Dr. Clark T.-C. Nguyen
Microsystems Technology Office
Micro-Electrical-Mechanical Systems Programs at MTO

Micro-electro-mechanical systems, or MEMS, is one of three core enabling technologies being pursued by the Microsystem Technology Office. As such, MEMS technology presently forms the foundation for many new and exciting programs at DARPA.

Throughout the last decade, DARPA has funded numerous projects to demonstrate MEMS in a range of potential military applications. One can find examples of MEMS technology in all four military domains: land, sea, air, and space.

For land applications, such as precision munitions, MEMS rate sensors have been tested as key elements within ultra-miniaturized guidance systems. Such MEMS-based sensors are not only small enough to fit inside severely size-limited platforms, but powerful enough to provide the required performance accuracy and rugged enough to survive 50,000 g's of shock during deployment. No other commercially available rate sensors have survived such tests and, due to their tiny size, these MEMS rate sensors have the potential to lower the overall cost of the guidance package for this application.

For sea applications, we are funding development of the safe-arm-and-fuze unit for the next-generation anti-torpedo torpedo (ATT), which, among other attributes, must be small, fast, agile, and precise. For this particular application, conventional components from substantially larger torpedoes simply cannot satisfy the performance requirements and volume constraints of the ATT. On the other hand, the tiny size of MEMS devices make them ideal candidates for use in this application.

Using commercially available MEMS flow sensors, pressure sensors, and accelerometers, as well as custom-designed MEMS fuzing devices, we have developed a safe-arm-and-fuze device that is more than 100 times smaller than the conventional counterpart, and recent sea-run tests have shown that this MEMS exploder satisfies all the basic functional requirements of the platform. One example of an air application is the microshear stress sensor developed at Caltech that has recently been tested side-by-side with a state-of-the-art commercial sensor on an F-15. The MEMS device is 4 orders of magnitude smaller than its Stanton counterpart and consumes far less space and power. Most important, it outperforms the competition, exhibiting 10 times the response bandwidth. In fact, using this MEMS shear stress sensor, we were able, for the first time, to accurately resolve high-frequency fluctuations in shear stress resulting from turbulent flow around the plane—a very important breakthrough previously unachievable by conventional devices, but made possible by MEMS technology.

And finally, for space applications, MEMS technology is being utilized in pico satellites, which are tiny versions of what we normally think of as satellites, each weighing less than 1 kg. The goal of the DARPA pico satellite program is to develop a low-cost space platform to demonstrate MEMS sensors, actuators, and communication components in space. Potential uses for ultraminiaturized satellites include cooperative constellations, sparse aperture antennas, inspection and servicing missions for other space vehicles, and launch-on-demand robust communications and surveillance systems for short-term missions.

So far, we have successfully launched, deployed, and operated two separate pico satellite test missions. In these demonstrations, MEMS-based devices not only survived the harsh launch procedures, they also functioned well in the space environment. In particular, low-loss RF MEMS switches, which are important for communications antenna reconfiguring applications, were successfully operated on pico satellites.

Speaking of communications, one of the most critical factors in establishing battlefield superiority is timely and accurate information and assessment of the theatre. A distributed, wireless microsensor network that can be quickly deployed would be able to establish surveillance and intelligence gathering in a way never before possible.

In addition, with the availability of such sensor networks, one can implement condition-based maintenance, health monitoring, and environmental monitoring on a range of platforms, including battleships, aircrafts and rotorcrafts, land vehicles, and space-borne platforms. We've demonstrated such a wireless diagnostic sensor network on board the USS Rushmore, and field-tested another at 29 Palms to detect land vehicles and troop movement using distributed wireless seismic and acoustic sensors. Given the impact that previous MEMS-based programs have had on military platforms, the development of MEMS technologies by MTO continues in several new programs.

Micro Power Generation (MPG) is one of three new MTO programs enabled by MEMS technology. The goal of the MPG Program is to generate power at the microscale in order to enable stand-alone, perhaps embedded, microsensors and micro-actuators. The packages for these semi-autonomous devices are also expected to house wireless communication and on-board electronics, all of which require additional on-board power. To provide sufficient power for true autonomy in these systems, we must explore alternatives to existing batteries. One promising alternative is to use a battery fuel with a higher energy density. In particular, chemical energy storage in the form of solid or liquid fuels is inherently much higher in density than the best lithium ion batteries. For example, the energy density of methane is more than 12,000 W-hr/kg, which is at least 100 times higher than the best batteries. With these numbers, even assuming a modest conversion efficiency of 10 percent, a methane-based electric generator should still last 10 times longer than an equivalent battery. The success of this program will enable new strategies for weapons systems and battlefield monitoring.

There are several approaches by which chemical energy can be extracted in the micro scale. One is to create micro-internal combustion engines to generate mechanical outputs as in the case of the UC Berkeley microrotary engine. Another is to convert thermal energy into electricity using thermoelectric generation, as done by the Princeton combustion chamber. In both cases, we have demonstrated the capability to machine high-temperature materials, such as SiC and alumina, to create microcombustion engines and combustion devices. One of the most important breakthroughs thus far demonstrated is self-sustained combustion within a 1-cubic-mm chamber using hydrogen and air in the fuel mixture.

