Charge Pumping for High-force, Large-displacement MEMS
and a Vision for Charge Scavenging and Storage Infrastructure

Ian R. Harvey[*], Brian W. Baker[*], Ronald Boutte[*], Alexander L. Hogan[**], and Kurtis R. Ford[***]

[*]University of Utah Nanofab, SLC, Utah, USA,
IRHarvey@eng.utah.edu, BBaker@eng.utah.edu, mems.man@gmail.com
[**]Blackrock Microsystems, SLC, Utah, USA, ahogan@blackrockmicro.com
[***]Sandia National Lab, Albuquerque, NM, USA, krford@sandia.gov

ABSTRACT

Charge-pumping represents an unusual approach to MEMS actuation with the potential benefits of large displacement coupled with high force, as well as simple out-of-plane motions, large-scale self-assembly, simple single contact and even the possibility of non-contact actuation. Charge pumping is conducive to energy scavenging techniques such as tribolectric harvesting, useful in aerospace and satellite applications, but it comes at the cost of modifications to the electronics control infrastructure now based on two-terminal (power/ground) voltage and current paradigms.

Non-contact examples will be shown, including devices that can be used for microscale biomimetic optics.

Keywords: MEMS, supercap, charge-pump, biomimetic accommodating lens, energy harvesting

1 BACKGROUND

MEMS device actuation design can benefit from physical scaling laws that result in the large dominance of effects related to surface area, over effects related to volume, such as mass, gravitational and inertial effects. So instead of simply making machines smaller that worked well in the macro world, we envision a new class of machines that are specifically designed to take advantage of what works well in the micro-scale world. This discussion represents a class of devices that require a different mentality in both design and control methodology because they depend neither on the passage of current (the typical approach to electromechanical design) nor directly on capacitance or voltage, but rather on manipulation of the fundamental unit of charge. Not quite static, and not dynamic enough to be concerned with current, but focused on how materials and geometeries allow charge to be collected on a surface and redistributed in controlled fashion, in order to mechanically take advantage of fundamental coulombic repulsion and attraction effects, which have enormous relative capacity for both high force and large displacement at the micrometer scale and below. An outcome of this design approach is the setting aside of the two-terminal (power/ground) thought process in favor of a single point of contact and control, and even the possibility of non-contacting methods, using field emitters, beta particle emitters, or triboelectricity. [1-6]

2 CHARGE-PUMPING APPLICATION

Recent work in our group [7-14] can be categorized in terms of efforts to realize large-force, high-displacement radial motion that would be compatible with the demands of a biomimetic accommodating lens. It had become clear that traditional MEMS actuation would not be capable of providing these attributes, at least with any reasonable speed. First we discuss the benefit of out-of-plane actuation, then describe efforts to convert out-of-plane motion to in-plane actuation of a radial lens-pulling device.

2.1 Out-of-plane Displacement

We previously demonstrated large-force and high displacement in a simple coiled spring, deployed out-of-plane using coulombic repulsion by charge pumping [7]. Whereas most MEMS actuators are capable of only a few percent displacement compared to their size, this device was easily capable of out-of-plane displacement equivalent to the size of the device footprint on the silicon chip, without contacting the device. See Figure 1. In this case, the ratio of displacement to Si footprint was greater than 2:1.

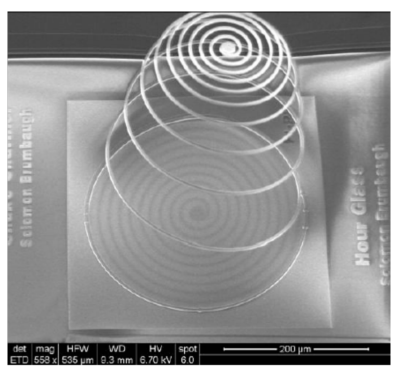

Figure 1. Scanning electron micrograph of the maximum deflection of the spiral beam actuator that was observed during SEM imaging. The measured deflection was 220 µm corresponding to an equivalent point load of 2 µN. [7]

