National Science Foundation workshop on:

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

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Organizing Committee:
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How this started ...

My group is aimed at design and control of micro-fluidic systems and we are generally frustrated by the low degree of collaboration and communication between modelers, fabrication people, control theorists, mathematicians, organic chemists, …

We keep having to recreate on the micro scale what researchers have been doing for years on the macro scale (e.g. “control ready” modeling) …

And we aren’t the only ones with this problem …

So through Maria Burka and Kishan Baheti, I went to NSF and proposed …

A workshop that will bring together the control and systems design community with the micro- and nano-system fabrication and device design communities. It would identify high-payoff interdisciplinary research directions, and it would provide input to NSF for future basic science research needs …

This talk gives a summary of the discussions and recommendations from that workshop.
Micro/Nano Systems are Characterized by …

• Extremely small length scales (down to molecular scales for nano systems)
  ➔ Can pack lots of actuators and sensors into a tiny space = amazing capabilities.
• The interaction of many different physical phenomena across many different length and time scales.
  ➔ Extremely complex phenomena, hard to understand and to quantify.
• Large manufacturing variability, sensitive dependence on trace quantities of chemicals
  ➔ Lots of system uncertainty.
• Need dedicated, delicate, expensive equipment to measure even basic quantities
  ➔ Measurements are limited and can be noisy. Is hard to debug system errors.

Control & System Integration Design Tools are Characterized by …

• Distributed control and sensing techniques (J. Burns, B. Bamieh, R. D’Andrea, ..)
  ➔ Optimal placing of actuators/sensors, coordinated control, data extraction, …
• System analysis/design tools built to capture coupling across temporal and spatial scales
  ➔ These tools may aid understanding the physics (but their application will not be simple – no “silver bullet”)
• Control theory tools have been built to address robustness (J. Doyle + many others)
  ➔ Quantify and design for uncertainty.
• System identification tools, design of experiments, data mining, other?
  ➔ Some of these mathematical tools may help. Need research collaboration.

These two groups should talk
Thanks to:

Organizing Committee:

Gregory Chirikjian  
Liwei Lin  
Costas Maranas  
Marvin White  
Minami Yoda

National Science Foundation:  
Kishan Baheti, Maria Burka, Delcie Durham, and Masayoshi Tomizuka

Logistical Support:  
Becky Copeland, Jeff Coriale, Dale Morey, Lisa Press, and Susan Warren at the University of Maryland. Cheryl Muza at NSF.
Workshop was organized according to six theme areas chosen by NSF and the organizing committee ...

• MEMS Design/Fabrication, Devices, and Systems.
• Nano Fabrication
• Biological (or Biomolecular/Biochemical) and Chemical Systems on Micro/Nano- Scales.
• BioMEMS and/or Nanobiotechnological Systems
• Control Systems with a MEMS and/or Nano Perspective
• Measurement, Modeling, and Model Validation at the Micro- and Nanoscale.
Workshop organization:

DAY ONE:
• Seminars in the morning: one overview + one per theme.
• Theme discussions by area of expertise.
• Theme representatives report back to the main audience with initial recommended research areas.

DAY TWO:
• Two overview seminars.
• Theme discussions with audience randomly reorganized.
• Theme representatives report back to main audience with finalized list of research recommendations per theme.
• Discussion in main audience.

AFTER WORKSHOP: Draft of report sent out for comment.
All participants at the workshop submitted quad charts on their research goals, research approach, and bottlenecks.

These quad charts are a very succinct summary of some really fascinating research efforts. They are all available at:

http://www.engr.umd.edu/nsf/

*It is amazing how the same research themes repeat across very different research areas ...*
Self-assembled Nanostructures in Thin Films

Efstathios Meletis
Louisiana State University

Goals and Potential Impact if Successful

Control self-assembly of oxide and metallic nanostructures through fundamental understanding for:
- nanofabrication and nano-imprinting
- nanopatterning and templating
- nanoelectronic devices, nanosensors, memory devices, etc.

Development of a novel ‘bottom-up’ method to design and manufacture nanodevices.

Require fundamental understanding of the self-assembling mechanism through innovating experimentation coupled with atomistic modeling and simulation to capture the nanoscale physical phenomena involved.

Integrating nanostructures in devices.

Approach and/or Accomplishments

EXPERIMENTAL:
Device and design appropriate experiments to explore and understand the role of processing and material parameters on the resulting self-assembled nanostructures.

MODELING:
Use combined atomistic (molecular dynamics and kinetic Monte Carlo) and mesoscale simulations to model nanostructure growth and extend the model to design future systems of interest.

