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TUTORIAL 5418

Driving Microelectromechanical Systems (MEMS) with Precision Control

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Abstract: The number of uses for microelectromechanical systems (MEMS) is growing—they allow us to do jobs once considered impossible. This tutorial explains the applications for MEMS and the increasing need to provide precision control and drivers for these devices. Design and manufacturing considerations are also discussed.

Driving a microelectromechanical system (MEMS) is much like driving a motor vehicle. It depends on the application. Motor vehicles run the gamut from a motor scooter to the largest trucks (**Figure 1**) used in mining operations. MEMS also serve diverse markets. As large as mining trucks can be, MEMS move in the opposite direction toward the microscopic (**Figure 2**).

Figure 1. A mining truck is one of the larger motor vehicles.

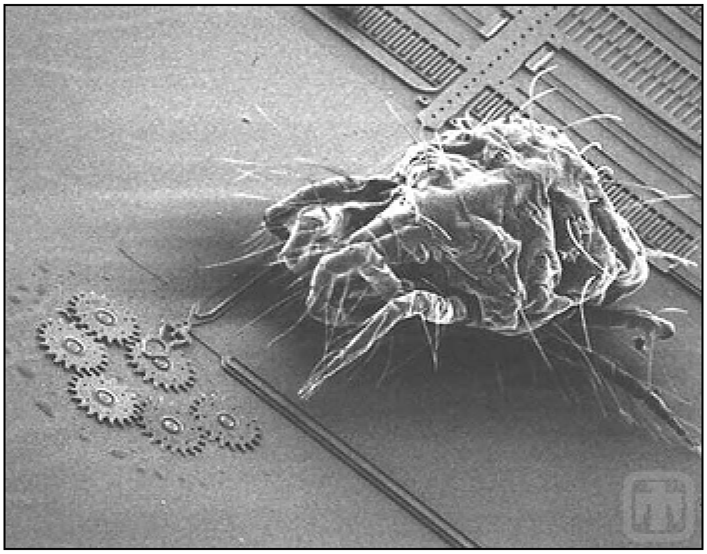

Figure 2. A spider mite (~0.5mm (~0.020 inches) long) on a MEMS to compare the gear size.[4] Courtesy of Sandia National Laboratories, Summit Technologies.

The variety of MEMS applications is as diverse as the human imagination. They range from inertial and noninertial sensors, accelerometers, actuators, switches, and relays, to fluid, gas, and biological sensors. They also include radio frequency (RF) wave guides, antennas, resonators, oscillators, filters, switches, optical microphones, gratings, and gyros[1, 2, 3]. The MEMS universe is exploding, as is the need to provide precision control and drivers for these devices.

To sort the MEMS applications, let's split them along a system usage line. Some are used for sensors and measurements. These MEMS produce the input to the system (left side of Figure 3). On the other end of the system, MEMS can be utilized as output devices to control, actuate, move, and produce results (right side of Figure 3).

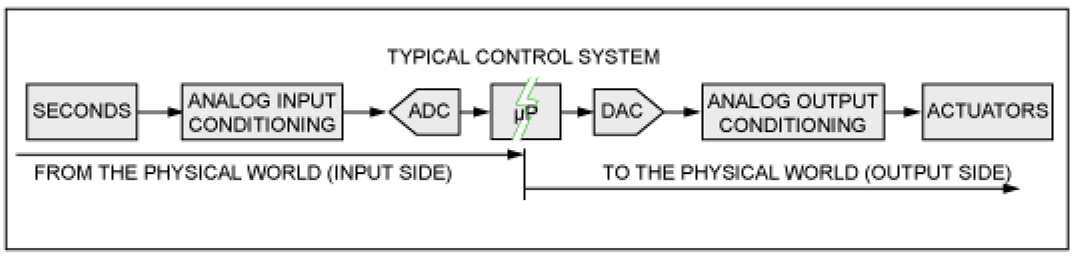

Figure 3. Splitting the MEMS market place by input and output function.

As with any analog-to-digital interface calibration for offset, gain and linearity may be required. To speed automatic testing, digitally assisted analog, such as a digital potentiometer (digipot) or digital-to-analog converter (DAC) may be convenient. When the noise on sensors is an issue, a very low-noise voltage reference can be used to supply power. More application notes, calculators, and system tips can be found here.