 CTSI-Cleantech 2014, www.ct-si.org, ISBN 978-1-4822-5819-6

2.2 Biomimetic Accommodating Lens

Several design implementations (Figure 2) were directed at translating strong out-of-plane motion into radial in-plane actuation. Out-of-plane motion is desired due to the large opposing surface areas that can be used to maximize the advantage of coulombic effects. In the figure, two sail-based designs are shown with the sail parallel to the substrate for maximum repulsion effect. The sails are constructed of doped (conductive) polysilicon, but none of the structures have electical contact toground. So as charge is applied through the action of scanning an energetic electron beam over the device, accumulated charges redistribute over the available surface in order to create as much separation betweeen charges as possible. At some point, the crowded charges begin to face each other across the gap between the lower part of the sail, and the underlying substrate, and tremendous forces are exerted on the sail. There is some difficulty in modeling these effects as commercial multi-physics software systems are not set up for these effects and require definition of a ground plane per the traditional two-terminal electric model.

We previously described [8] the electron beam conditions under which a MEMS designer may choose to create a net-positive charge condition, or a net-negative charge condition. This permits designers to create conditions of both attractive forces between separated unlike charge states on design elements, or repulsive forces between design elements due to the presence on each mechanical element of like charges, per Coulomb's law.

The upper design of Figure 2 was created with multiple parallel sails in an attempt to multiply the applied force. The design shown in the lower part of the figure took advantage of a negative poisson compliant mesh [11], arranged to accommodate radial expansion, in order to avoid mechanical hinges. Both designs unfortunately had insufficient tolerences between individual sails, creating pinch points and wedging the sails together as the devices deployed. The effects of out-of-plane deployment by charge pumping were thus demonstrated without the benefit of creating a working accommodating lens actuator.

2.3 Demonstration of Coulomb's law

While the electron beam is useful for simultaneously (and in a non-contact mode) embedding charge *and* visualizing the resulting dynamic effects, other sources of charge pumping are similarly effective. In the lab, a Van der Graaff generator was used effectively both in contact mode and in non-contact mode by holding a probe over the device to shower the device with electrons escaping from the tip. Manual triboelectric charging is also effective.