The University of Southern California is funded to pursue another project based on thermoelectric conversion. In this approach, a microcombustor is fabricated using a unique micromachining technique that allows the creation of true three-dimensional structures, in which long counterflow channels are rolled up in three dimensions to maximize the thermoelectric element surfaces between the cool in-coming reactants and the hot combustion products. This design also minimizes the loss of thermal energy to the environment.

One of the keys to this approach lies in the ability to fabricate and integrate thermoelectric elements on the surfaces of the counterflow channels. Fortunately, the prospects of doing this are aided somewhat by the fact that this design contains no moving parts in the core of the elements.

Another approach to micropower generation is the micro-fuel cell concept funded at Case Western Reserve University. A conventional fuel cell consists of a proton exchange membrane, or PEM for short, that extracts electrical energy from hydrogen and oxygen. One of the key innovations in this project that facilitates a MEMS-scale implementation is the use of sodium borohydride as the source for hydrogen, eliminating the need for a cylinder of compressed hydrogen gas and allowing substantial size reduction. Parallel to this approach, Battelle is developing a micro-fuel reformer to extract hydrogen from liquid fuel, which will then be integrated into another variation of the micro-fuel cell.

A second, recently established MEMS-enabled program is titled "Nano Mechanical Array Signal Processors." In this program, we are developing arrays of nanoprecision, mechanically vibrating resonators that operate at the UHF band for frequency-domain, analog signal processing, such as needed for wireless communication applications. The program goal is to achieve 100 times reduction in size, 100 times reduction in power consumption, and 10 times improvement of spectral efficiency compared to conventional electronic means for frequency processing.

The basic incentive for this program comes from the observation that when used as a passive frequency filter, a mechanically vibrating resonator is inherently superior to a CMOS circuit in performing analog signal processing in the frequency domain. For example, a conventional superheterodyne transceiver relies on a number of off-chip passive components, including SAW filters, inductors, capacitors, and quartz crystals. All these off-chip components perform functions that manipulate analog signals in the frequency domain, and they do these functions with several orders of magnitude higher frequency selectivity than possible using conventional integrated circuits. However, these off-chip components are relatively expensive and bulky, often occupying up to 80 percent of the real estate on a typical cell phone PC board. If we can eliminate them by integrating MEMS resonators that perform the same functions directly onto the CMOS circuits, we can dramatically decrease the size of the entire transceiver and lower the cost of manufacturing.

But attaining smaller size and cost really only scratches the surface of what microresonator technology can deliver. As a matter of fact, this technology also makes possible a paradigm-shift in wireless transceiver architecture that should lead to substantial power savings and improved robustness of wireless communications. In particular, if one has available a large array of ultra-high-Q, extremely selective microresonators, each individually on/off switchable, one could use them to replace the entire RF front end of a transceiver, electronics and all, thereby substantially reducing power consumption and extending battery lifetime. For example, given the high Q of each element in such a microresonator array, one can perform channel selection directly on the signals collected from the antenna by simply turning on the resonator with the chosen channel frequency. This approach will greatly reduce the bandwidth requirement on the front-end low-noise amplifier, thereby significantly reducing the power consumption. Beyond frequency selection, we can also use the array as a tunable local oscillator to switch the frequency band. Even the down-converting mixer can be implemented with mechanical resonators. This new MEMS-based architecture, with its dramatically reduced size and power consumption, promises great potential in enabling a UHF radio and GPS receiver in the size of a wristwatch.

Beyond communications, there are other potential uses for arrays of nanoprecision mechanical resonators. Examples include spectrum analyzers, Fourier transformers, frequency converters, tracking filters, and parametric amplifiers—all these functions characterized by the need for high-precision analog signal processing in the frequency domain.

The latest MEMS-enabled program is titled "Chip-Scale Atomic Clocks." Its objective is to literally shrink the entire atomic clock onto the chip level using MEMS technology. The overall program goal is to enable an atomic time and frequency reference unit within the volume constraint of 1 cubic cm, a power consumption around 30 mW, and an accuracy of 10-11 Allen deviation integrated over 1 hour. The success of this program should greatly improve the mobility and robustness of military systems and platforms with sophisticated UHF communication and navigation requirements. In particular, an ultrastable frequency reference derived from an atomic source will substantially improve the channel selectivity and channel density in military communications. Such a device will also enable ultra-fast frequency hopping in synchronized spread-spectrum communication platforms for improved security and jam resistance and for strong-encryption in data communication. Since the number of applicable military scenarios increases as the size of the atomic clock decreases, a chip-scale atomic clock is highly desirable.

When used in military GPS receivers, a chip-scale atomic clock will greatly extend the jamming margin of a communicator used in a high-jamming environment, while also improving its reacquisition capability and position identification accuracy. In surveillance applications, chip-scale atomic clocks can be used to improve resolution in Doppler radars and to enhance the accuracy of location identification of radio emitters.

Other important uses include missile and munitions guidance, robust electronic and information defense networks, and high-confidence identification of friends and foes. All these applications will be characterized by significant power reduction and ultraminiaturization, while meeting or exceeding the performance levels of state-of-practice approaches.

In closing, the described new MEMS-enabled programs illustrate future trends of MEMS activities within MTO, as well as other DARPA offices. These programs will continue to emphasize the transitioning of the many successful research results in the MEMS program into Defense systems and commercial applications. As a core enabling technology, MEMS will continue to serve as the foundation for many new and exciting programs to come.

Thank you.