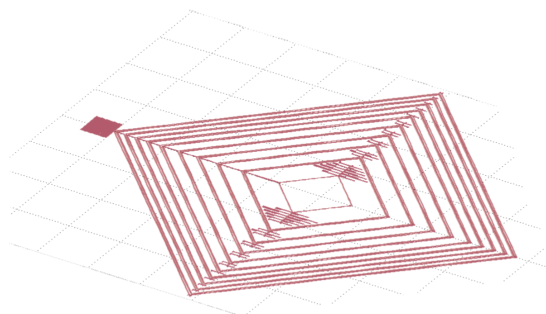
Multiple Interconnected Parallelogram Actuators And Parallelogram Rigid Frames

Dina Rastakhiz
Undergraduate Student, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA94720 e-mail: dina@cory.eecs.berkeley.edu

Ramin Rastakhiz
Undergraduate Student, Department of Mechanical Engineering, University of California, Berkeley, CA94720 e-mail: ramin_r@uclink.berkeley.edu

Abstract
In this paper, we present the design and simulation results of multiple interconnected parallelogram actuators and parallelogram rigid frames that can be used for large amplitude static displacement. The design stands as an un-optimized example of the basic idea of accumulating displacement and force through the multiplication of similar, interconnected smaller units. For a MUMPs structure of ten parallelogram actuators and frames with side lengths ranging from 200µ to 1099µ, a max of 39.9µ lateral displacement and 21µN force (at 73V) was achieved through simulation.



1. Introduction

With the new multilayer surface micromarching processes emerging, the next generation microactuation schemes are becoming more attractive and therefore are subjects of many ongoing researches. Microsteam engines [1], surface-tension-driven micropumps [2], and milli-rotary internal combustion engines [3] are all examples of this new trend among the MEMS community. However, good old electrostatic microactuation is still considered by many to be the most popular and easy to design form of actuation, with many practical applications and more room for growing.

Among the electrostatic actuators, one may find two basic designs. The first design utilizes parallel plate capacitors with one moving plate that is allowed to displace in the direction of the major field lines. The second basic design utilizes the fringe field of capacitors to drive the moving plate parallel to the fixed and perpendicular to the major field lines. Suitable for medium-low static displacements [4] or small amplitude resonant displacements [5], larger structures consisted of several smaller units of these actuators do not yield larger amplitudes relevant to their size increase and will ultimately reach a saturation limit, thereafter only the force gets proportionally larger with the addition of each smaller unit. There are also other forms of non-electrostatic actuators that suffer from the same limitation, such as the heatuator [6] where an amplitude increase cannot be achieved through multiplication of the basic unit.

In this paper, we present the design and simulation results of a multiple interconnected parallelogram actuators [7] and parallelogram rigid frames (MIPARF) that can be used for large amplitude static displacement in places where precise positioning is also highly desirable, an example of which would be in optical devices for lateral control of micromirrors (or shutters). The design stands as an un-optimized example of the basic idea of accumulating displacement, on top of force duplication, through multiplication of similar, interconnected smaller units.

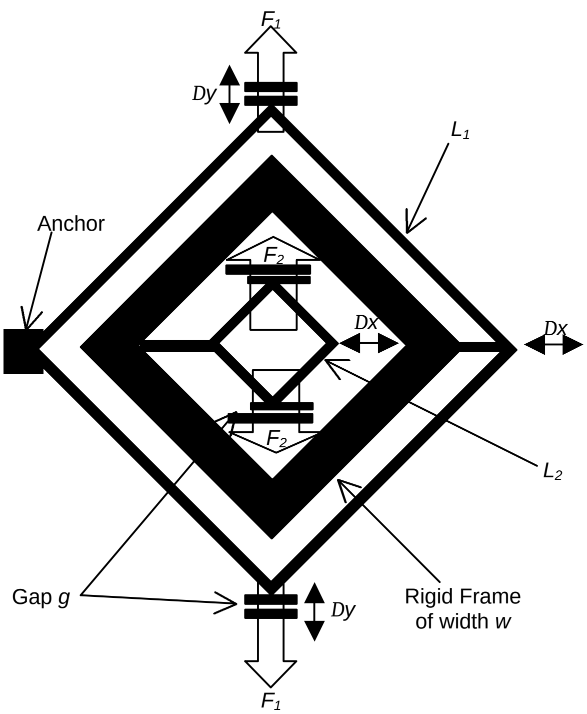


Figure1: Principle behind the motion and transformation of the multiple inter-connected parallelogram actuators and rigid frames

2. Design

Figure 1 illustrates the principle behind the motion and force transformation achieved by the parallelogram structure. A normal force, F_1, is developed across a gap, *g*, between the electrode plates on the top and bottom of the suspended parallelogram structure, resulting in a deflection *Dy* at each of the two parallelogram electrode plates. The deflection at the plates is approximately given by:

$$Dy = \frac{F_1 L_1^3}{12EI} \qquad (1)$$

where L_1 is the length of one parallelogram side, *E* is the Young's modulus of the structural material and *I* is the moment of inertia of the parallelogram beams. The deflection *Dy*, which is proportional to the square of applied voltage, is in turn transformed into a deflection *Dx* at the other vertex (the vertex of action) of the parallelogram. Therefore, the deflection *Dx* is controlled with the applied voltage. The relation between *Dy* and *Dx* is given by:

$$Dx = 2Dy \qquad (2)$$

when one vertex of the parallelogram is fixed to the substrate. Through the inner rigid parallelogram frame of width *w*, the force and displacement vectors of the vertex of action are transferred to the second parallelogram actuator, pulling it to the left of Fig. 1. A normal force F_2 is developed across the gap *g* between the electrode plates on the top and bottom of the surrounded parallelogram structure, in such a way that $F_2 L_2^3 = F_1 L_1^3$, resulting in a deflection *Dy* at each of its electrode plates. Thus, this parallelogram actuator, itself moved to the left by *D*x, moves the new vertex of action to the left by another *Dx* resulting in a total displacement of 2*Dx* with respect to a fixed location. Repeating the same type of parallelogram actuator/frame structures until constrained by the inside geometry, it is possible to accumulate a large number of *Dx* displacements. The area surrounded by the inner most parallelogram actuator is the load area where the final vertex of action gets connected to the load (ex: mirror or shutter).

Because of the small beam deflections in each parallelogram, use of the simple beam theory is adequate for the design and other calculation purposes [8].

Eliminating *Dy* from equations 1 and 2 and replacing F_1 with the electrostatic force using parallel plate theory, the overlap area required for generating the force can be determined. Figures 2 and 3 show the layout of the actual design in MUMPs process.

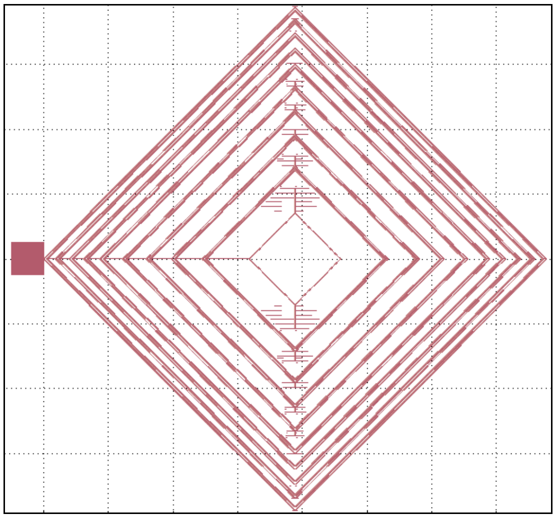


Figure 2: The actual layout of the design shows that more gap-closers are required for the inner parallelogram actuators.

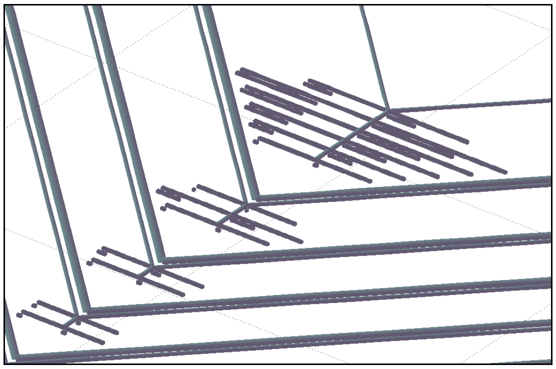


Figure 3: For the inner actuators, the path of the beam connecting the gap-closers to the parallelogram structure should be clear of the anchored electrodes while the overlap area should remain constant throughout the actuation.

3. Fabrication

The simulation of our design is based on MUMPs fabrication. Our task was to observe the MUMPs design rules as much as possible. The moveable structure is made of Poly1 layer. The electrodes are also Poly1 anchored to Poly0 to provide electrical connection.

4. Results

For a 3µ gap, *Dx*=2µ, *w*=7µ, *v*=73V, and a 200µ x 200µ real estate designated for the load area (i.e., mirror), a total nodal displacement of 39.9µ and a max of 21µN was achieved through simulation. It is expected that the performance of our fabricated design would follow the theoretical trends established in Fig. 4.

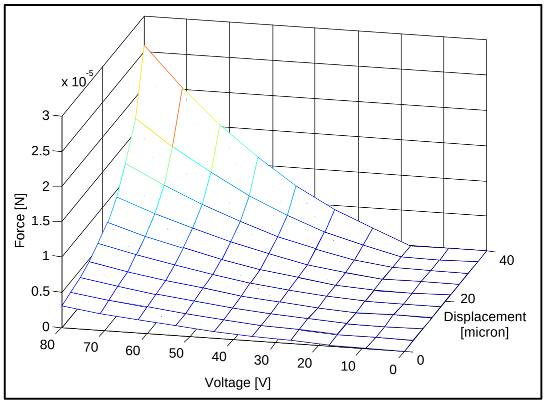


Figure 4: Theoretical force excreted by MIPARF versus applied voltage for different nodal displacements

5. Discussion

Although the simulation pointed to a successful operation, there are many concerns about this design. Nonlinearity sources are influential at the extreme ends of each cycle. At the first moments of actuation, fringe fields cause forces against the desired direction of motion. Before the end of each cycle, they cause up to 8 percent reduction in the system's overall spring constant by exerting forces favorable to the direction of motion. When operating at large amplitudes, fringe field effects are also pronounced near the half-cycle.

During release in the MUMPs process, the large beams might stick to the substrate due to surface tension. The same failure may occur during high voltage operation due to electrostatic attraction between the beam and the substrate. Although bushing will prevent such failures, it was not included in our layout because of the simulator limitations. Also, the theoretical determination of static displacement is dependent on the accuracy of both Young's modulus (165GPa) and the suspension beam widths and depths. Our model assumes perfect geometric dimensions whereas the actual structure will have dimensions that vary slightly with the fabrication process.

6. References

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