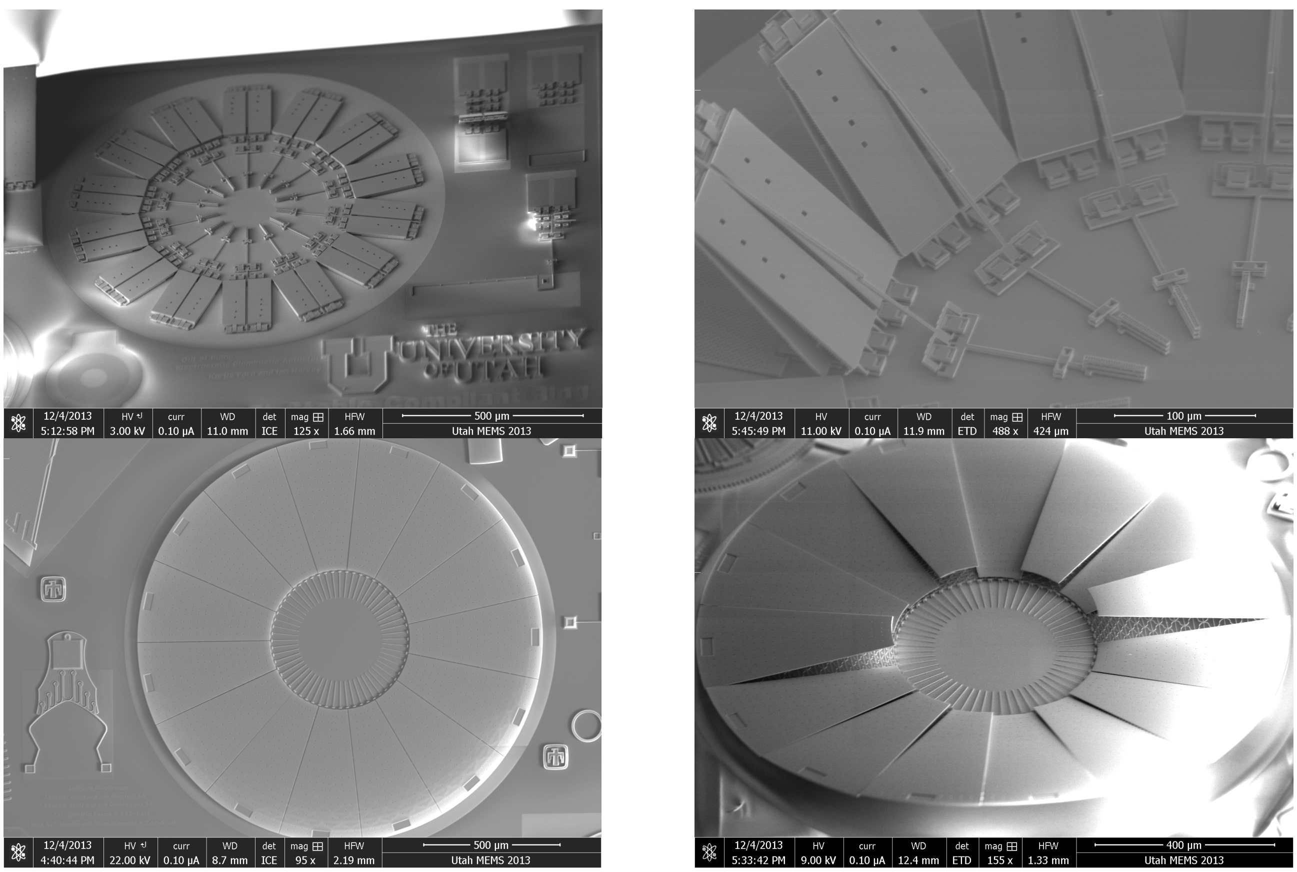

Figure 2: Two versions of biomimetic lens stretching actuators, (L) base state as-built in-plane; (R) biomimetic lens stretchers actuated out-of-plane by charge pumping. In these cases, the charge pump is the electron beam also used to image the deives.

The best demonstration of Coulomb's Law is the same one used in Freshman Physics: The Braun Electroscope is a device with a needle pivoting on a rigid vertical bar. When amber and fur are rubbed together, the amber accumulates a net excess charge through triboelectric effects, and when discharged to the electroscope, the ungrounded conductor re-distributes the charges across the surface. The pivoting needle then responds by being repelled from the rigid vertical shaft, into a position perpendicular to the shaft. In our implementation of the Braun demonstration, the ring of the Braun electroscope was fabricated in-plane with the substrate, hinged for effect to two other rings. Upon actuation by charge injection, the rings self-deployed perpendicular to the substrate, as the needle responded perpendicular to the rigid shaft (Figure 3).

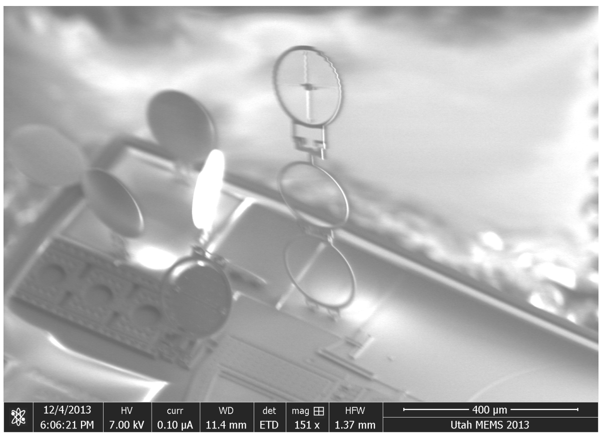

Figure 3. Micro-scale braun electroscope, fabricated in-plane and deployed by charge pumping from the SEM, showing coulombic effects.

2.4 "Traditional" In-plane MEMS Actuation

Remarkably, the conditions we used for e-beam charging of the devices shown in Figure 2, were also effective in continuously driving the Sandia-designed torsional ratcheting actuator (TRA) [15-17]. It was remarkable since no attempt was made to ground either terminal. Under the action of the electron beam, the floating nodes differentially charged to the point where the interdigitated fingers attracted to each other, touched and discharged, then sprung back to the base state to begin another cycle, engaging the ratchet with each step. Figure 4 shows the device under charging conditions that produced voltage contrast between the sets of opposing fingers.

