as it was the most derivative of our variables, and carries great weight to the objective function – meaning that small variations in the geometry from real fabrication could lead to variation from the theoretical values.
4. Not all of the mass on the robot is necessary. A simulation of the stresses within the robot would allow for removing mass, while keeping the robot structurally stable.

3 CONCLUSION

The modified design, though optimized, does not have a higher J/kg ratio due to the other modifications made to the system. However, these modifications offer such functional use that the design is still viable and worthy of further study.

4 ACKNOWEDGEMENTS

Problem Derivation:
Manohar derived equations for spring deformation and relevant forces
Audra derived equations for the electrostatic forces, geometry, and limitations due to MEMS fabrication.

Implementation:
Both implemented these equations into the MATLAB fmincon code for the objective function, and non-linear constraints

Debugging:
Manohar did majority of the debugging, with the fixes ranging from conceptual ones, mistyped equations, and ensuring values fell within realistic values

Writing:
Both collaborated on writing the abstract and report.

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