Inchworm-Motor-Driven MEMS Microgears in a single-mask SOI process

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ABSTRACT

We have demonstrated a novel approach to driving MEMS microgears with inchworm motors, a departure from conventional designs. To a first order approximation, the gears can be driven to 3000 RPM at relatively low voltages (< 50V). Higher voltages can yield higher forces and torque in driving the gear. Our test structures are fabricated in a simple single-mask silicon on insulator (SOI) process with post fabrication laser micromachining.

INTRODUCTION

In recent years, with the maturation of MEMS processing and design technology, researchers have moved towards the creation of increasingly complex mechanical systems. Of particular interest are devices such as inchworm motors, microgears, and linear racks and shuttles. As in the macroscopic world, figures of merit such as large force, large displacement, high torque, and high rpm (revolutions per minute) are design goals in MEMS actuation. MEMS microgears, though different on the size scale, serve the same function, to drive gear trains, and perform work [6]. Rotational motion needed to drive a gear, however, is not easy to provide. This has been done previously by such mechanisms as electrostatic comb-drive actuators [4], hula-hoop-like wobble motions circling a bearing [5], and piezoelectric actuators connected to drive belts [3]. In general, gears of this sort are fabricated in a complex multi-mask process such as Sandia National Laboratories' Summit V process [1], [2], [4], [6]. The general principle in each is the same: a linear actuator generates motion that pushes tangentially on a gear, causing it to rotate.

Another form of linear electrostatic actuation that has been shown to achieve respectable displacements and force densities is an inchworm motor. Instead of providing long, continuous motion, an inchworm motor moves in short, discrete steps. The driving mechanism of an inchworm motor successively engages and disengages its load, pushing it intermittently [7]. With proper coordination and alternation of these drivers, continuous movement can be achieved.

With these previously introduced notions in mind, we propose to drive a microengine gear with linear inchworm motors. The inchworm motors will be driven by a pair of gap-closing actuator (GCA) arrays that apply linear forces to rotate the gear, enabling the driving of gear trains, linear shuttles, and other loads.

SYSTEM DESIGN

The basic system design consists of three main components: (1) the inchworm motors, (2) the main gear being driven, and (3) a load that the main gear drives. A high-level block diagram is shown in Figure 1.

![High-level block diagram of inchworm-motor-driven gear](image)

Figure 1: High-level block diagram of inchworm-motor-driven gear

In this basic design, there are two inchworm motors, each consisting of two GCA arrays that engage the pawl in the x-direction with the gear (the clutch), and once engaged, move the gear in the y-direction (the drive actuator), respectively. These motors can either take turns rotating the gear (similar to the design in [7]) to provide a continuous motion, or run in phase to provide more net torque. Figure 2 demonstrates one cycle of the former.

ANALYSIS

When operating properly, the inchworm motors rotates the main gear, subsequently allowing it to drive other gears and loads useful in a number of applications. For the purposes of this analysis, we will simply consider an inchworm motor driving an unloaded gear. The required forces and features for multiple drivers and loading can be found by adjusting these results accordingly.

In this system, the drive actuator array must provide enough force to rotate the gear, while the clutch array must provide enough force to engage the drive array with the gear. To make the calculations simple, the gear is modeled by an inner circle of diameter $d_i$ (the fixed center) surrounded by a
of the frictional surface. This ring’s mass is given by:

\[ m = \rho \pi h \left( \frac{d_0}{2} \right)^2 - \left( \frac{d_i}{2} \right)^2 \]  

(1)

Given this, the static friction force can be found by:

\[ F_{fs} = \mu_s mg \]  

(2)

For silicon, the density \( \rho = 2330 \, \text{kg/m}^3 \), and the coefficient of static friction \( \mu_s = 0.3 \).

Following this, simple electrostatics and several equations in [7] can be used to derive a simple expression for the electrostatic force due to the actuator array.

\[ F_{electrostatic} = \frac{1}{2} \varepsilon_0 V^2 N \frac{A}{g_0} \]

\[ = \frac{1}{2} \varepsilon_0 V^2 N \frac{L_{ext}}{g_0} \]  

(3)

We equate the force expressions to find the minimum number of fingers needed in the drive array for various applied voltages, assuming a gap size equal to the distance between two gear teeth (since the actuator must rotate the gear enough to catch the next tooth after it resets itself). The results are shown in Figure 4, using a basic test structure with an outer diameter of 120\( \mu \)m, an inner diameter of 90\( \mu \)m, and 32 gear teeth being driven by a GCA with 100\( \mu \)m finger overlap.

### Voltage needed vs. number of fingers

![Voltage needed vs. number of fingers](image)

**Figure 4:** Graph showing the minimum applied voltage necessary to move the unloaded gear, as a function of the number of fingers in the gap-closing drive actuator.

#### Rotational Speed

Free ring made (the part that actually moves) by subtracting this inner circle from an outer circle of diameter \( d_0 \), as shown in figure 3.

