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Emerging Research in Micro and Nano Systems: Opportunities and Challenges for Societal Impact

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ABSTRACT

In just a few decades, micro and nano technologies have changed the way that we live – how we work and communicate; the food and medicine that we consume; the clothing that we use; and the entertainment that we seek. While these technologies are being actively investigated in several research communities, the potential for continued societal impact is constrained by resources available for system-level research. Given the long time-lines and levels of investment that are typically necessary to develop functional systems, strategic prioritization of research directions from the perspective of societal needs can be helpful. This paper outlines the findings of an NSF-sponsored road-mapping workshop that was held in 2009, with the intention of initiating a conversation about the opportunities and challenges for micro and nano systems. Four areas of need were discussed: environmental sensing; health care; infrastructure monitoring; and energy alternatives. Possible research trajectories were identified by envisioning technological goals for the year 2040, and linking these to horizons for 2015 and 2025. This paper also provides few examples of current research in each of the four application domains. It is noted that a systems perspective can help to keep the research focused, accelerating and amplifying the societal gain with available resources. Practical and affordable solutions at the system level will require partnerships between specialists, and also between academia and industry.

Keywords: environmental sensing, health care, infrastructure monitoring, energy, power

1. INTRODUCTION

As a society, we lack the resources to advance technology by the exhaustive enumeration of every good idea. Consider that the U.S. National Science Foundation budget request for fiscal year 2010 was about $7.0 billion[1]. The requests for NIH, DARPA, and NIST, were about $31 billion and $3.2 billion, $1 billion, respectively. As a point of comparison, the Troubled Assets Relief Program (TARP) created in 2008 to purchase failing bank assets in the U.S. – the first bailout of the current economic cycle – was budgeted for $700 billion.

According to the U.S. Census Bureau[2], the population in this period was about 307 million. Hence, NSF budget numbers represent $23 per capita expenditure, annually, which is $57 for an average consumer unit (i.e. family) of 2.5 people. According to the U.S. Department of Labor[3-4], the average consumer unit spent $49,638 in 2007 (and earned $63,091 before taxes). For this consumer unit, the annual expenditures on tobacco products and smoking supplies were $323 – just about the same as the expenditure on NSF, NIH, DARPA, and NIST, combined. (Of course, there are other mission-oriented federal agencies that also support science and engineering research in selected topics, but the point remains that resources are very constrained.)

The use of micro and nano technologies is pervasive in industrialized nations, and affects how we work and communicate; the food and medicine that we consume; the clothing that we use; and the entertainment that we seek. Active research is underway in both industrial and academic settings[5]. Despite this, we are decades away from seeing the full societal benefits micro and nano systems. Much of the research is confined by disciplinary boundaries, with system-level applications envisioned only in the very distant future. Researchers are often asked how soon a fundamental discovery or invention can be ready for general use. The answer is irrelevant if nobody is working on the system-level application of that technology. This presents a challenge for engineering and scientific research, particularly if we seek to impact society in practical ways… with limited resources, and in finite time.

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2. ROAD-MAPPING: MICRO & NANO SYSTEMS FOR HIGH-IMPACT AREAS

If we must have a transformative impact upon society using available resources, strategic planning can help to motivate and prioritize research efforts both along and across disciplinary lines. For engineering research, one approach is to consider how proposed efforts may contribute to functional systems by establishing goals for utility, the identification of appropriate benchmarks, and based on these, developing guidelines for performance targets.

At the National Science Foundation, the Directorate for Engineering has historically demonstrated a strong interest in supporting research in micro and nano technologies from a systems perspective. With the intention of stimulating a conversation that may ultimately provide guidance for investments in micro and nano systems (MNS), a workshop was organized in June 2009, in Denver: the *MNS Horizon 2040 Workshop*. Four specific domains of societal impact were discussed: (1) Environmental Sensing/Monitoring; (2) Infrastructure Monitoring and Homeland Security; (3) Health Care; and (4) Energy/Power.

The workshop participants included 44 panelists (with 39 of these being from the U.S.; 5 international), divided between the four topical disciplines. The panelists, drawn primarily from academia, are some of the leading researchers in these disciplines, and in general, represent both the technology developer side of the research spectrum and the end-user side. Each topical panel had two co-chairs who guided the discussions and reported the findings. The workshop also included 15 observers from academia, national laboratories, government agencies (NIH, NIST, NASA, and DARPA), and industry.

