Control and System Integration of Micro- and Nano-Scale Systems

Report from the National Science Foundation workshop
March 29–30, 2004

Edited by Benjamin Shapiro
Photo credits, front cover
(top to bottom)

1) Micro Calorimeter. 1.8 mm plate, 3.5 µm tether width. Chris Dubé, Draper Laboratory
2) Molecular dynamics simulation of water inside a functionalized carbon nanotube. N.R. Aluru, UIUC
3) Kinetic Monte Carlo simulation of gallium arsenide deposition. Martha Gallivan, Georgia Tech
4) A structure that grabs a masago (sushi) egg. Chang-Jin “CJ” Kim, UCLA
5) Metin Sitti, Nano Robotics Lab, Carnegie Mellon University
6) Lactoferrin Transition from 1lfg.pdb to 1lfh. Gregory Chirikjian, Robot and ProteinKinematics Lab, Johns Hopkins University

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Control and System Integration of Micro- and Nano-Scale Systems

Report from the National Science Foundation workshop, March 29–30, 2004

Edited by:
Dr. Benjamin Shapiro, University of Maryland at College Park.

Workshop organizing committee:
Dr. Gregory Chirikjian, Johns Hopkins University
Dr. Liwei Lin, University of California at Berkeley
Dr. Costas Maranas, Pennsylvania State University
Dr. Marvin White, Lehigh University
Dr. Minami Yoda, Georgia Institute of Technology

Workshop participants:

NSF support provided by:
Dr. Kishan Baheti, Control, Networks and Computational Intelligence, ECS.
Dr. Maria Burka, Process and Reaction Engineering, CTS.
Dr. Delcie Durham, Engineering Design, DMII.
Dr. Masayoshi Tomizuka, Dynamic System Modeling, Sensing and Control, CMS.
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<tr>
<td>Y. C. Lee</td>
<td>University of Colorado</td>
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<td>Qiao Lin</td>
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<td>Mike Ramsey</td>
<td>Oak Ridge National Laboratory</td>
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<td>Florian Solzbacher</td>
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<tr>
<td>Darrin Young</td>
<td>Case Western Reserve University</td>
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<tr>
<td>Babak Ziaie</td>
<td>University of Minnesota</td>
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<tr>
<td>George Barbastathis</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>Tianhong Cui</td>
<td>University of Minnesota-Twin Cities</td>
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<tr>
<td>Jun Jiao</td>
<td>Portland State University</td>
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<tr>
<td>Nikolai Lebedev</td>
<td>US Naval Research Lab</td>
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<tr>
<td>Liwei Lin</td>
<td>UC-Berkeley</td>
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<td>Efthathios Meletis</td>
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<tr>
<td>Brad Paden</td>
<td>UC Santa Barbara</td>
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<tr>
<td>Massood Tabib-Azar</td>
<td>Case Western Reserve University</td>
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<tr>
<td>Fred Terry</td>
<td>University of Michigan</td>
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<tr>
<td>Narayan Aluru</td>
<td>University of Illinois at Urbana-Champaign</td>
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<tr>
<td>Rod Beresford</td>
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<td>Daniel Burns</td>
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<td>Gary Fedder</td>
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<td>Chang-Soo Kim</td>
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<td>Martin Schmidt</td>
<td>MIT</td>
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<tr>
<td>Sharon Smith</td>
<td>Lockheed Martin Corporation</td>
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<td>Shankar Sundaram</td>
<td>CFD Research Corporation</td>
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<td>Marvin White</td>
<td>Lehigh University</td>
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Executive Summary

This report summarizes the findings and recommendations of ninety experts in control, modeling, system integration and micro/nano-scale fabrication who met at the National Science Foundation for a two-day workshop in March 2004. The goal of the workshop was to identify research and education issues that must be addressed to enable the transition from micro and nano components to integrated systems. Discussions were organized around six theme areas, and only those research directions that required multi-disciplinary collaboration between themes are listed here. Recommendations are grouped according to three subjects: system integration, system control, and education and infrastructure needs.

