Designing and Operating
Electrostatically Driven Microengines

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ABSTRACT

Microelectromechanical engines that convert the linear outputs from dual orthogonal electrostatic actuators to rotary motion were first developed in 1993 [1]. Referred to as microengines, these early devices demonstrated the potential of microelectromechanical technology, but, as expected from any first-of-its-kind device, were not yet optimized. Yield was relatively low, and the 10 micronewtons of force generated by the actuators was not always enough to ensure reliable operation. Since initial development, these engines have undergone a continuous series of significant improvements on three separate fronts: design, fabrication, and electrical activation. Although all three areas will be discussed, emphasis will be on aspects related to mechanical design and generation of the electrical waveforms used to drive these devices. Microtransmissions that dramatically increase torque will also be discussed. Electrostatically driven microengines can be operated at hundreds of thousands of revolutions per minute making large gear reduction ratios feasible; overall ratios of 3,000,000:1 have been successfully demonstrated. Today's microengines have evolved into high endurance (one test device has seen over 7,000,000,000 revolutions), high yield, robust devices that have become the primary actuation source for MicroElectroMechanical Systems (MEMS) at Sandia National Laboratories.

INTRODUCTION

Electrostatically driven microengines utilize the electrostatic attraction that results from an electric field between two objects to induce motion. Although this attraction always exists between bodies not held at the same potential, it is typically insignificant and disregarded in the macroscopic world. In the micro regime, however, it has long been demonstrated that this force could bend cantilever beams and drive simple actuators [2,3]. To harness this force, two surfaced micromachined electrostatic actuators were oriented at right angles to each other and interconnected with two linkage arms and a 50-μm drive gear (figure 1) to transform the linear actuator displacements into rotational motion [1]. Shortly afterwards, this new rotary actuation assembly, referred to as a microengine, was shown to be capable of driving other micromechanical loads [4,5]. While these were very successful demonstrations, device yield was low and harnessable power was very limited. The technology was simply not developed enough to mass produce reliable systems or drive significant mechanical loads.

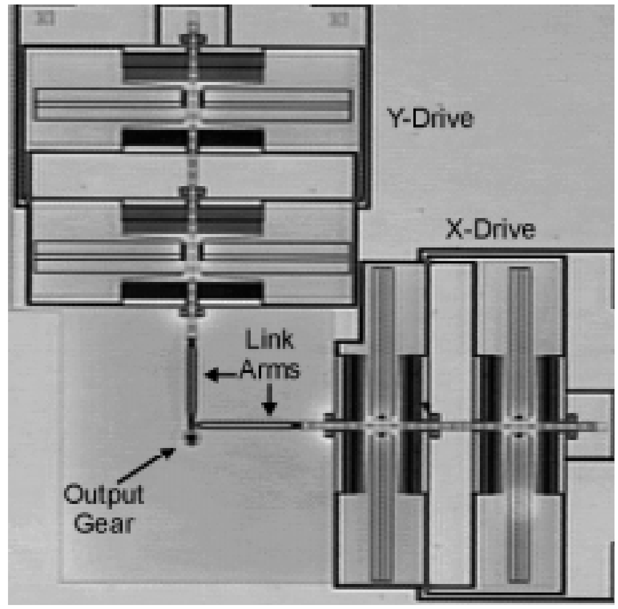

Figure 1. The microengine translates orthogonal displacements from the X and Y comb drives to rotational motion of the output gear.

In recent years, we have developed microengines into robust, high yield assemblies that have become the primary actuation mechanism for many microelectromechanical systems. Today we know how to better design, build, and operate these rotary actuation assemblies. We have also learned how to fabricate multistage transmissions that provide tremendous gains in the amount of torque that can be derived, and how to transform this increased force back into linear motion. No longer just barely capable of moving themselves, the latest generation of microengines and transmission assemblies has demonstrated the ability to actually shear teeth off the polysilicon gears from which they are constructed. Although all the components described in this paper were fabricated in the Sandia Ultra-planar Multilevel MEMS Technology (SUMMiT) [6,7], the concepts stated are true for other technologies.

