Workshop on Control of Micro- and Nano-Scale Systems

Micro- and nanoscale systems are those with device features ranging in size from hundreds of microns ($\sim 10^{-4}$ m) down to nanometers ($\sim 10^{-9}$ m), a size that corresponds to six times the distance between the nuclei of two bonded carbon atoms. These systems enable such applications as biomedical sensors, lab-on-a-chip biochemical analysis systems, single-molecule sensors and manipulators, microscale inertial systems, implantable drug delivery devices, telecommunication optical fiber components, and miniaturized energy sources like fuel cells and microengines.

Since 1989, the year the term microelectromechanical systems (MEMS) was coined, the field of microsystems has grown significantly. By 1997, 80 U.S. companies were involved in the field of MEMS, the combined MEMS world market had reached approximately US$2 billion, and the filing rate for MEMS patents was about 160 per calendar year [1]. The younger field of nanotechnology is also growing. More then 2,800 nanotechnology patents have been issued since 1996 [2], and government and private spending on nanotechnology research and development reached US$8.6 billion per year in 2004 [3].

There are opportunities for control theory and practice to contribute to the development of micro- and nanoscale systems. The reverse is also true: miniaturized sensors and actuators will enable new applications in distributed control and sensing. Commonalities between control and micro-/nanoscale systems are discussed below.

By integrating components with micrometer and nanometer dimensions, it is possible to pack functionality into mesoscopic (less than 10^{-3} m $\times$ 10^{-3} m $\times$ 10^{-3} m) or microscopic (less than 10^{-6} m $\times$ 10^{-6} m $\times$ 10^{-6} m) volumes. Alternatively, miniature sensors and actuators can be dispersed over large volumes to perform distributed sensing and actuation tasks. Micro- and nanoscale technology can provide control practitioners with miniaturized sensors and actuators. Conversely, research developments in distributed control and sensing can be used to help integrate systems and networks of miniaturized devices.

Micro/nanosystems exhibit chemical, electrical, mechanical, fluidic, and biological phenomena over a range of length and time scales. The range of length scales is influenced in two basic ways. First, surface-to-volume ratios are large and, thus, surface effects with nanometer length scales compete with bulk effects with length scales up to microns or millimeters. Furthermore, micro- and nanoscale systems must be integrated with human interfaces that have centimeter length scales. For nanometer systems, this integration means that system length scales can vary over seven orders of magnitude, namely, from 10^{-9} m to 10^{-2} m. To create functioning micro/nanosystems, analysis and design tools must span these length and time scales. Controls research in subsystem coupling, model reduction, and averaging across length and time scales can help address this need.

Micro- and nanoscale fabrication techniques, along with the physical effects found on the micro- and nanoscales, create geometric, parametric, and dynamic uncertainty in system components. System integration must allow for and design around this uncertainty. Specifically, producing components with dimensions at or near the limit of fabrication techniques creates geometric uncertainty. In microfabrication techniques, the wavelength of light determines the minimum feature size that can be created. Using visible light, the wavelength of which varies between 0.4 μm (violet) and 0.7 μm (red), an optical mask feature that is smaller than about one micron cannot be resolved. A MEMS device with components that are five microns in size will thus have a $\pm$20% variability in geometry. Nanofabrication techniques, which are distinct from microfabrication techniques, do not encounter this wavelength of light limitation. However, the same type of argument applies and the component shapes created at the limit of fabrication techniques have large geometric uncertainties.

Parametric uncertainties are caused by uncontrolled chemical processes in the fabrication sequence. For example, variations in the precise etch time or chemical contaminants in an etch step can create uncertain material compositions and variable surface properties. Dynamic uncertainties arise from poorly understood or unknown physical phenomena. A microfluidic component might have unmodeled adsorption and desorption chemical kinetics at its surface, which create dynamic uncertainty in the bulk chemical concentrations. The uncertainty management tools developed in the controls community can help analyze and design for these uncertainties.