System integration refers to combining numerous micro/nano components to form integrated systems, such as implantable drug delivery systems, micro machines (for instance, artificial insects or miniaturized surgical robots), and bio-chemical pathogen detection systems. Participants recommended research in two topics that could not be addressed by fabrication researchers alone, namely: the development of diagnostics and characterization tools for micro- and nano-scale systems; and the creation of parsimonious (keep essentials only) mathematical models that will enable system design, optimization, and control.

System control recommendations were focused on: control of fabrication processes to improve the manufacture of micro/nano systems (off-chip control), and on incorporating control into micro/nano systems to enable new and improved functionality (on-chip control). Topics included: research in fabrication process control; control for nano assembly and manipulation; requirements for the development of ‘on-chip’ control to direct the internal behavior of micro- and nano-scale systems; comments on the challenges in controlling heterogeneous systems; and research needs relevant to control of systems that combine biology and engineering.

The education and infrastructure recommendations were focused on training the next generation of cross-disciplinary students and faculty, and on modeling, measurement, and fabrication infrastructure needs.

Workshop History and Format

The workshop organizing committee, consisting of Benjamin Shapiro (chair), Gregory Chirikjian, Liwei Lin, Costas Maranas, Marvin White, and Minami Yoda, was selected in December 2003, based on input from Maria Burka, Kishan Baheti, and Masayoshi Tomizuka at NSF. The committee formally announced the workshop in January 2004 and solicited applications from academia, industry, and government, until the closing date of March 1, 2004. Over four hundred applications were received. During the first week of March, the committee selected and invited ninety participants to attend the workshop.

Discussions at the two-day workshop were organized according to six theme areas:

1. Biological (or Biomolecular or Biochemical) and Chemical Systems on the Micro- and Nano-Length Scales
2. BioMEMS and/or Nanobiotechnological Systems
3. Control Systems with a MEMS and/or Nano Perspective
4. Measurement, Modeling, and Model Validation at the Micro- and Nanoscale
6. Nano Fabrication

On the first day of the workshop, the participants met within their respective theme areas. On the second day, the audience was randomized across themes so that researchers in nano fabrication, for example, would interact with researchers in controls. Each theme area was charged with producing a short list of cross-disciplinary recommendations (each recommendation would require a collaborative effort between at least two themes) that would address micro/nano system integration and control challenges.
This report is a summary of the discussions and recommendations at the workshop. An electronic copy of this report and further details, such as the workshop program and participant quad charts, are available at: www.isr.umd.edu/CMN-NSFwkshp/.

**System Integration: Needs in Measurement and Modeling for Control and Design**

System integration goals included: integration across length and time scales (from nano meters and femto seconds up to meters and years); integration between soft and hard fabrication techniques; integration of inorganic, organic, and living biological materials; and integration of in-situ sensors, actuators, and components for real time systems control. The benefits of feedback control that have been demonstrated on the macro scale (such as the ability to guarantee robust high performance in uncertain noisy environments, even in the presence of sub-system failures) are also required on the micro- and nano-scale.

Participants identified research in measurement techniques and the development of parsimonious (essentials only) models as two major needs. Research in these two areas will improve the physical understanding needed for system integration and enable the models and real time sensing capabilities required for feedback control. It was also noted that industry should become involved as early as possible in the modeling and simulation process so that practical issues, such as common system failure modes and the effect of harsh environments, can be incorporated into the modeling effort.

**Parsimonious (Keep Essentials Only) Models for System Design and Control**

Both system optimization and control design typically requires models of the system, actuators, and sensors. Models used should be carefully chosen: they must contain enough physics to be predictive, but they must remain computationally tractable to enable design and control. At present, there is a disconnect between available micro/nano modeling tools and analysis, design, and control needs. For example, finite element models are commonly used to represent MEMS systems but these models cannot be used directly for control design and control implementation. Research should focus on creating minimal models for classes of micro- and nano-scale systems. Minimal models can be accomplished by combining physical insight (what are the dominant physics?) and model reduction techniques (dramatically reduce model size with a minimal sacrifice of model accuracy). Methods are needed to determine the point at which a model is good enough, and to validate such models using a combination of (more computationally expensive) physical first principle models and a reasonable number of (difficult, expensive, and time-consuming) experiments.