For a road-mapping exercise directed research in engineered systems, there are a number of questions that can be identified that apply to every topical discipline. These include, for example:

a) What is the current state of the art within the research and commercial sectors? What are the scientific and technological concepts that currently motivate the use of MNS in each of the four topical disciplines?

b) Looking ahead to 2040, what are the potential capabilities and applications for MNS in these topical disciplines? In addressing this question, it is helpful to identify the following: what is the anticipated function and utility of the system; who are the potential customers – i.e., who will pay for the product, and who will use it; how many people may be impacted by the technology, both directly and indirectly; what kind of cost and performance targets are necessary and how does the MNS solution compare to other approaches in these respects; and what is the primary motivation for utilizing MNS in these scenarios?

c) What are the scientific and technological challenges that must be addressed to realize the vision for 2040? In the MNS context, for example, answers to this question may separately address transduction modalities for sensing and actuation; design methods, including modeling and simulation; manufacturing technologies, including the availability of materials, device processes, and packaging; interface circuits, including signal conditioning and communication circuits; data storage, processing, and mining; system integration; calibration, testing, and reliability.

d) What are the pathways for addressing the scientific and technological challenges that were identified? Given the goals, what should be the research priorities for the coming 5-year period (Horizon 2015), the following 10-year period (Horizon 2025), and the subsequent 15-year period (Horizon 2040)? While recognizing that the boundaries between these periods are fluid, and that the discoveries and innovations in the earlier periods will have an impact on later work, is it possible to perform a triage of funding priorities for these periods? Can we identify the resources that are needed – access of equipment and facilities, manpower, standards, etc. – that are not on the necessary trajectories?

e) Is there a role for alliances – internationally linking universities, government-supported research laboratories, and industry – in executing this vision? If yes, then what is needed to facilitate these alliances?

It should be recognized that not all of these questions have clear or definitive answers. To the extent that a consensus emerges for some of these questions, of course it can provide guidance not only to organizations that control research and development funds, standards, and public policy, but also to researchers, publishers, and educators. An on-going, informed debate about the issues that fail consensus can be just as beneficial.

The recommendations of the *NSF MNS Horizon 2040 Workshop* held in 2009 are presented below in a highly abbreviated form. The panels recognized that, given the breadth of each of the topical domains, these recommendations are only a starting point, and are expected to evolve as the debate progresses.

2.1 Environmental Sensing/Monitoring

With growing threats to the environment posed by global warming, worldwide population growth, and increasing industrialization, there is a need for a better understanding of the changing conditions of both atmospheric and aquatic environments. A variety of chemical, physical, and biological sensors are necessary for measurements that are distributed in both space and time. Some of these applications demand power sources that operate over prolonged periods of deployment in remote or inaccessible locations, perhaps by scavenging energy from the environment. Further, environmental monitoring systems must be configured in a manner that permits the data to be collected, processed and interpreted in an intelligible and timely manner. The panel reviewed some of the opportunities and challenges that lie ahead, and recommended the following priorities.

a) Horizon 2015:

1. Better low-cost sensors for detecting/analyzing microbes (presence, function, activity)
2. MNS for complex mixtures of stressors (air, water, food; chemical and physical)
3. System integration, including location and timing (potentially GPS); algorithms for intelligent sensing
4. Research to reduce manufacturing cost, increase reliability, reduce calibration frequency (self-calibration)
5. Standards and protocols for implementation
6. Packaging, barrier/interface properties, performance of sensors in harsh environments

b) Horizon 2025:

1. Nanoparticle sensors (sensors/systems for detecting/analyzing nanoparticles)
2. MNS aerosol (particle) monitors that provide size, count, and composition (sub-micron to nanometer size)
3. Personal exposure monitors - combinations of sensors
4. Comprehensive water quality monitoring systems
5. Advanced sensors/networks for use in complex environments containing numerous analytes (e.g., toxic industrial contaminants, and complex biological systems)

c) Horizon 2040:

1. Zero-impact (readily retrievable or degradable) MNS for oceanic, arctic, and other environments
2. Continued progress in advanced sensors for use in complex environments containing numerous analytes

2.2 Health Care

Health care applications have inspired research in MNS for many decades. Research directed at implantable neural probes, retinal prostheses, and various other types of sensing and stimulating systems, has often set the bar for miniaturization, power-efficiency, and reliability. Research in microfluidics is paving the way for transformational changes in diagnostic tools for applications ranging from blood sorting to DNA analysis. Given this rich history and the sizable quantity of current research, what are the opportunities for MNS that can be envisioned? The roadmap must anticipate emerging challenges in healthcare, given demographic, economic, and environmental trends. For example, the average age of the population is rising in many developed nations, whereas the incidence of diabetes, cardiac disease, and lung disease is rising in many developing nations. The panel recognized that MNS provide a compelling vision for health care. By 2040, we may have MNS that contribute to the following:

- Personalized medicine: genetic tests, profiling, and developing biomarkers are carried out at individual levels
- Synthetic biology: building from the basic building blocks, DNA, proteins and cells
- Instruments for studying proteins and subcellular phenomena, and for constructing genetic networks from and within single cells
- Instruments for detecting, isolating and treating single cells, resulting in methods for early detection of cancers and markers for single tumor cells and mutations
- A merger of stem cell and tissue engineering resulting in artificially constructed organs grown from the body's own machinery, augmented by biomimetic or biologically inspired synthetic materials
- Synthetic or "synflex" materials that lead to smart catheters and smart blood vessels, blurring the boundaries between the body part and the synthetic part

With regard to *in vivo* systems, the perception was that future advances with come from merging biological systems with MNS and information systems. The hope is that these will lead to intelligent implantable devices with the ability to sense and act autonomously, e.g., insulin pumps that self-regulate; deep-brain stimulators that sense neuro-chemical and electrical activity; and implantable devices that are both diagnostic and therapeutic, providing an interface to the outside world. With regard to *in vitro* systems, the hope is for more advanced composite systems (analytical lab-on-chip systems) that accommodate pico and femto liter samples, adapt to the chemical requirements, and incorporate purification, separation and detection. For analytical microsystems, sample preparation can be a significant challenge, so the ability to perform functions such as whole blood analysis at the point of care (using low-cost devices that are mass produced by micro and nanofabrication technologies) is also seen as important. The systems may utilize advanced detection using on-board resonant mass sensors, and other means of mass spectroscopy. Ultimately, this would lead to microfluidic MNS that perform separation, purification and detection of antibodies, aptamers, peptides and metabolic markers.

The panel recommended the following priorities:

a) Horizon 2015:

1. "Impedance" (compatibility) matching (materials and muscle, photoreceptor-electrode)
2. Surface, sample preparation (isolation of bacteria from blood, virus for CD4)
3. Sample preparation for surfaces, anti-fouling phenomena (basic issue: how does it occur?), coatings
4. Capture of circulating tumor cells from whole blood
5. Neuromorphic circuits

b) Horizon 2025:

1. Multi-cellular, organ technologies (e.g., tissue and vessels)
2. Advanced strategies for powering systems (self or body powered)
3. Super-capacitors, biocompatible batteries, beyond photovoltaic methods
4. Cellular matrix, neural regenerative circuits, neural wiring

c) Horizon 2040:

1. Robustness, intelligence (e.g., implantable devices able to last a lifetime)
2. Repair, regeneration and replacement
3. Implanting functional spinal cord, brain tissue
4. Mature biotic/abiotic interface

2.3 Infrastructure Monitoring and Homeland Security

There is an obvious role for MNS in monitoring civil infrastructure – with respect to both reliability and security. The needs are vast, and include, for example, MNS for monitoring:

- Transportation infrastructure: bridges, roadways, railways, tunnels, shipping docks, levees, aviation;
- Public spaces: office buildings, schools, shopping malls, cinema theaters, sports stadiums, airports, train stations;
- Utilities: electrical grids, power plants, water works, sewage systems, oil and gas pipelines;
- Communication infrastructure: telephone, internet, TV, and radio.