In general, MEMS are manufactured using modified integrated circuit fabrication (fab) techniques. As with any engineering endeavor, there are technical trade-offs. Decisions are made and gated by the laws of physics and the advancement of technology. Some aspects of the fab process that make ideal MEMS devices are not always the processes that make good integrated circuit components. Fab processes have had to be modified and invented to make practical manufacturable MEMS. As with many emerging technologies, there are many proprietary procedures at different manufacturers. As the field grows, more external drive circuits will become integrated onto the same die as the MEMS. External drive circuits are convenient to optimize and speed MEMS prototypes development. However, it is not always optimum, practical, or affordable to integrate every circuit with the MEMS. We will discuss ideas for MEMS drivers to stimulate designers and allow them to pick and choose the best mix of architecture for their applications.

Sensor Excitation

MEMS sensors, like all sensors, convert a change in physical parameter (e.g., pressure, movement, acceleration, light, or tilt) to a measurable change, typically in resistive, capacitance, voltage, current impedance, or resonance. Or, the reverse may occur—a change in electrical bias will result in a movement by the MEMS device (as in the case of a MEMS mirror array), as discussed later in this tutorial.

In sensors, signal to noise is a major limiting factor. The sensor signal may be amplified, filtered, and conditioned for offset and bias before being applied to an analog-to-digital converter (ADC). In addition to direct current excitation, more complex waveforms may be generated using DACs. Depending on the application, a complex waveform can be used to improve the signal-to-noise ratio (SNR) of the sensor system. Also discussed below is the use of a steam engine to cool an infrared (IR) sensor to improve the SNR.

A silicon pressure sensor is an example of a MEMS device that has been in use since the 1970s. Today, silicon strain-gauge sensors are inexpensive, have large output levels, and are relatively robust. However, there is a negative. These sensors suffer from large temperature effects and have a wide tolerance on initial offset and sensitivity. Tutorial 3545, "Resistive Bridge Basics: Part Two" focuses on the high-output silicon strain gauges. Pairing the characteristics of delta-sigma ADCs and current-driven silicon strain gauges can create simple ratiometric circuits. Calculation examples are provided to understand the ADC resolution and the dynamic range necessary to compensate these sensors.

MEMS sensor compensation has historically been based on an analog architecture. Increasingly, we see digital aiding analog circuits. High-performance calculating engines for digital-sensor signal processing (DSSP) are now practical for use in pressure sensors. Tutorial 743, "Approaches for Compensating Span and Offset in Pressure Sensors" details the DSSP architecture.

MEMS for Control and Actuators

Mirrors, gears, and motors are used to respond to output control signals. A motor-driven mirror like the one in Figure 4 is used to deflect laser communication light from one input to one of many outputs to act as an optical routing switch.

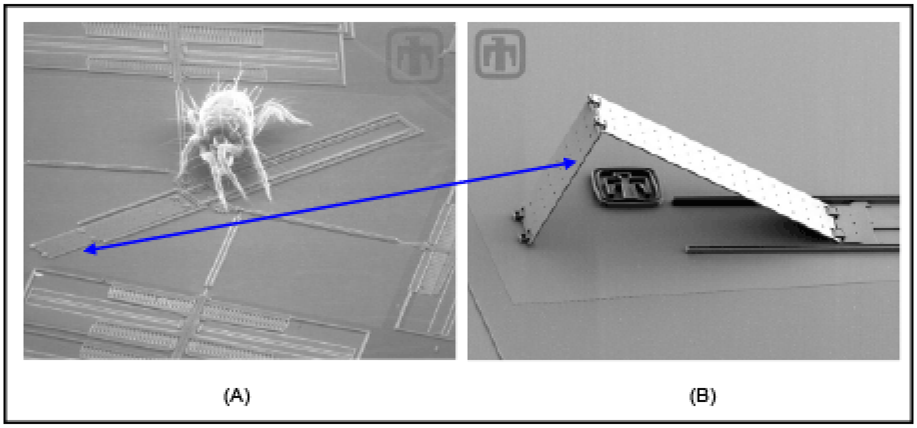

Figure 4. (a) A mite on a mirror assembly; (b) close-up of the elevated mirror. Courtesy of Sandia National Laboratories, Summit Technologies.

Actuators moving mirrors really use small motors if we define a motor or an engine as a machine that converts energy to movement. The next section emphasizes that conversion, and yes it does include microscopic steam engines.

Motors: Electrostatic, Magnetic and Steam Engines

The comb structure (**Figure 5**) increases the electrostatic motor's power. Instead of returning with a spring, a second comb structure can be used. Driving both combs differentially results in a balancing action that could use the small granularity of a precision DAC as an advantage.

