# Surface Micromachined Gear Trains Driven by an On-Chip Electrostatic Microengine

J. J. Sniegowski and E. J. Garcia

***Abstract* - Test results for a polysilicon, surface-micromachined, electro-statically-actuated micro-engine driving multiple gears are presented. The microengine provides output in the form of a continuously rotating output gear (50 micrometers in diameter) that is capable of delivering torque to additional geared mechanisms. The microengine can be operated at varying speeds and its motion can be reversed. A rotational speed of up to 200,000 revolutions per minute while driving multiple gears has been obtained. Drive of a 1600 micrometer diameter optical shutter has also been demonstrated. The resultant microengine and gear train, produced by polysilicon surface-micromachining techniques, are completely batch-fabricated without the need for piece-part assembly.**

## Introduction

Typically, surface-micromachined micromotors [1,2,3] have not demonstrated the availability for power take-off and drive of other microgeared mechanisms. One recent micromotor has a means of power take-off present in its design, but has not been used to drive other mechanisms [4,5]. Several gear-type elements have been demonstrated [6, 7], but have not been driven by on-chip means. In these cases, external means such as manual probe manipulation or directed gas streams have been used to activate the gears.

The present work is the first demonstration of polysilicon, surface-micromachined gears being driven by an on-chip micromachined engine. This demonstration illustrates the potential application of this microengine [8] as a drive and power source for micromachined mechanisms (micromechanisms that are also sized on the order of micrometers) such as optical switches, electrical switches, micropositioners, or any other micro-sized device requiring mechanical power. In addition to gear trains comprised of 2 to 4 additional gears, a 1600 micrometer diameter gear which acts as an optical shutter has also been rotated by the on-chip microengine. Thus, this work presents a proof-of-concept for driving geared micro-tools by on-chip microengines.

## Microengine Principle of Operation

For the microengine, we have taken the approach of adapting an array of linear electrostatic comb actuators [9] to drive a rotating output gear. The principle for its operation is shown schematically in Fig. 1 and is analogous to two orthogonal pistons connected to a crankshaft in an internal combustion engine. Specifics on the differences in design and details of the fabrication process relative to a macroscopic engine have been presented earlier [10,11]. The direction of rotation of the output gear is controlled by either leading or lagging the input of the actuator Y relative to X. Other linear actuators compatible with surface micromachining processes could also be used in place of the comb drives if they produce sufficient force and displacement [8, 12].

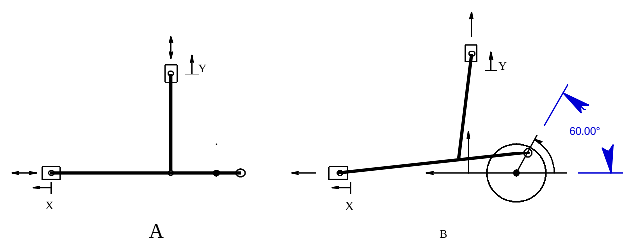


Fig. 1. Schematic illustrating the principle of operation for the microengine. Fig. 1A represents the as-fabricated or starting position, while Fig. 1B illustrates rotation through 60° by positive motion of both the X an Y linear actuators. The linear actuators are depicted as the rectangular boxes at the X and Y positions on the links to the circular gear.

Fig. 2 is a scanning electron micrograph of the output gear of the microengine connected to two additional gears to be driven, while Fig. 3 is an SEM of the entire microengine, including the linear electrostatic comb drives and a 1600 micrometer driven gear.

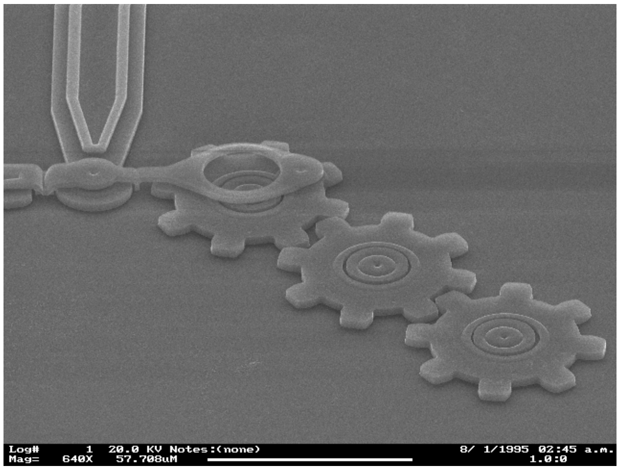


Fig. 2. SEM perspective view of the microengine output gear and two additional driven gears. Gear extreme diameter is approximately 50 micrometers and gear thickness is 2.5 micrometers.

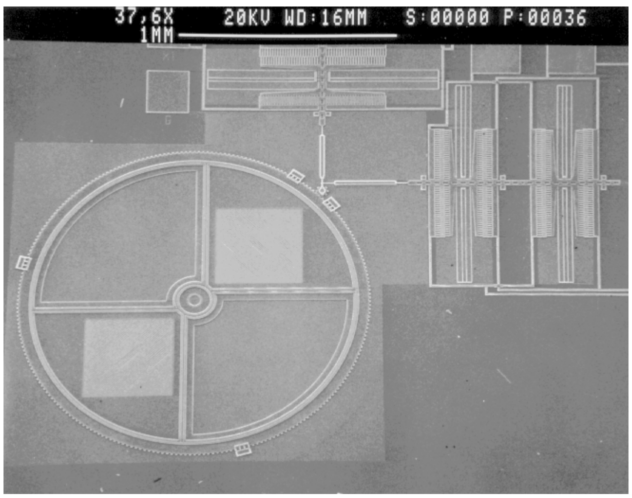


Fig. 3. SEM micrograph overview of the microengine and 1600 micrometer diameter optical shutter gear.