Unfortunately, the infrastructure in the U.S. is aging. A report by the American Society of Civil Engineers estimates[6] a need for about $2.2 trillion in investment in the coming 5-year period.

The vision is that amongst other things, MNS can contribute to distributed sensing systems by providing power-efficient sensors, wireless communications, and integration into cyber-physical systems that provide awareness, data driven decision-making, and rapid response. MNS can be potentially embedded within structural materials, providing security, safety, and long-term savings through the avoidance of failures. The panel recommended the following the following items, amongst others:

a) Horizon 2015:

1. High sensitivity/selectivity sensors and systems for water, air, and food monitoring
2. Application of reliable sensor systems to infrastructure
3. Sensors and packaging for harsh environments relevant to infrastructure
4. Low-power wireless communication with deployed systems – devices, algorithms, and protocols
5. Energy harvesting
6. Efficient data compression and sparsification algorithms that deal with the voluminous raw sensor data

b) Horizon 2025:

1. Sensor-informed decision analysis systems
2. Low-cost ultra-miniature analysis systems
3. Mobile sensing systems
4. Damage precursor identification and safe-life-remaining models

5. Integrative sensor/structural models
6. Data fusion combining sensor input and health/usage monitoring

c) Horizon 2040:

1. Cyber-physical systems
2. Seamless integration into infrastructure
3. Extremely remote sensors

2.4 Energy/Power

As noted previously, the focus of the energy/power topical panel was to determine the potential for MNS to contribute to macro-scale needs in society. Total power usage in the world is presently on the order of 15 terawatts. It is expected to more than double by 2040 because of increasing industrialization and growing populations. There were two general questions of posed to the panel. First, with regard to MNS for power conversion, which of the currently emerging approaches might be translated, in a cost-efficient manner, to meet macro-scale power needs? Is it possible to scavenge sufficient power (for example, from vibration, RF radiation, or thermal gradients) to serve the minimal needs of a family unit, perhaps in a developing nation? A successful solution would provide high energy density, and means of scaling up production. Second, how can MNS help to improve efficiency of conventional and emerging methods of power generation, distribution, and storage? Are there ways to use MNS to improve the performance of solar photovoltaic cells, thermoelectric converters, or ionic and proton exchange fuel cells? What are the ways by which MNS can be employed to improve the efficiency of existing power plants, or to reduce energy consumption?

The panel recommended the following priorities:

a) Horizon 2015:

1. System level analysis over the full life cycle for generation, harvesting, use, and energy storage categories
2. Fundamental research in energy materials/systems
3. Heterogeneous materials integration into systems
4. Power conversion for micro-systems that is scalable to the macro-scale needs
5. Energy efficient sensor networks for efficient energy usage (Smart Grid)

b) Horizon 2025:

1. Fabrication of systems for mass production
2. Heterogeneous integration, including the bio/machine interface
3. New methods of harvesting and converting energy
4. Capture energy cascade

c) Horizon 2040:

1. Energy amplification to convert low potential energies to high potential (low quality to high quality)
2. Broad research in energy materials/systems

3. CURRENT RESEARCH

Researchers are already exploring MNS for a variety of applications, many of which are pertinent four topical disciplines of interest in this paper. Since the body of relevant work is vast and spans many research communities, the reader may find collected works[7-8] to be convenient points of entry into the published literature. A few illustrative examples are noted here.

In the context of environmental monitoring, Zellers *et al.*[9] recently described silicon-based microsystems for complex gas phase environments that include microfabricated (chemi-resistor) gas detectors, micromachined separation columns for chromatography, micromachined pre-concentrators, and in one case a micromachined pump to drive the gas flow. Optical gas detection recently described by Fan's group can be built into the separation columns[10]. Reviews of gas sensors by U. Bonne[11], and of aqueous phase chemical sensors by R. Franklin, *et al.*[12], cover a wide range of relevant systems. On-chip gas micro-discharges have been explored for spectroscopic sensing of chemicals in harsh environments; gas discharges also provide a means to sense nuclear radiation[13].

In the health care sector, a brief review of implantable devices that are in commercial use is provided by Audet, *et al.*[14]. Applications range from cardiac rhythm management to drug delivery devices. There are also a number of on-going academic efforts. Implantable neural microsystems, for example, represent a compelling example of things to come.