**Systems Level Measurement: Diagnostics and Micro/Nano-Sensors**

To enable system integration workshop participants recommended research investment in diagnostics and sensors from the component to the systems level. Improved diagnostics (detailed and comprehensive measurement techniques) are required to: i) clarify physical phenomena that are dominant at the micro- and nano-scale; ii) provide basic input to physically based models – a lot of basic fluid/solid properties are still largely unknown; and iii) validate both physically-based and reduced-order models. Whereas diagnostic techniques refer to laboratory measuring systems, sensors refer to devices that can be incorporated into a micro/nano-system and provide less detailed or single point measurements. Integration of sensors (and actuators) into a micro/nano-scale system remains a major fabrication and system integration challenge whose solution is required to enable real-time control: both in terms of allowing control of behavior inside micro- and nano-scale systems and in terms of using micro/nano-scale sensors and actuators for sensing and control of behavior externally on a larger scale. Challenges include: incorporation of sensors within a very limited space, sensor accessibility (getting signals in and out), and limiting the addition of any sensor fabrication steps that may reduce system yield.
It was also recognized that there is a need to bridge the gap between molecular scale modeling and continuum length and time scales. For example, molecular dynamic simulations, though providing a tool for predicting behavior at the atomic scale, cannot reach the length and time scales of interest for system design. There is a need to create/extend averaging or model reduction tools that can provide the link between molecular and continuum scale models.

**System Control: Applications in Fabrication, Object Manipulation, On-Chip Control, and Control of Systems Combining Biology and Engineering**

Feedback control is ubiquitous in engineering and biological systems; both engineering and living systems use feedback loops to sense and correct for departures away from desired performance. These sense–compare-and-react loops allow integrated systems to function reliably and with high performance even in the presence of noisy environments, unknown parameters, changing requirements, and sub-system failures. Workshop participants saw many opportunities for feedback control to contribute to micro- and nano-scale systems development. There were examples where micro-systems combined with control algorithms could be used to create and manipulate nano objects; feedback control could be used to handle uncertainty and limit the variability of nano-fabrication techniques; and, using nano-scale systems, there are opportunities to understand, access, and adapt molecular based “wet-ware” control loops inside biological systems. It was recommended that expertise in MEMS fabrication be used to create microscale testbeds for fabrication, handling, analysis, and control of nanoscale systems.

**Fabrication Process Control**

It was noted that it is difficult to achieve reproducible fabrication results at the nano-scale; for example, when fabricating carbon nano-tubes, “we repeat the same procedure and get different results each time,” Jun Jiao (Portland State). Clearly, there is a lack of knowledge off and an inability to prescribe the relevant process parameters. Control was seen as an enabling technology that, through real-time process monitoring and appropriate actuator responses, would be able to help identify and control process parameters, and thereby improve device yield and reproducibility. Further, yield and fabrication reproducibility should be considered as research issues on the same level as the development of new fabrication processes. To enable process control, sensor and actuator type and placement issues should be considered at the early stages of the fabrication plant design; if these issues are only addressed after the plant has been built, it may be impossible to include the type of sensors and actuators needed for real-time process control. Efforts should focus on isolating the dominant physical phenomena in nano growth and deposition, important process control parameters must be identified and their effects must be understood, real time sensors must be developed and integrated into the fabrication plants, and effective control algorithms must be developed and validated.

There is also an intriguing possibility to use micro-systems and control to generate nanosized features, in short: “micro + control = nano.” Liwei Lin (Berkeley) showed a case where resistive heating (control) applied to a microbridge created nanowires. Hence an opportunity exists to exploit interesting physics (growth instabilities, parameter dependent self-assembly) to create and shape nano-objects using control theory and MEMS platforms.