ELECTROSTATIC ACTUATOR BASICS

The fundamental actuation mechanism for the microengine is the electrostatic comb drive [3]. The actuator shown in figure 2 is a comb drive sub-assembly that illustrates the basic components. Two of these are cascaded together to create the x-drive shown in figure 1. Grayed areas indicate the sections of the assembly that move back and forth, while the areas that are only outlined indicate stationary components. The large gray area in the center of this figure is referred to as the shuttle. Symmetrical arms are attached at right angles to both sides of this shuttle, and attached to these arms are a series of fingers in comb like arrangements. This entire assembly is supported in the air by dual folded beam support springs, and each spring assembly is anchored to the underlying ground plane at a single point near the shuttle. This arrangement provides for very compliant shuttle movement along the desired line of motion, while providing stiff resistance to motion at right angles to this line. In close proximity to each end of the shuttle are plates that are securely fastened to the substrate to prevent movement. Protruding from each of these plates is a bank of fingers, which intermesh with the fingers attached to the shuttle.

Applying a voltage to the two banks of fingers on one side causes the shuttle assembly to move toward that side. The electrostatic force that provides this motion results from the fringe fields between the interdigitated fingers and is given (for the ideal case) by $F = aV^2$, where V is the applied voltage and *a* is the electrostatic force constant. Note that *a* is always positive; electrostatic forces attract but do not repel. For this reason, banks on opposite sides of the shuttle are required to displace the shuttle in both directions from its fabricated position. A mechanical restoring force generated by the shuttle support springs is given by $F = -kx$, where *k* is the spring constant and *x* is the displacement from its unbiased equilibrium position [8]. In equilibrium, $kx = aV^2$, or $V^2 = x(k/a)$. Thus the displacement is directly proportional to V^2, and experimentally, actual devices have been found to closely follow this ideal relationship [9].

In general, the electrostatic attraction between parallel plates is much stronger than that generated by the fringe fields about comb elements, but it exhibits a very limited controllable range of motion and is typically avoided. However, this is a force that must be dealt with when designing comb drives as the parallel plate attraction can lead to nonlinear behavior and clamping of the drive assembly [10]. As long as the fingers are precisely cen-