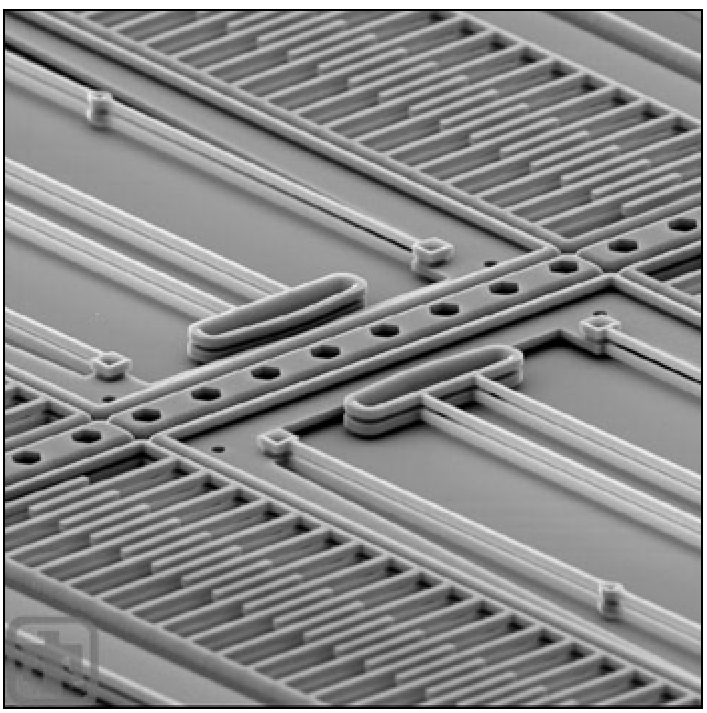

Figure 5. A comb motor. The springs in the center provide the restoring force, returning the electrostatic comb teeth to their original position. Courtesy of Sandia National Laboratories, Summit Technologies.

However, what if there are only a few or even only one set of plates with relative large spacing? The electrostatic force is not linear, it follows Coulomb's Law. The size, shape, and contour of the electrodes or plates control the shape of the attraction curve. This is why DACs are used to drive such nonlinear devices. By picking and choosing digital values, we can approximate any arbitrary curve.

Let's say we need an exponential curve at one end (the left end for this discussion). Change occurs slowly, so here we might need a granularity of 6 bits. At the opposite right end of the curve, the rate of change is must faster, so we may need 16 bits for approximation. So a 16-bit DAC is used; on the left side, codes are skipped to give 6-bit resolution. As we progress from left to right, the number of codes skipped progressively decreases until at the right side, we are using all of the 16-bit codes. This waveform fitting can be measured and placed into memory to calibrate a given device. Or a general or typical curve may be adequate, depending on the application.

MEMS magnetic motors operate using magnet attraction and repulsion just like bigger motors. External wire coils can motivate the MEMS, or coils can be integrated into the MEMS structure. With a two-phase stepper motor and the circuit in **Figure 6**, we can drive the stepper with the appropriate power levels. One DAC and amplifier drive phase one and the other DAC and driver will serve phase two. Other motors may require three, four, or more phases. A square wave of the proper phase difference between phase one and two will cause the motor to run clockwise or counter clockwise. Why would one derive a square wave using a pair of DACs, let alone a precision DAC? Here are two reasons: at microscopic sizes, atomic forces add to the normal friction and stiction. It may be desirable to increase the drive amplitude for a few cycles to start movement and to hold position; reducing the drive current will reduce power dissipation. The second reason is that a stepper-motor phase can be smoothed and more precisely controlled by applying a sine wave or other waveform to provide acceleration and position control.

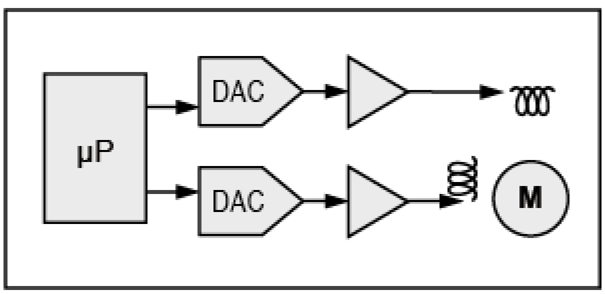

Figure 6. Motor driver for a two-phase stepper motor.

At first, a MEMS steam engine seems like a return to the past on an integrated circuit. We love seeing and hearing a steam locomotive on railroads, why bother on a MEMS? Steam has some great characteristics—the piston engines driving the wheels on railroads have maximum torque at zero revolutions per minute (RPM), exactly what is necessary to move large loads.

To a MEMS device, just about everything in the universe is a large load. A steam engine only needs a source of heat to operate. The fluid needs to change from liquid to vapor and back at a convenient temperature. And where we are trying to reduce heat in most circuits, heat now becomes our friend. When we think about a heat pipe with a fluid transferring heat from one area to another, we might think of it as an engine that doesn't do external work as a steam engine does. So as bizarre as it sounds, **Figure 7** illustrates a MEMS steam engine.