![Free ring](image)

**Figure 3:** Simplified model of a gear used for analysis. We model the rotating gear as a ring rotating around a fixed center.

**Figure 2:** One cycle of inchworm motion driving the gear, which follows these steps: (a) initial stage, where neither inchworm is engaged; (b) one inchworm engages, while the other remains idle; (c) the first inchworm drives the gear; (d) the second inchworm engages the gear; (e) the first inchworm releases as the second drives the gear; (f) the first inchworm re-engages the gear.

**Force**

First, we consider the force needed to rotate the unloaded gear system. In this case, we only need enough force from the drive array to overcome the frictional forces on the outer ring (with diameter \( d_i \)) of the gear. To do this, we find the mass of the ring as the ring's weight acts as the normal force
Next, we look to find the angular velocity of the gear due to this gap-closing force. By considering the torque applied on the gear by the drive array, we can use the following equations from simple physics to find the angular velocity:

\[
\omega_{final}^2 = 2\alpha \Theta \\
= \frac{2}{I} \Delta \Theta
\] (4)

Approximating the gear as a hollow cylinder with outer radius \(d_o\) and inner radius \(d_i\), the moment of inertia of the gear is given by:

\[
I = \frac{1}{2} M \left[ \left(\frac{d_i}{2}\right)^2 + \left(\frac{d_o}{2}\right)^2 \right]
\] (5)

Using the same structural dimensions mentioned above for the basic test structure, we can theoretically achieve an angular velocity of up to 3000 RPM.

**FABRICATION**

Our structures are fabricated in a single mask silicon on insulator (SOI) process. As shown in the process cross-section in Figure 5, the SOI wafers consist of a 50\(\mu\)m thick silicon layer used to create device structures resting upon a 2\(\mu\)m sacrificial SiO\(_2\) layer. The silicon is etched to define structures, followed by a timed oxide etch, which undercuts silicon by 10 to 20\(\mu\)m, allowing small structures to be released and large anchors to remain attached.

![Cross-section of a structure in the single-mask SOI process](image)

**Figure 5: Cross-section of a structure in the single-mask SOI process**

It is important to note the difficulty to create a gear in a single mask process because of the impossibility to fabricate a pin joint. Therefore, in the fabrication process, a minimum width "sliver" is drawn between the gear and the anchor in the middle, keeping the gear from floating away during processing. Post fabrication, this can be laser-micromachined away, freeing the gear for motion. The design rules are followed in the test structure designs, though aggressively, with minimum spacings and widths appearing throughout the design. Careful processing must be done to ensure proper operation. Full design rules are available online at [http://www-bsac.eecs.berkeley.edu/~elliot/ee245/design.html](http://www-bsac.eecs.berkeley.edu/~elliot/ee245/design.html).

**TEST STRUCTURES**

We have laid out four test structures in the Cadence design environment to test the following cases:

1. **Basic unloaded gear**: This structure is conceptually identical to the schematic image used in Figure 2. We will use this structure to confirm and/or debug proper operation, and show maximum unloaded rpm.

2. **Second-gear load**: Here, the inchworm-driven gear from the basic test case drives another gear of the same size. This is a minimal gear train that can be used to do work.

3. **Gear plus Linear Shuttle load**: Extending the idea of the second-gear load, here we have the second gear doing work to drive a linear shuttle. The initial layout for this structure is shown in Figure 6.

4. **Force measurement**: To see how much force the gear can drive, we create our final test structure as shown in Figure 7. A main gear drives an equal sized “half gear.” A comb drive drives a stopper into the side of the gear with a given force dependent on applied voltage. The idea is to see how much friction force is required to balance out the driving force of the inchworm motors. This structure can determine the maximum amount of force that can be extracted from this inchworm driven gear.

**EXPECTED RESULTS & CONCLUSION**

Admittedly, the analysis that was performed is far from complete, and the results of the calculations may not be accurate. For instance, when approximating the rotating gear ring as a hollow cylinder, we ignore the effects of the individual gear teeth on the device’s rotation, and when calculating the force provided by the gap-closing actuators, only the electrostatic force between one gap (of each finger pair) was considered. Ultimately, these simplified approximations cannot compare to actual fabrication and measurement. In the worst case, we anticipate that our numbers will err on the side of not providing enough force to rotate the gear, since gear teeth design and loading have not been optimized. To compensate for this and provide more force, we have included many more fingers in the gap-closing actuator arrays driving the gear than calculated in our test structures. Barring any unanticipated problems in fabrication or friction between gear teeth, we believe that the system will function as expected with these adjustments.
Our design offers an alternative to conventional forms of microgear actuation that can be driven at lower voltages and/or higher force. Further exploration into this approach will (hopefully) yield its benefits over previously introduced methods of driving gears and the potential applications to microrobotics and other MEMS actuation, or ultimately prove the futility of our design.

References