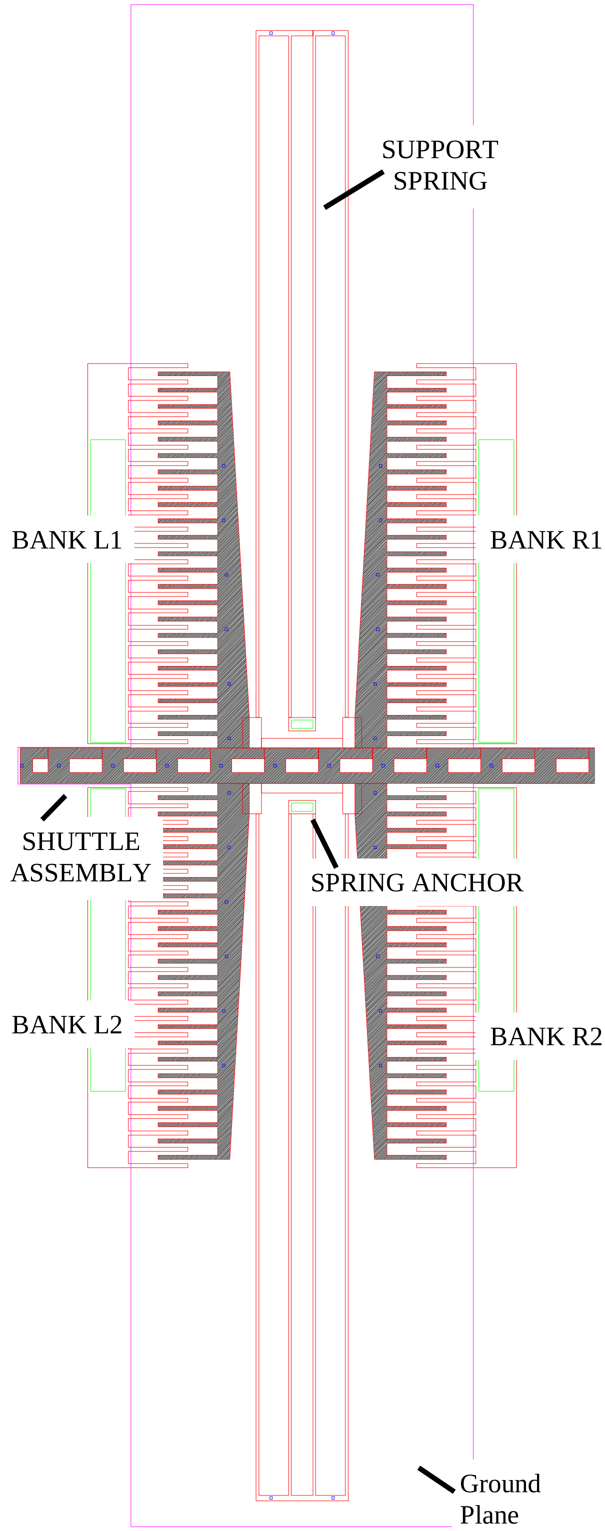

Figure 2. Basic electrostatic sub-assembly. Typically two of these units are cascaded to form a single comb drive assembly as shown in figure 1.

tered in their corresponding gaps, the lateral force components that act on each finger exactly cancel. In actual practice, however, truly symmetrical systems are virtually impossible to realize. Even micromachined components defined by precision photolithographic techniques are not perfect. These slight asymmetries give rise to a net lateral force that can cause the fingers to bend into each other or cause the entire shuttle assembly to be laterally displaced until all the fingers touch (figure 3). At best, such an occurrence prevents operation of the device. At worst, the fingers short out or weld together destroying the actuator.

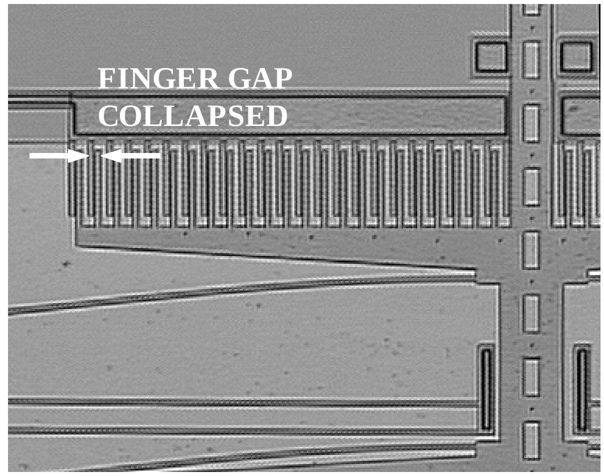

Figure 3. Asymmetrical lateral forces under electrical bias pulled this shuttle assembly to the left until it came in contact with the banks of stationary fingers.

COMB DRIVE GEOMETRY

In an ideal environment, it is desirable to make the fingers as narrow as possible since the total force generated by the comb drive is directly proportional to the number of fingers. It is also desirable to keep the gaps as narrow as possible to increase the magnitude of the electrostatic force constant, *a* [8]. In the SUMMiT process, both the fingers and the gaps between can be defined to be a single µm wide. Doing so, however, creates a very compliant comb assembly that easily distorts under electrical bias. Experimentation has shown that 3-µm wide fingers and gaps are adequate for fingers up to 50 µm in length with 100 volts applied between them. The lateral stiffness of a finger varies as the cube of its width, but flexibility increases as the cube of the finger length [3]. Therefore, finger width needs to be increased as length increases. As a result, large displacement comb drives are able to produce less force per unit area than optimized short throw assemblies.