Lithographically micromachined electrode arrays have been used for both sensing and stimulation of the central nervous system. Micromachined systems are being used to map neural activity at cellular resolution, and may prove vital in the treatment of disorders such as epilepsy and Parkinson's disease. The newest versions of these microsystems can be equipped with not only on-board signal processing, wireless reception of power, and wireless communication with the external world[15], but also embedded microfluidics for localized drug delivery[16]. Microsystems for recording activity from cultured neurons have also been reported[17]. Research in medical microsystems extends to smart stents and catheters with embedded sensors and actuators[18-19].

Current research in the health care sector is also directed at lab-on-a-chip analytical MNS[20]; much of this work is being performed in academia, and much of it involves optical methods. For example, Chiou is developing optoelectronic tweezers that use dielectrophoretic forces to manipulate droplets on substrates coated with amorphous silicon[21]. Que is developing label-free biosensors that utilize nanopore-enhanced Fabry-Perot interferometers on a chip[22]. Xie is developing a miniature Fourier transform infrared spectrometer for chemical sensing and other applications[23]. Zhang is developing plasmonic near-field scanning probes that may be useful in the future for imaging cell membranes and performing gene perturbation[24]. Jiang has reported the use of temperature-sensitive hydrogels to form liquid microlenses[25]. Huang has reported the use of solutes in liquids to implement a liquid gradient refractive index (L-GRIN) lens for microanalytical applications[26].

There are currently a number of research efforts directed at the use of MNS for monitoring the safety and security of civil infrastructure. With respect to bridges and buildings, for example, there is interest in monitoring motion, loading, and corrosion[27-30]. The prospect of using wireless MNS and MNS-enabled networks, however, can change the paradigm in a substantial way. Instrumentation of this type would be not only inexpensive to manufacture, but also relatively inexpensive to deploy and maintain. Systems that combine sensing capability with the appropriate communication and computational capabilities at each node allow a great deal of flexibility in harnessing the data that is acquired. The data can be processed to varying extents at the sensing node itself, and subsequently, as needed, higher in the hierarchy, permitting interpretations that are meaningful at different levels. A number of bridges and other structures have been instrumented with sensing nodes in early research efforts.

In many contexts the deployment of infrastructure and environmental monitoring systems is constrained by the availability of inexpensive and long-lived power sources. For these applications, gathering energy from ambient vibrations is particularly appealing because many such systems cannot rely on a source of light or a temperature gradient to provide energy. Microsystems that operate by scavenging energy from ambient vibrations have been reported in the past[31]. Efforts are also underway to develop MNS that convert the vibrational energy that resides at the lower end of the spectral range to higher frequencies, making it easier to capture as electrical energy[32].

In the energy sector, even as its commercial market grows, solar cell technology remains a subject of current research. Efforts are directed at increasing conversion efficiency, reducing manufacturing cost, and increasing substrate flexibility. Other transduction methods are also being explored. For example, there has been significant interest in highly efficient thermoelectric conversion. Majumdar and Yang have reported a figure of merit ZT that exceeds 0.6 for silicon nanowires[33], which is exciting because of the abundance and relatively low cost of silicon. Meanwhile, Wang has reported the use of nanowires for piezoelectric conversion[34]. Embedding ZnO nanowires in flexible substrates can provide conversion efficiency as high as 6.8%; this may lead to fabrics that permit energy scavenged from body movements to be converted into electricity. There are also efforts to develop tiny fuel cells using silicon micromachined structures. Shannon recently reported a metal hydride and water vapor fuel cell that is only 9 mm^3 in volume[35].

4. CONCLUSIONS

In reviewing the scope, vision, and status of research in MNS, it appears clear that these technologies are poised for major societal impact in all four topical domains: environmental monitoring; health care; infrastructure monitoring/homeland security; and energy/power. The research challenges and trajectories differ to some extent by topical domain, but there are also overlapping needs. As research progresses in these domains, a systems-oriented perspective can help to keep efforts focused, maximizing societal gain for the available resources. Practical and affordable solutions will require interdisciplinary work toward engineered MNS. Partnerships between specialists, and between academia and industry will dictate success.

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