Micro-Electro-Mechanical Systems: Scaling Beyond the Electrical Domain
Clark Nguyen

Smaller is better.

Probably not a phrase you'll hear often in everyday conversation, but one that curiously rings true time and again in the Microsystems Technology Office.
After all, smaller has certainly been better in the electrical domain, where computer chips run faster, consume less power, and simply do more things, as the transistors they're made of get smaller and smaller.
But can one really say that "smaller is better" in a more general sense?
I mean, how many other things in this world really get better as they get smaller?
As I'll explain in the next few minutes, quite a few things, including and especially mechanical ones.
In fact, the advantages of scaling in the mechanical domain are so compelling that technologies capable of shrinking mechanical mechanisms, such as Micro Electro Mechanical Systems (or MEMS) technology, might very well be THE catalysts for an upcoming revolution in mechanical applications to rival the recent integrated circuit revolution for electronic applications.

DARPA began funding the development of MEMS technology in the early 90's, and in these early years, MEMS technology could be described literally as the use of fabrication methodologies and tools similar to those used for planar integrated semiconductor circuits, but now applied to make movable mechanical microstructures on chip.
In this period, MEMS technologies were driven mainly by their ability to reduce the size of numerous applications and by their compatibility with integrated circuit transistors.
As an example of compatibility, a polysilicon surface-micromachining process involves depositing films of polysilicon, oxide, and nitride-which incidentally are the exact same films needed in CMOS processing-patterning them to delineate microstructures and form vias, the same way CMOS gates and contacts are done, and releasing structural layers by etching sacrificial layers underneath them using the same wet etchants used in CMOS processing.
Once released, movements well out of the plane of a silicon substrate are possible.
And all this attained using the same equipment found in IC fabs.

This compatibility with CMOS or other integrated circuits was deemed extremely important in the early 90's, because at the time it was actually assumed (and incorrectly, as we soon discovered) that small size meant poor mechanical performance, and thus, low noise signal conditioning circuits were needed to compensate.
As a result, the roadmaps for MEMS in this era often consisted of plots of the number of micromechanical elements versus the number of transistor elements, and the farther a device stretched out into the upper right hand corner of this curve the more advanced it was considered.
And considering the number of useful devices it turned out, this roadmapping philosophy was a good one, and was probably the right one at the time.
Among the devices that rolled out of this roadmap and that benefited enormously from DARPA funding were: MEMS-based accelerometers that can now be found in nearly every vehicle sold today, as the principle device deploying the airbag during an accident; microfluidic devices capable of handling tiny volumes of fluids to diagnose a given patient in record time; probe-based data storage devices capable of storing 1 Tb/in2 of data in nm-sized holes, all accessed quickly using mechanical elements; and optical MEMS devices, such as the TI digital micromirror device (or DMD): millions of tiny MEMS mirrors that work together to give us the sharpest in video quality ... and I should say, even at this very moment, since the projectors that project the images you see beside me are using this same DMD technology.
More importantly, MEMS technology is now interspersed throughout the different offices at DARPA, and can now be found in several MANTECH programs as the technology is transitioned into actual DoD applications.

The Army's Common Guidance Common Sense program, which attempts to use MEMS accelerometers in high-g munitions guidance applications, is an excellent example of this.

Although very successful at fueling MEMS development in the early 90's, this plot of "number of MEMS versus number of transistors" is no longer the best roadmap for military applications of MEMS today, and is even less so looking forward towards the future of MEMS technology.

The reason is that it conceals the fact that the performance of MEMS devices is much less coupled to the transistors they're integrated with than to the performance advantages obtained by scaling of the MEMS devices alone.

For example, the digital micromirror device can work with sufficient speed in its video application because tiny mirrors can move much faster than larger macro-scale counterparts; in other words, the smaller a mechanical device, the faster it is.

Today's focus in MEMS technology at DARPA recognizes first that performance is paramount for military applications, and second, that scaling of mechanical devices is the key to attaining the needed performance.

In particular, as a mechanical device becomes smaller, it becomes faster, it consumes less power, it can be more easily integrated together with other mechanical (and non-mechanical) devices to create more capable mechanical circuits, and it costs less.

The degree to which scaling can improve the performance of a mechanical device is quite substantial, and examples of scaling-induced advantages are on the rise throughout the existing and up-and-coming MEMS-based programs at DARPA.