3 E-HARVESTING APPLICATIONS

We have demonstrated the power of charge pumping in actuating micromachines both in-plane and out-of-plane. This source of powering MEMS is unique in the ability to provide large displacement without the traditional sacrifice of high force. Manipulation of discrete charges is perfectly suited for energy harvesting approaches based on triboelectricity. This effect is familiar to each of us in day-to-day living, in how clothes cling due to static buildup, as well as the shocking discharge when touching a grounded object.

4 FUTURE WORK

Our objective in publishing this work at this conference is to seek development partners interested in capitalizing on abundant and free energy sources readily attainable through triboelectric effects. Challenges to be overcome include learning how to convert charge stored in a single terminal trap, into current that can be applied in traditional electric applications. Otherwise, it involves how to invent the machines and control systems of the future that operate strictly on discrete bursts of relocated charge, in preference to performing work via continuous or alternating current. Future work will concentrate on development of high-surface area, mechanically stable charge traps and the system of both trapping and controlled releasing discrete amounts of charge.

5 SUMMARY & CONCLUSIONS

It is truly a paradigm shift to begin thinking in terms of applying force and performing work, directly using the fundamental unit of charge, designing how charges interact with each other, in preference to the traditional engineering of power using secondary effects of charge: charge in motion (current), charge in storage (voltage) or induced charge (capacitance).

The ability to accumulate charge from the ambient environment could lead to the elimination of batteries and allow MEMS to operate indefinitely. A triboelectric MEMS trickle charge pump could enable the powering of an entire cell phone or other mobile electronic devices, by dumping the collected charge into a single terminal supercap that acts like an infinitely rechargeable battery. In space-based MEMS, this would give advantages in weight, form factor, and energy storage. The trickle charger would replenish on-board power supplies for electronic function and it would alleviate the static charge build-up that occurs in normal space operation, where charging is otherwise a nuisance.

The infrastructure for these devices is not batteries, converters, power supplies, and function generators. It is rather triboelectric generators, single-terminal capacitors, MEMS switches, and a host of new power management tools that allow the control circuitry to be managed through classical, two-terminal voltage switching. In other words, while the "work" is done by controlled positioning and repositioning of static charges, yet the control is managed through classical interfaces.

This potential saving of space (form factor), weight, and energy efficiency are of great interest in space based applications, where triboelectric charge can be "harvested" simply by nonmechanically collecting the abundant charge on high surface area storage media (single-terminal supercaps). This factor also applies in terrestrial applications, wherein charge-pumped MEMS can be powered simply by appropriate harvesting of charge through rubbing materials together with differing triboelectric tendencies.

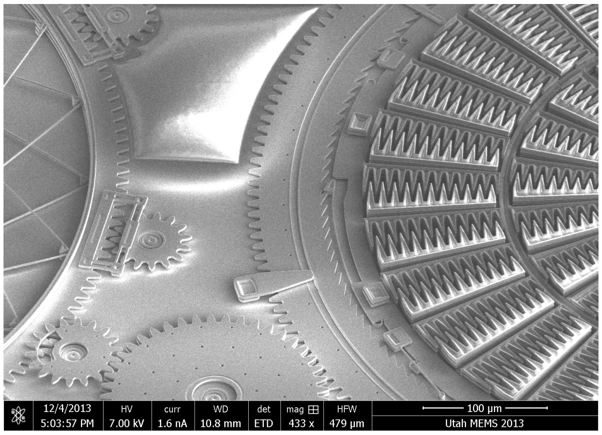

Figure 4. Sandia-designed torsional ratcheting actuator [14-16] showing voltage contrast in the comb fingers, actuated here by non-contact (SEM) continuous charge pumping.

REFERENCES

[1] Z. Liu, M. Kim, N. Shen and E. Kan, "Actuation by electrostatic repulsion by nonvolatile charge injection," Sensors and Actuators A, vol. 119, pp. 236-244, 2005.