**Control for Nano Assembly and Object Manipulation**

Atomic Force Microscopy (AFM) probes can be used to push, pull, cut, indent, and lithographically deposit nanoscale objects. Open control challenges for nanorobotic manipulation are summarized in the report from the 2003 “NSF workshop on Future Directions in Nano-Scale Systems, Dynamics and Control,” Metin Sitti (CMU) available online at [www.me.cmu.edu/faculty1/sitti/NSF_Report_Sitti.PDF](http://www.me.cmu.edu/faculty1/sitti/NSF_Report_Sitti.PDF). They include: generation of autonomous AFM systems for imaging and 3-dimensional, parallel manipulation;
in-situ real-time nano-scale control concepts for high-frequency nano-electromechanical systems; and hybrid modeling (continuous and discrete, multi length and time scales) of nano-mechanics to enable control design and implementation.

‘On-Chip’ Control Inside Micro/Nano Systems

For self-contained miniaturized systems, the sensors, actuators, and control hardware must be included inside the system. On-chip ‘control inside’ packaging is required for miniature systems such as implantable drug delivery platforms, micro-sense-and-report systems, and, in the long term, micro-robots such as artificial insects. Integrating the control into the micro- or nano-scale system raised additional issues: i) Sensors, actuators, and control logic circuits must be optimally distributed inside a very small volume; ii) In many instances software and DSP based control is not practical (it takes up too much real estate and cannot address the fast dynamics found on the nanoscale) and analog type controllers must be designed instead; and iii) There is a need for a high degree of robustness and fault tolerance especially when the miniaturized system must operate inside unknown, hostile environments which can cause a large number of the sensors and actuators to fail. It was felt that robust control, distributed control, model reduction, state estimation, and optimization tools could be used to effectively address these questions.

Control of Heterogeneous Systems

On the micro- and nano-scale, there are interactions between continuous and discrete dynamics: micro-fluidic devices often have continuum flows but contain discrete objects such as cells or DNA chains that display stochastic motion; there is coupling between disparate length and time scales: phenomena on the macro scale can be used to control behavior on the nano scale and vice versa; and there is cross talk between interfacial and bulk phenomena. For systems that include organic or biological materials, the interfaces between inorganic and organic/biological components are heterogeneous and they must also be understood and controlled.

Thus, there is a need to develop modeling and control tools to address heterogeneous systems. This is a challenging area that is already receiving attention within the controls community. It was judged that, although there are notable exceptions, there is currently an insufficient link between efforts underway in the controls community and research carried out by scientists in micro/nano fabrication, chemistry, biology and modeling. It is recommended that collaborative teams of researchers (including control and micro/nano experts) focus on developing tools for specific sub-areas, such as control of discrete objects inside continuum flows or control of chemical processes at interfaces.

Control of Systems that Combine Biology and Engineering

BioMEMS and control workshop participants noted the tremendous opportunity for implantable medical sensors and systems. Applications raised at the workshop included miniaturized hearing aid implants, neural prostheses, in-vivo active blood pressure controllers, and glucose monitoring and drug delivery systems for diabetes management. Research is required to better address problems of coupling the sensor (materials, contact geometry, sensing modality, etc.) with the biology sample (cells, blood, tissues, etc.). It is necessary to address issues related to physical and chemical adaptation and to better control device surfaces to conform to cell growth. There is a need to improve the measurement and data extraction methods by which the true responses from the targeted entities (DNA, proteins, drugs, metabolites, etc.) is detected and transduced more sensitively and selectively from the large amount of non-specific and background interferences. The control algorithms that will control the behavior of the implantable devices must be developed. These algorithms must adapt to biological conditions and must work together with the complex feedback mechanisms found in the human body.

Conversely, using micro- and nano-scale measurement techniques there is now a real opportunity to learn from biological systems that are truly amazing examples of complex, integrated, micro/nano systems with feedback control. Ideas
for study of biology based control approaches include: i) In organisms, random processes generate organized structures at larger scales. Based on this, it should be possible to learn to control random, distributed, (self-organizing) processes to create and direct desired structures. ii) Natural biomolecular processes are often based on nanostructure “interlocking” molecules that control the self-assembly of complex structures. There is a possibility to use fabricated structures, polymers, and genetically engineered microorganisms (for example, as used by Angela Belcher, MIT) to control the assembly of micro/nano systems. iii) Nature routinely implements wet-ware (chemically based) sensing, feedback, control, and automation in biological systems. There is a potential to mimic this capability and to engineer molecular pathway (chemical and biochemical) based sensing, actuation, control, networks, logic, and system architectures to perform desired tasks.