Perhaps the most direct example of how brute force scaling leads to orders of magnitude increases in mechanical speed is what happens when one shrinks a guitar string down to micron-scale dimensions.

On the macro-scale, a guitar string made of nickel and steel, spanning about 25" in length, and tuned to a musical "A" note, will vibrate at a frequency of 440 Hz when plucked.

In vibrating only at 440 Hz, and no other frequency, this guitar string is actually mechanically selecting this frequency, and is doing so with 100 times more selectivity than an on-chip electrical circuit could do.

Interestingly, selecting a frequency like this is exactly what a wireless phone must do, except it must do so at much higher frequencies, from the 30-88 MHz VHF range of military SINCGARS, to frequencies well into the GHz range.

In order to achieve such frequencies with superior mechanical selectivities, researchers in the Nano Mechanical Array Signal Processors program, managed by Dr. Dan Radack, are shrinking guitar strings from 25" down to only 10 microns, constructing them in stiffer, IC-compatible materials (like polysilicon), and exciting them electrostatically or piezoelectrically rather than plucking them.

In this fashion, through brute force scaling, frequencies around 100 MHz with selectivities more than 1,000 times better than achievable via electrical circuits have been attained.

By changing the geometry from a flexural-mode beam to an extensional-mode disk and using polydiamond as the structural material, vibrating mechanical resonators have now reached frequencies on the order of 1.5GHz with selectivities still more than 1,000 times that of electrical circuits.

This is far and away the best frequency-selectivity capability achieved to date at this frequency by any on-chip integrated device at room temperature, and beyond sheer size reduction, has revolutionary implications for the RF front-ends in military communications.

This kind of performance begs the question:

"How might I change my communication architecture to take advantage of this brand new on-chip frequency selectivity that allows me to use as many ultra-selective, high-Q resonators as I please?

Is RF channel-selection now possible?"

Probably questions worth considering for a new DARPA program.

Another important illustration of the advantages of mechanical scaling can be found in the Chip-Scale Atomic Clock program, which is a program that attempts to reduce the size of some of our most accurate atomic timing references from the large 60W tabletop versions used in GPS satellites, down to a one cubic centimeter, 30 mW size capable of fitting onto a wristwatch.

Since time is effectively the same as location, such a portable atomic clock would make possible operations in GPS-denied environments, including navigation, tracking, and targeting.

Atomic clock timing and frequency stability in a portable size would also make possible jam-resistant GPS, high security communications with ultra-fast frequency hopping rates, high-channel density communications, high-confidence identification of friends or foes, and missile and even munitions guidance.

Like quartz oscillators and clocks, atomic clocks function by generating a very stable frequency off of a very stable reference.

The main difference is that a quartz oscillator derives its frequency from a mechanically vibrating reference, which makes its frequency subject to long-term changes in mechanical dimensions and stress.

An atomic clock, on the other hand, derives its frequency from the energy difference between the hyperfine states of an alkali metal atom, which is a constant of nature, and thereby, much more predictable and stable.

Unfortunately, however, the alkali metal must be maintained in a vapor state to operate the atomic clock, which means power must be consumed to heat the atomic vapor cell.

For a tabletop atomic clock, this takes tens of watts of power.

But when one shrinks the atomic cell to less than 10 cubic millimeters, which represents a 50,000X reduction in size, the amount of power needed to keep the atoms in a vapor state reduces to a projected value of less than 10 mW.

In effect, the smaller the mechanical structure, the less power it takes to heat it to a given temperature ... and less by several orders of magnitude!

And power is really the big deal here, more so than size.

It's the low power consumption that separates a MEMS-based atomic clock from any other and makes it deployable in the largest number of portable applications, including and especially the tiny microsystem applications described by Zach Lemnios before me.

After all, the performance of our best military electronic systems is often limited by the performance of the clocks they use, and the size and power consumption of atomic clocks is partially responsible for keeping our best capabilities on tabletops, and out of the hands of our soldiers.

As a result, soldiers today are forced to access our best electronic capabilities remotely.

When the Chip-Scale Atomic Clock program delivers a tiny clock that operates on only milliwatts of power consumption, this remote-access paradigm can change, and more of our best capabilities can be placed right in the hands of our soldiers, making them invincible even in GPS free environments.