The minimum displacement required for the electrostatic actuators used in the microengine is determined by the design of the rotating sub-assemblies and the technology rules that specify spacing and overlap requirements between the various fabrication layers. SUMMiT design rules dictate that the center of the pin joint, the point where the linkage arms attach to the gear, needs to be at least 17 µm from the hub center (figure 4). This implies that the comb drives need to be able to move +/- 17 µm from their neutral position. This is true for the "X" comb drive assembly. However, parasitic film protrusions that occurred during the fabrication of the linkage joints forced the "Y" comb drive displacement to be twice this radius or 34 µm in one direction and 0 µm in the other [10]. Most existing microengine data is based upon this geometry. Planarization of the

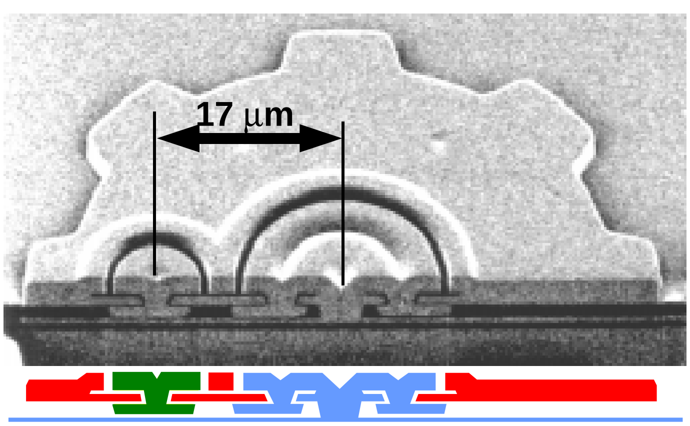

Figure 4. Cross section of early microengine output gear. Process design rules force the pin joint to be at least 17 µm

upper level of polysilicon now permits the same drive configuration to be used for both the "X" and "Y" actuators [11].

While design rules limit how close a pin joint can be to a hub, manufacturability issues limit the length of the support springs. Shorter springs consume less die area and increase the actuator resonant frequency. Longer springs, however, reduce operating voltage requirements. Microengines typically require peak drive signals on the order of 80-100 volts [10], so in most cases the longest practical springs are employed. The fabrication process ultimately limits the maximum length to about 500 µm. Surface micromachines are created by removing patterns of material from alternate thin (approximately 2-µm thick) layers of oxide and polysilicon [7]. These oxide depositions are often referred to as sacrificial layers since they are totally etched away during the final processing steps. Normally oxide is only used to support and help define the polysilicon during fabrication. Surface tension from the liquid etchant used to remove the oxide distorts and pulls on polysilicon structures. Features such as the support springs can easily be pulled down to the underlying substrate and remain adhered if they are made too long and compliant.

MULTI-LEVEL ACTUATORS

The force per unit area, reliability, yield, and robustness can all be simultaneously and substantially improved by utilizing most, if not all, of the layers available in a multi-level polysilicon technology to construct the comb drives. Actuator force is proportional to the thickness of the fingers [8], so defining a second layer of fingers on top of the first will essentially double the comb drive output without consuming additional valuable die area. The big gains, however, result from fabricating support springs above each other, and connecting them together at regular intervals (figure 5). The cubic relationship between thickness and the out of plane or "z" axis stiffness still holds true, and even the air gap between the polysilicon layers counts. The spring force constant will only double in the desired line of motion, and the additional level of fingers automatically compensates for this effect. Two 2-µm thick springs separated by 2 µm of oxide will be 27 times stiffer in "z" than a single 2-µm thick spring. This helps considerably in overcoming surface tension effects during the final release and thus increases initial yield. It also creates a structure that is much more robust and less susceptible to external