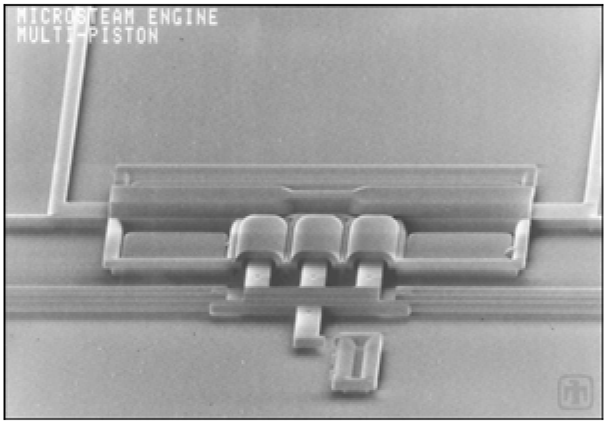

Figure 7. A triple-piston microsteam engine. Courtesy of Sandia National Laboratories, Summit Technologies.

Water or other fluid inside of three compression cylinders is heated by electric current and vaporizes, pushing the piston out. Capillary forces then retract the piston once current is removed. A movie of a single piston steam engine operating is available.[5] A very practical application of a steam engine is a Sterling engine used as a refrigerator for cooling IR sensors and low-noise amplifiers (LNAs).

Faster operation is possible with electrostatically driven mirrors.

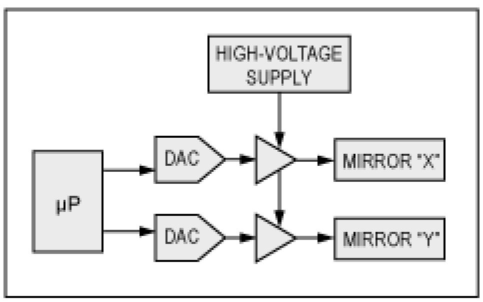

Figure 8. The drive circuit for a two-quadrant electrostatic mirror.

Electrostatic MEMS devices often require high DC-bias voltages (40V to 100V) at low current (< 1mA), but the available supply voltage may be < 12V. Application note 1751, "High-V DC-DC Converter Is Ideal for MEMS (Warning: High-Voltage Circuit)" highlights a DC-DC converter that combines inductive and capacitive step-up circuitry, achieving the high voltage without the need for a costly transformer.

Examples of MEMS-Based Products

One use of a MEMS device is in the DS3231M, a low-cost, extremely accurate (±5ppm), I²C real-time clock (RTC). A MEMS resonator provides the oscillation frequency, and the resonator is mounted on top of a digital logic chip that contains the phase-locked loop (PLL) and other control logic. The device incorporates a battery input and maintains accurate timekeeping when main power to the device is interrupted. The integration of the MEMS resonator enhances the long-term accuracy of the device, shrinks the size of the RTC, and reduces the piece-part count in product manufacturing.

The uses for MEMS are growing—they allow us to do jobs once considered impossible. Biological applications can produce and monitor chemicals inside our bodies, and there is the potential to diagnose, treat, and cure many diseases that trouble mankind. "MEMS-inside" machines are proliferating in many fields.[3] As MEMS devices are invented, electronic engineers will invent and adapt analog and digital circuits to optimize driving MEMS.

References

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4. The spider mite is alive, one can see a movie of him riding on a gear: http://mems.sandia.gov/gallery/movies_bugs_on_mems.html.
5. A movie of an operating steam engine: http://mems.sandia.gov/gallery/movies_steam_engines.html.
6. Selected application notes for RTCs:
   Application note 504, "Design Considerations for Maxim Real-Time Clocks"
   Application note 3506, "Interfacing a DS3231 with an 8051-Type Microcontroller"
   Application note 3644, "Power Considerations for Accurate Real-Time Clocks"
   Application note 3816, "Selecting a Backup Source for Real-Time Clocks"

Related Parts		
DS3231M	±5ppm, I²C Real-Time Clock	Free Samples
MAX3600	Laser Driver for Projectors	Free Samples
MAX5621	16-Bit DACs with 16-Channel Sample-and-Hold Outputs	Free Samples
MAX5631	16-Bit DACs with 32-Channel Sample-and-Hold Outputs	
MAX5632	16-Bit DACs with 32-Channel Sample-and-Hold Outputs	Free Samples
MAX5633	16-Bit DACs with 32-Channel Sample-and-Hold Outputs	
MAX619	Regulated 5V Charge Pump DC-DC Converter	Free Samples

Application Note 5418: http://www.maximintegrated.com/an5418
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