We actually now have a first working chip-scale atomic clock ... not yet with the power performance or stability goals of the program, but close, and getting ever closer.

Close enough, in fact, to start contemplating other uses of atomic cell technology.

For example, could chip-scale atomic magnetometers be next, with the same low power advantages of the clocks?

And speaking of power, micro-scale miniaturization using MEMS technology is also being employed to make available tiny power sources with higher energy densities than conventional batteries.

In particular, the Micro Power Generation program has been constructing tiny micromachined fuel cells and microengines that can harness high density hydrocarbon fuels with efficiencies from 20-40%, yielding effective energy densities more than 10X that available from conventional batteries.

Among the successes so far in this program are tiny formic acid fuel cells capable of producing 150 mW/cm2 of power; a micro solid oxide fuel cell using a swiss roll counterflow heat exchanger to produce a micro-scale record 370 mW/cm2; and a miniaturized Wankel rotary engine producing 4W of output power.

In these applications, size reduction leads to large surface-to-volume ratios, which on one hand force creative thermal loss management solutions, but on the other hand enhance capillary forces to allow pumpless operation and allow better efficiency in power generators based on heat emission and collection, such as thermophotovoltaics.

Small size also allows some micro engine designs to take full advantage of chamber resonances for higher efficiency.

With an already successful MPG program, what's next?

Well, one need only consider the fact that hydrocarbon fuels, although much better than conventional batteries, are still nowhere near the most energy dense fuels around.

To find out where we're going next, just look around for fuels with even higher energy density and think of ways that scaling can improve the efficiency of their converters.

Yet another application where larger surface-to-volume ratios obtained through scaling proves quite beneficial is that of chemical sensing.

For example, some our best tabletop chemical sensing instruments first separate a mixture of analyte and interferant chemicals before it is received by a detector.

This substantially eases the job of the detector and leads to a lower incidence of false alarms-something badly needed in fielded chemical warfare agent detection systems today.

Unfortunately, today's methods for separating gas mixtures are too slow and power hungry to be used on the battlefield.

For example, a tabletop gas chromatograph, in which different chemical species are separated by their interactions with the walls of a long tube as they proceed down this tube, can take upwards of 15 minutes to separate out a sample.

By scaling the dimensions of the tube by several times using MEMS technology, large surface-to-volume can again be employed to greatly enhance gas-to-wall interactions, and speed up the separation process to the point of taking only seconds now-a potential for 300X improvement!

And on top of this, because of its now much smaller size, the column takes only milliwatts of power to heat for temperature ramping, as opposed to several watts on the macro-scale-all on the order of about a 1000X improvement.

A new program, titled Micro Gas Analyzers, just kicked off to take advantage of scaling for chemical sensors.

In the meantime, there remain a plethora of unexplored opportunities in applications that can benefit from mechanical device scaling and that raise interesting possibilities.

For example, with the impressive read and write speeds already demonstrated in probe-based data storage devices, can a scanning probe be used to direct write lines of semiconductor material and eventually construct a VLSI circuit using advanced transistors in a reasonable amount of time? Can a scanning probe be used for input/output addressing of molecular circuits?

Is it possible to implement a completely mechanical circuit that perhaps does computation in the frequency domain, rather than the time domain, with power and speed advantages for a certain set of problems, and superior radiation hardness relative to existing technologies? Would this circuit need to be on a nano-scale, rather than micro-scale, to attain the needed speeds? These are the types of questions and opportunities that should fuel continued interest in micromechanical, or perhaps soon, nanomechanical technologies, at DARPA.

In conclusion, if what I've said in the last 15 minutes regarding scaling sounds very familiar, then maybe it should.

In fact, the scaling advantages just described for mechanical devices nearly exactly parallel those already seen for transistors during the integrated circuit revolution.

Specifically, smaller size leads to faster speed, lower power consumption, greater complexity, and lower cost.

Could MEMS, or soon-to-be NEMS, for nano electro mechanical systems technology, be the "IC revolution" for applications that use mechanical devices?

If so, is there a killer application, equivalent to the microprocessor, just waiting in the wings for MEMS technology to catch up to it?

In my opinion, definitely a question worth pursuing.