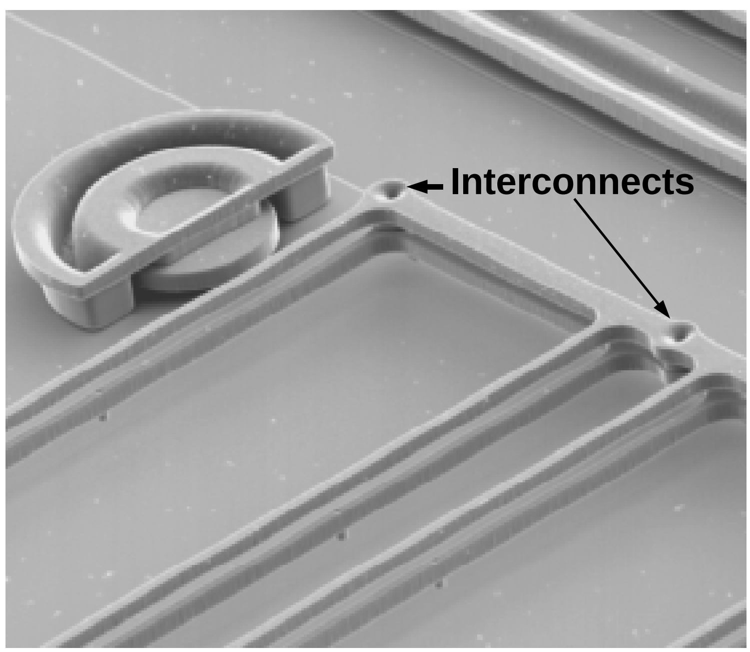

Figure 5. Outer edge of a multi-level folded beam support spring. Note the interconnects between the upper and lower sections that are required to make structure function as a single thick spring.

forces, which translates into increased reliability. Incorporating additional polysilicon levels in a similar manner will continue to increase these benefits [12].

OPERATION

We have previously reported detailed descriptions of the forces that act upon and the forces produced by an operating microengine, and how to create optimized drive signals that account for these forces [8,9,13]. Inertia on this scale is almost negligible, and without inertia to smooth out the ripples, precise timing and phase relationships between the drive signals become very important. Under some circumstances, microengines can be driven by simple sine waves. However, startup will be problematic, the output force will be highly non-uniform, and lifetime will be very limited. By using arbitrary waveform generators to implement the optimized waveforms, it has been demonstrated that microengine lifetime can be extended by many orders of magnitude (one microengine accumulated over 7 billion revolutions), and that a microengine driving an external load can endure millions of start/stop cycles.

Here we show a simple scheme for generating drive signals that can be quickly implemented while more optimized drive signals are being developed. Although it assumes that the engine will be operated well below its resonant frequency, this is generally not a problem. Typical resonant frequencies for existing microengines are on the order of 100,000 rpm [13], so this approach is generally good for tens of thousands of revolutions per minute.

First the slope of the voltage^2 vs. displacement line needs to be determined for the actual electrostatic actuators used in the microengine. This is best accomplished by fabricating test structures and the microengines on the same die. The test structures in this case are essentially comb drives without the linkage arms. Recall that $V^2 = x(k/a)$. Therefore the constant term, k/a, is equal to V^2/x, and its units are $V^2/\mu m$ [9]. These values are easily determined in the lab by recording the shuttle displacement at several points while ramping up the drive voltage. This data should plot a straight line over the intended operating displacement, and any deviations should be closely investigated. Figure 6 indicates a clamping situation where the parallel force attraction acting on the tip of the drive fingers exceeds that resulting from the well behaved fringe field before the required shuttle displace is obtained (34 µm in this case). This condition was later corrected by redesigning the structure to increase the gap at the tip of the fingers with the shuttle fully displaced.