## Fabrication

The driving microengine and the driven gears are fabricated of polysilicon on a single wafer using surface-micromachining batch-fabrication techniques [13]. The fabrication of the device produces a complete microengine and driven micromechanism rather than relying on assembly of separately fabricated piece-parts. The basic concepts of surface micromachining have been modified and extended to allow fabrication of these parts. The microengine and driven mechanisms are formed using surface micromachining of multiple polysilicon films with intervening sacrificial oxide films. The fabrication of the microstructures, including the electrostatic comb-drives, the interconnecting linkages, the power output gear, and the driven gears, requires four depositions of polysilicon. The first of the polysilicon layers serves to provide a voltage reference plane and electrical interconnect, while the remaining three polysilicon layers serve to form the mechanical elements.

The basic gear tooth design is of the involute type. However, due to fabrication and layout constraints optimum tooth designs are not readily accomplished. A detailed explanation of the design and layout trade-offs made to accommodate for fabrication constraints is found in earlier reports [8,10,[14]].

## Results

Analysis [11] reveals that the microengine is capable of very high angular velocities. Average angular velocities of 40,000 rad/s have been predicted by an analytical model (40,000 rad/s is Å 380,000 revolutions per minute (RPM)) and measured velocities of up to 300,000 RPM, for the microengine alone, have been verified.

For the preliminary microengine tests, rotation of the output gear and gear train was achieved by the application of 90 V square wave inputs to the comb-drive actuators. This level of drive voltage agrees with model predictions. These tests were performed in ambient air and full rotation of single and multiple gear configurations was demonstrated. During tests conducted using low frequency square waves, the motion observed is similar to that of a stepper motor. With each step in the applied signals, the output gear moves to an equilibrium position and remains in that position until the next change of the applied signals. Due to the low inertia of these structures, the movement to the equilibrium positions occurs on a sub-millisecond time scale. Several devices were operated at square wave frequencies ranging from 0.5 Hz to 3333 Hz which corresponds to 30 RPM to 200,000 RPM. Fig. 4 is an optical micrograph at 250X magnification of the drive gear and gear train operating at 200,000 RPM.

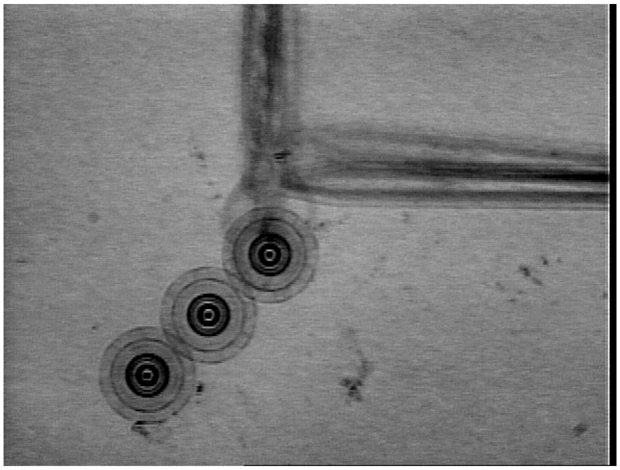

Fig. 4. Optical micrograph at 250X magnification taken during the operation of the microengine driving two additional gears at 200,000 RPM (50 micrometer gear diameter).

Experimental measurements of the gear angle as a function of time are shown in Fig. 5, where the measurements were obtained using a phase adjustable strobe light. The approximately constant angular speed is achieved using drive signals that result from dynamical modeling of the system. Without this type of predictive modeling, the output of the gear would not be constant angular velocity, but highly varying as given in reference [10].

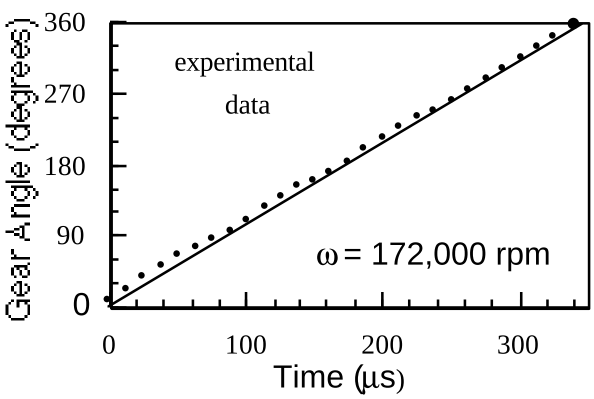


Fig. 5. Dynamical measurements of an engine output gear (driving no load) illustrates the ability to achieve controlled operation of the microengine, such as delivering constant angular speed.

Further, the dynamical modeling accounts for the inertial load of the output gears. For example, a simple step ramp of the drive signals to the engine produces a maximum speed of 600 RPM for the 1600 micrometer diameter gear, while a modified ramp of the drive signals as predicted by the modeling has allowed a speed of 4800 RPM to be obtained.

## Conclusions

Successful operation of a surface-micromachined, polysilicon microengine capable of transmitting motion and power to another geared micromechanism has been demonstrated. The implication of this success is that the basic microengine can be used to actuate and power other micromechanisms of comparable size. The microengine and gear train are completely batch fabricated with all links, joints, gears, and other elements formed as part of a batch process. The extremely small size of the microengine and gears permits achievement of output angular velocities of 200,000 rev/min.

This preliminary success demonstrated that several issues regarding friction and stiction [15] are not insurmountable in this type of device. We have now been able to use the microengine to drive a large gear with an optical shutter, a goal that provided the original motivation for developing these devices.

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