ACCOMPLISHMENTS:
Self-assembled nanorods have been achieved in Co/DLC nanocomposites and La$_{0.8}$Sr$_{0.2}$MnO$_3$/LaAlO$_3$ epitaxial films.

Bottlenecks and Open Research Questions

- **Appropriate processing techniques** that can capture and control range of parameters dominating the self-assembling process are needed. This applies to both, ceramic and metallic nanostructures.
- **Better coordination between experimental and theoretical studies.**
- **Multiscale modeling and simulation methods** are needed to better handle the time and length scales involved.
- **Lack of appropriate methods** for integrating the self-assembled nanostructures into nano/micro devices.
Workshop recommendations are grouped according to three subjects …

• System integration
• System control
• Education and infrastructure needs
Micro/Nano System Integration Research Recommendations

What are the tools required for integration? (Focus on needs that required cross-theme collaborations.)

System integration goals:
- Integration across disparate length and time scales
- Integration between hard and soft fabrication techniques
- Integration of inorganic, organic, and living systems.
- Integration of in-situ sensors and actuators for real time control

Workshop participants identified two major needs …
- Systems level measurement: diagnostics and micro/nano sensors
- Parsimonious (keep essentials only) models for design & control
Systems level measurement: diagnostics and micro/nano sensors
Needed to: clarify physical phenomena, and provide input and validation for models of micro/nano systems.

- Improve diagnostics = benchtop micro/nano measurement methods
- Integrated sensors = miniaturize diagnostics for real time control

Parsimonious (keep essentials only) models for design & control
Need models for system design, optimization, and control.

- Models must be carefully chosen: must contain enough physics to be predictive, but must remain computationally tractable
- Create by physical insight (crucial) and model reduction (helpful)
- Available FEM/CFD modeling tools not appropriate for design: controls researchers must have a hand in creating new modeling tools
- Need to bridge gap between molecular and continuum scale models
- Methods needed to determine point at which model is good enough
System Control Research Recommendations
Micro/nano systems have lots of uncertainty, ability to sense/actuate in a distributed way on tiny length scales, plus desire high performance → many opportunities for feedback control.

Fabrication Process Control
Difficult to achieve reproducible results at the nano scale. Nanotubes: “Repeat the same procedure, get different results each time” Jun Jiao

- Control: real time process monitoring to improve reproducibility
- Consider sensor/actuator placement early in the plant design.
- “Micro + Control = Nano”, e.g. Resistive heating + microbridge = nanowires.
Control for Nano Assembly and Object Manipulation
Metin Sitti will talk about that next …

‘On-Chip’ Control inside Micro/Nano Systems
For self-contained miniaturized systems, sensors, actuators, and control hardware/software must be included inside a micro system.

• Modeling for control design
• Sensors, actuators, and control logic circuits must be optimally distributed inside a small volume
• Software and Digital Signal Processing (DSP) too slow/big: will need to go back to analog control logic in some instances
• Need high degree of robustness, noise rejection, and fault tolerance

Robust control, distributed control, system identification and state estimation, and optimization tools could be used to address issues.
Control of Heterogeneous Systems
Interactions between continuous and discrete dynamics, interfacial and bulk effects, organic/inorganic interactions, …

- Need modeling and control tools for heterogeneous systems: a challenging area that is already being addressed by controls researchers, but need closer link between control and micro/nano research.

Control of Systems that Combine Biology and Engineering
Aiming at implantable medical sensors and systems.

- Control devices to conform to cells/living organisms.
- Improve measurement and data extraction methods.
- Develop algorithms to control behavior of implanted devices: algorithms must adapt to feedback mechanisms inside the body.
- There is an opportunity to learn control from biological systems.
Education, Collaboration, and Infrastructure Rec’d

Education next generation of cross-disciplinary students and faculty

- Cross-disciplinary student exchange programs. Co-advise students.
- Gordon conference type summer workshops in AFM, micro-fluidics, ..
- Cross-disciplinary curricula for undergrad and grad level.
- Tenure process: should encourage, not penalize, collaboration.

Modeling infrastructure for system integration and control

- Commercial and academic modeling tools must be “control ready”.
- Peer reviewed database of models for sub-classes of systems.

Develop widely available fabrication infrastructure

- MOSIS for bio-chemistry and bio-medical applications.
- Publicly funded/available nano fab facilities.
All workshop information (program, quad charts, report, everything) is available online

http://www.controlofmems.umd.edu/nsf.html