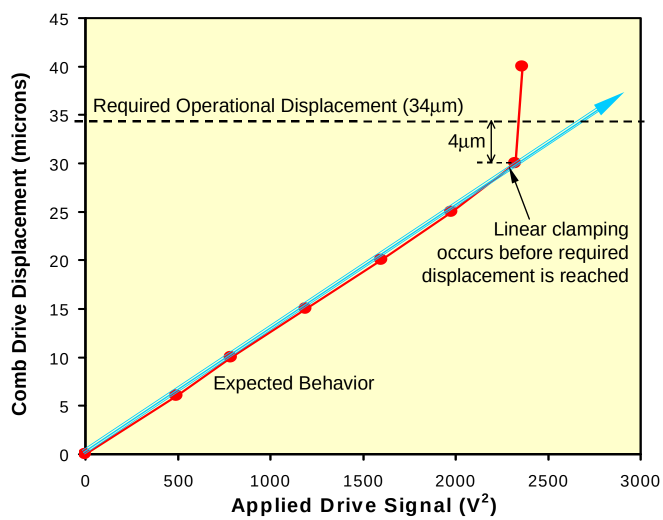

Figure 6. The expected behavior of this comb drive is interrupted by a parasitic parallel plate attraction before the desired displacement is obtained.

Now refer to figure 7, which shows a microengine drive gear in its neutral or fabricated position. X_0

and Y_0 represent the coordinates where the linkage arms connect to the pin joint, φ represents the angle this point is rotated from 0^0 about the hub, and r represents the radius or distance from this point to the center of the hub. Note that in this case X_0 and Y_0 are negative quantities, while r is always positive. The coordinates of the pin joint as the gear rotates θ degrees from this position are simply:

$$x = r\cos(\theta - \varphi)$$
$$y = r\sin(\theta - \varphi),$$

and the distance the pin joint is displaced in each direction from its neutral position is given by:

$$x = r\cos(\theta - \varphi) - X_0$$
$$y = r\sin(\theta - \varphi) - Y_0.$$

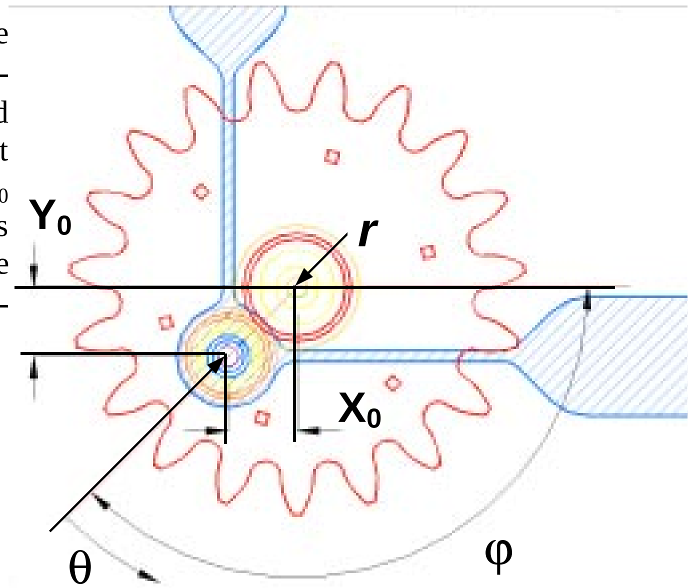

Figure 7. CAD drawing of microengine output gear with linkage arms.

The voltage required to displace the comb drives a given distance, *x*, is given by:

$$V = \sqrt{x(k/a)}$$

Therefore, the following voltages should be applied to each comb drive as function of θ:

$$V_x = \sqrt{[r\cos(\theta - \varphi) - X_0]\,k/a}$$

$$V_y = \sqrt{[r\sin(\theta - \varphi) - Y_0]\,k/a}$$

If V_x is positive, this voltage should be applied to the X comb drive so that it moves at 0 degrees, and if negative, this voltage should be applied to the X comb drive so that it moves at 180 degrees. Similarly, a positive V_y specifies Y comb drive displacement at 90 degrees, while a negative value specifies 270 degrees. Displacement is polarity independent; the sign only indicates to which side of the comb drives the voltage should be applied.