**Education, Collaboration, and Infrastructure Recommendations**

A repeated topic across all themes in the workshop was the need to educate the next generation of students, and faculty, in a cross-disciplinary fashion, cutting across traditional lines of math, physics, biology, and mechanical, electrical, and chemical engineering. As in many other areas, there is an inability to communicate effectively across disciplines: this makes it especially difficult to effectively describe and design systems that combine different specializations. A variety of mechanisms were suggested to address this need, many of which are already being implemented: i) Funded cross-disciplinary student exchange programs should be established/expanded whereby students in discipline A can spend a summer or a year doing research in discipline B; ii) Students should be co-advised by professors in different fields, and, importantly, funding mechanisms should be established which will encourage such co-advising; iii) More programs are needed for cross-disciplinary education of working engineers and training courses for technicians in state-of-the-art fabrication techniques; iv) Support should be provided for summer workshops in specific topics such as AFM, microfluidics, nanofabrication, and bio-systems – it was suggested that workshops follow the Gordon conferences model of a small number of scientists in a relaxed setting with a large amount of time set aside for informal discussions; v) Cross-disciplinary curricula should be developed at both the undergraduate and graduate level; and vi) There should be mentoring of junior faculty by senior faculty in other fields and funding mechanisms to permit and encourage faculty to take sabbaticals in areas outside their main expertise. A key concern was the nature of the tenure process: faculty should be encouraged, not penalized, to collaborate and write joint papers with scientists in other disciplines.

Insufficient infrastructure and mismatch of tools was a pervasive theme. Commercial modeling tools such as Coventor and Fluent have begun addressing phenomena on the micro- and nano-scale but, due to their computational complexity and the lack of accessibility to internal equations and algorithms, the resulting tools are not yet appropriate for control design and system integration. Some software companies are making an effort to address this need: CFDRC has a research effort in creating optimization ready models and FEMLAB software permits the creation of open source, coupled, PDEs (Partial Differential Equations) models. To help satisfy this need of design and control ready models, a peer reviewed database of software tools and public domain models for various sub-classes of micro- and nano-scale systems should be created: such a database must consolidate input from model developers and model users.

Similarly, access to standardized micro-fabrication techniques, especially for bio-chemistry, bio-medical, and related researchers should be improved. The availability of present foundry resources, such as MOSIS, MEMS Exchange, MUMPs, and Sandia’s SUMMiT, for MEMS and microelectronics, is acknowledged. However, aside from devices (not processes) offered through the Center for Neural Communication Technology at the University of Michigan, few resources exist which extend present foundry resources to the spheres of bio-chemistry and bio-medical engineering. And no resources extend the foundry concept to the nano-scale in general. To address the fabrication need it was recom-
mended that facilities be developed to extend the foundry concept to the nano-scale, and to the spheres of bio-chemical and bio-medical engineering.

Finally, there is a lack of diagnostics tools to characterize effectively both micro- and nano-scale systems. Although diagnostics tools exist for electrical phenomena, diagnostics for chemical, biological, thermal, optical, fluidic, and mechanical processes are much less well advanced. To address the measurement need, resources must be devoted to develop and make available micro/nano diagnostics tools.

**Summary**

This document lists recommendations on combining the techniques of systems and control with research in micro- and nano-scale fabrication. The match between these two areas is timely and is of benefit to both groups. Micro- and nano-scale fabrication techniques are moving from components and devices to complex systems – researchers in this area can benefit from controls and system integration tools that address component coupling, the management of and design for uncertainty, and system optimization and control. Controls researchers are now developing powerful tools in distributed control – they can benefit from the distributed actuation and sensing opportunities that are afforded by numerous tiny sensors and actuators packed into small volumes or scattered across large ones. Moreover, by using micro- and nano-scale measurement techniques, scientists now have access to the inner molecular workings of biological systems: there is no doubt that control researchers can learn a tremendous amount from the phenomenal control systems found inside living organisms.