[2] K. Lee and Y. Cho, "Laterally Driven Electrostatic Repulsive-Force Microactuators Using Asymmetric Field Distribution," Journal of Microelectromechanical Systems, vol. 10, pp. 128-136, 2001.

[3] S. He, R. Ben Mrad and J. Chong, "Repulsive-force out-of-plane large stroke translation micro electrostatic acuator," Journal of Micromechanics and Microengineering, vol. 21, pp. 1-12, 2011.

[4] D. Qiao, W. Yuan and X. Li, "Design of an Electrostatic Repulsive-Force Based Vertical Micro Actuator," in International Conference on Nano/Micro Engineered and Molecular Systems, Zhuhai, China, 2006.

[5] K. Ogando, N. La Forgia, J. Zarate and H. Pastoriza, "Design and Characterization of a Fully Compliant Out-of-Plane Thermal Acuator," Sensors and Actuators A, pp. 1-22, 2012.

[6] R. Duggirala, R. G. Polcawich, D. M. and A. Lal, "Radioisotope Thin-Film Fueled Microfabricated Reciprocating Electromechanical Power Generator," Journal of Microelectromechanical systems, vol. 17, no. 4, pp. 837-849, 2008.

[7] A.L. Hogan, K.R. Ford, and I.R. Harvey, Out-Of-Plane MEMS Actuation Using A Scanning Electron Microscope, Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012 November 9-15, 2012, Houston, Texas, USA IMECE2012-88128

[8] A. Hogan, B. Baker, C. Fisher, S. Naylor, D Fettig, I.R. Harvey, Biomimetic Accommodating Lens with Implementation in MEMS, MOEMS/MEMS SPIE Photonics West, San Francisco, CA, 21-26 January, 2012,

[9] K. Ecsedy, I.R. Harvey, A. Hogan, K.R. Ford, B. Baker, P. Stout, S. Brumbaugh, J. Piatt, “An Exploration of the Artistic Applications of MEMS: Gallery on a Chip “The International Journal of Technology, Knowledge and Society, Volume 6, Number 1, 2010, http://www.Technology-Journal.com, ISSN 1832-3669

[10] K.R. Ford, Compliant Micro-Joint Replacements, M.S. Thesis, Department of Mech. Engineering, The University of Utah, 2011.

[11] A. Hogan E. Anderson and I.R. Harvey, Investigation of Charge Pumped MEMS Actuation, The U of U Undergraduate Research Abstracts, Sp 2009, Vol 9., p.27, p. 120

[12] US Patent WO/2008/121845. Boutte, R.W.; Solzbacher, F.; Harvey, I.R.; Horn, J.A.; Meacham, T.M.; Gaskin, N.C. Baker, Brian W. Micro-Deployable Devices And Systems

[13] US Patent WO/2008/131088 Harvey, I.R.; Meacham, T.M.; Boutte, R.W.; Baker, B.W.; Harvey, I.E. MEMS Devices And Systems Actuated By An Energy Field

[14] Sandia National labs MicroElectroMechanical Systems (MEMS) 2005-2008, December 2011 (online).

[15] MEMS Technologies Department, Sandia National Labratories, "SUMMiT-V^{TM} Five Level Surface Micromachining Technology Design Manual," 10 April 2008.

[16] Sandia National Laboratories, "HiPref Comb Drive Actuator," Sandia Corporation, Albuquerque, 2011.

ACKNOWLEDGMENTS

Thanks go out to Solomon Brumbaugh for their design contributions of radial-pulling MEMS and working electrostatic repulsion based designs, respectively, which served as inspiration for our later designs. Thanks for the financial contributions of the University of Utah Technology Commercialization Program, the Center for Interdisciplinary Art and Technology (CIDAT), Undergraduate Research Opportunities (UROP), and the Mechanical Engineering Department at the University of Utah. Many thanks to Sandia National Labs for their support through the University Alliance design competition in reviewing designs, fabricating parts, and to SPIE for providing travel funds, and gracious hosting of budding engineers at their Albuquerque facility.

This work made use of University of Utah USTAR shared facilities supported, in part, by the MRSEC Program of the NSF under Award No. DMR-1121252. Ongoing work is supported in part by the Keck Foundation Education Program.