If friction and loading are negligible, leaving r at its measured value will produce a very smooth running microengine with almost no lateral forces on the hub. In order to overcome friction effects or to drive external loads, however, the value of r can be increased until reliable operation is achieved. The other constants, φ, X_0, Y_0, *k*, and *a*, should not be changed. Incrementing θ a few degrees per step is usually sufficient to obtain smooth operation. Increments greater than about 15^0 could begin to introduce binding and other problems.

MICROTRANSMISSIONS

In many cases, microengines may not produce enough torque to drive the desired mechanical load, since their electrostatic comb drives typically only generate a few tens of micronewtons of force. Fortunately, these engines can easily be driven at tens of thousands of revolutions per minute [8]. This makes it very feasible to trade speed for torque, and microtransmissions have been fabricated that demonstrate the practicality of this approach [14]. Such transmissions, or gear reduction units, can be fabricated in the same multi-level technology needed to produce the microengine, so additional processing steps are not required.

The first microengine/microtransmission assembly was used to drive a self-actuated mirror vertically out of its plane of fabrication (figure 8). It featured an overall gear reduction ratio of about 10:1 and generated a corresponding increase in torque. This particular design, however, was implementation specific. The more recent transmission shown in figure 9A was developed as a modular assembly that can easily be inserted between almost any microengine and micromechanical load. It is comprised of two dual level gears that provide an overall gear reduction ratio of 12:1, plus a third gear that can either be used as the output gear or as a coupling device that allows multiple units to be cascaded together. The assembly in figure 9B utilizes six of these modular transmission assemblies to provide a 3,000,000:1 gear reduction ratio and a 0.8 angstrom displacement of the output gear for each full turn of the microengine drive gear. By producing enough force to shear teeth off gears, it has been demonstrated that this configuration can dramatically increase the ability of electrostatic microengines to drive significant mechanical loads.

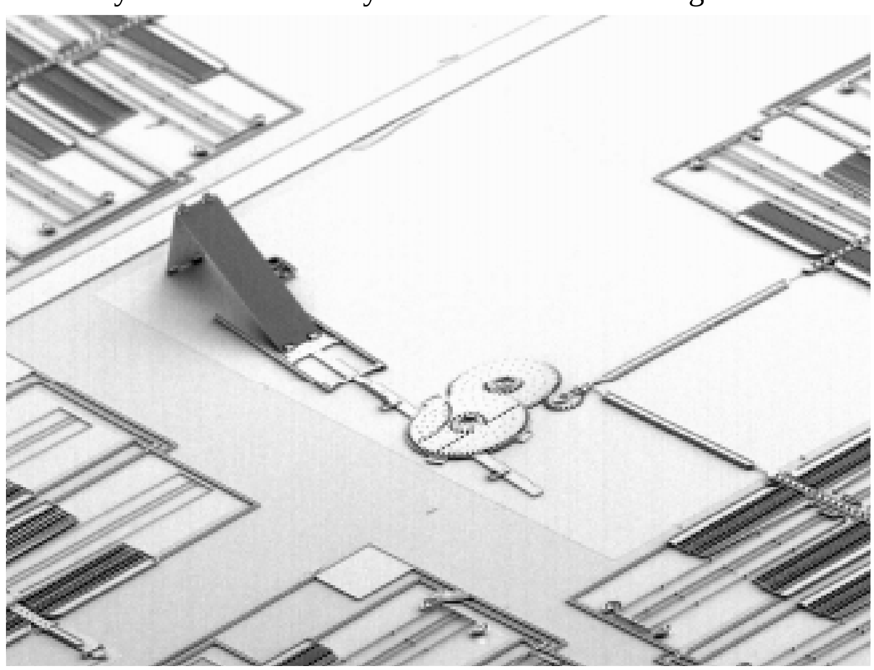

Figure 8. A 10:1 microtransmission assembly allows the microengine to pop up this self-positioning mirror from its flat fabricated position.

SUMMARY

A practical approach for designing and driving microengines that utilize orthogonal electrostatic comb drives as their actuation source has been demonstrated and proven. Since it is difficult to precisely model the slight asymmetries that may cause problems during operation, many of the parameters for existing designs have been optimized through laboratory evaluation. It is also difficult to predict at what point processing issues like surface tension effects will begin

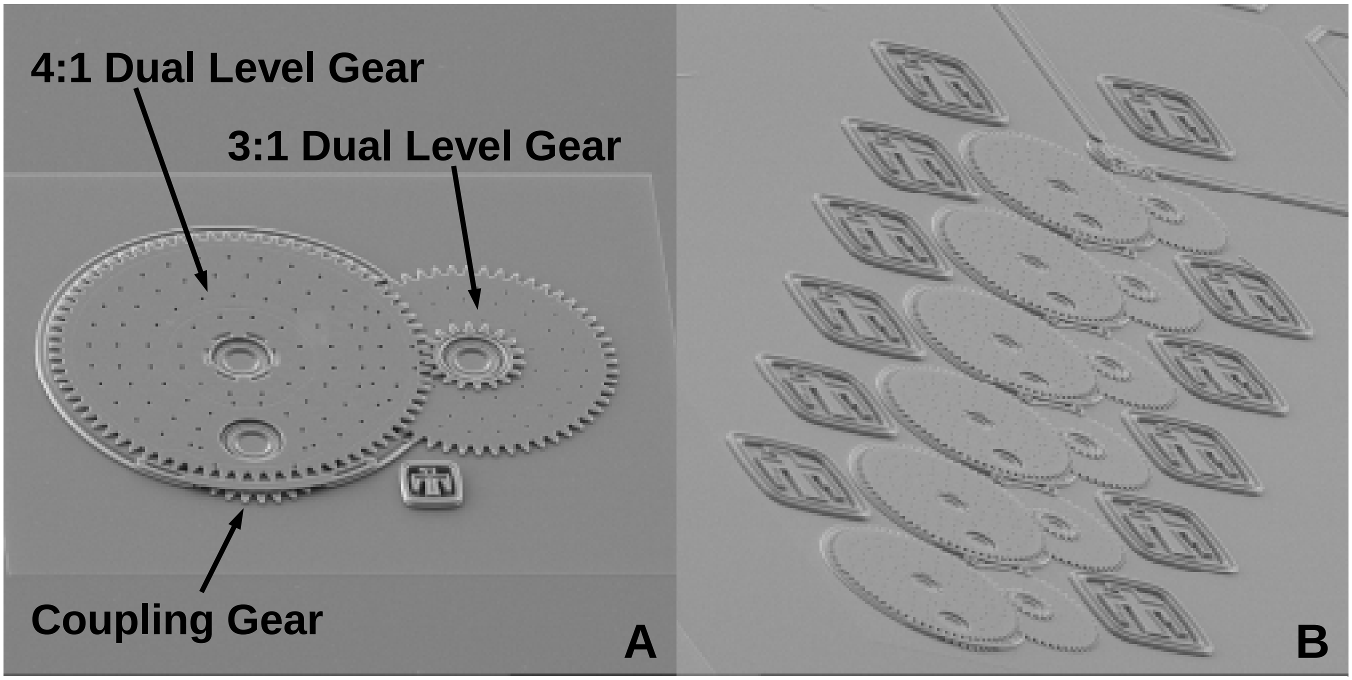

Figure 9. A) Each 12:1 gear reduction unit contains one 3:1 dual level gear, one 4:1 dual level gear, and one coupling gear. B) Six of these units are cascaded together to form a single 3,000,000:1 transmission assembly.

to significantly impact yield. Although the knowledge base is growing, the best approach in the meantime is to fabricate several variations of the same basic structure varying only one design parameter at a time. Drive parameters can also be finely tuned in the lab. Even though it may not be easy to experimentally determine independent values for k and a, the ration of these two constants can easily be obtained. Today's microengines are the result of years of continuous improvements in design, fabrication, and operation. Reliable actuation has permitted a significant expansion in the complexity of systems driven by these tiny engines, and this evolution will continue along with micromachine technology in general.

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