Characterizing, measuring, and verifying properties on the micron and nanometer length scales can be difficult, time consuming, and expensive since properties cannot be measured directly; instead, micro- and nanoscale phenomena must be used to infer component properties. For example, because of the wavelength of light, it is not possible to see submicron component shapes using an optical microscope. Using electron beams instead of photons (electron microscopy), it is possible to image smaller features. The wavelength of the electrons depends on their energy. Although high-energy electrons can be used to image individual atoms, the scattering of the electrons becomes more complex as the length scale decreases, and computer modeling of the magnetic lenses and the electron beam is necessary to infer the images. The component characterization process is time consuming for a number of reasons: individual experiments can be lengthy, multiple experiments are required to characterize a single component (different component properties require specialized machines), and some of the characterization machines are delicate and prone to failure. The component characterization and verification process is costly because the required equipment is expensive. For example, a transmission electron microscope (TEM) costs between US$500,000 and US$3 million, depending on the resolution and the number of postprocessing options. Additional machines are required for other measurement tasks involving chemical, thermal, electrical, flow, and pressure properties. To facilitate micro- and nanoscale component verification and system integration, the maximum amount of information must be extracted from the limited number of available measurements. Control strengths in system identification, filtering, and sensor fusion can help address this need.

Impetus Behind Initiating the Workshop

Controls researchers familiar with micro-/nanoscale systems have observed that the tools available to facilitate control design on the macroscale are not yet available on the micro- and nanoscales. Control design on the macro scale is aided by reduced-order modeling techniques that provide control-ready models, as well as by experimental testbeds created to test and validate control ideas. On the microscale, although model-reduction techniques have been applied to some of the more mature areas (such as MEMS accelerometers), these techniques have not yet been applied to other areas like microfluidics. For example, there are no reduced-order models for surface tension effects, chemical adsorption/desorption surface rate reactions, or lipid vesicle membrane dynamics. Likewise, experimental micro- and nanoscale control testbeds are rare because researchers in these fields generally focus on fabricating systems. Hence, existing testbeds tend to address fabrication and integration needs rather than control issues. In contrast, MEMS accelerometers and atomic force microscopy (AFM) probes have been used as experimental control testbeds since feedback control is an integral part of AFM probes and MEMS accelerometer operation. However, experimental testbeds have not yet been developed to examine control methodologies in microfluidic or nanoscale systems.

The development of tools for control of micro- and nanoscale systems will require close collaboration between researchers in miniaturized systems and researchers in control. The NSF Workshop "Control and System Integration of Micro- and Nanoscale Systems" was initiated to increase the level of interaction among fabrication researchers, modelers, control theorists, and biochemical researchers to develop tools for controlling micro- and nanoscale systems.

"Control and System Integration of Micro- and Nanoscale Systems"

The National Science Foundation (NSF) Workshop, "Control and System Integration of Micro- and Nanoscale Systems," held on 29–30 March 2004, was organized to improve the degree of collaboration among control researchers and micro-/nanoscale fabrication experts. Kishan Baheti, Maria Burka, Delcie Durham, and Masayoshi (Tommy) Tomizuka at the NSF provided workshop funding that covered organization expenses, as well as travel and lodging costs for the participants. The workshop was subdivided into six theme areas:

- biological and chemical systems on the micro- and nanolength scales
- bioMEMS and nanobiotechnological systems
- control systems with a MEMS or nano perspective
- measurement, modeling, and model validation at the micro- and nanoscale
- MEMS design/fabrication, devices, and systems
- nanofabrication.

The organizing committee, which was finalized in December 2003, consisted of Gregory Chirikjian from Johns Hopkins University, Liwei Lin from the University of California at Berkeley, Costas Maranas from Pennsylvania State University, Marvin White from Lehigh University, and Minami Yoda from the Georgia Institute of Technology. The committee announced the workshop in January 2004 and solicited applications from academia, industry, government labs, and funding institutions by posting the announcement on the Web, sending out flyers to deans and chairs at various university departments (engineering, physics, material science, biology, and chemistry departments), and using MEMS, nano, and control conference e-mail lists. Applications were solicited for the areas of modeling, control, MEMS, nano, and biochemical systems. As stated in the announcement, the goal of the workshop was ". . . to identify research areas, to foster interdisciplinary collaboration, and to recommend future research directions to NSF that will enable control and system integration on the micro- and nanolength scales." Between the posting of the announcement at the end of January and the workshop application deadline on 1 March 2004, 400 applications were received. Due to space and funding constraints, a total of 90 individuals were invited to attend the workshop.

Each applicant was asked to specify an area of expertise from the six themes designated for the workshop. Participants were then chosen according to the theme areas. Based on the applicant response pool, some areas (such as control) were assigned slightly more spots, while other areas (such as nanofabrication) that correspond to a smaller research community were assigned fewer spots. The pool of applicants was of such high caliber that it was not possible to include many people who are recognized as experts in their areas. Moreover, the committee made an effort to invite a group that was diverse across many axes: both junior and senior researchers were selected; scientists from industry, government labs, and funding institutions were invited; and the research backgrounds of the participants included biology, chemistry, micro- and nanoscale fabrication, measurement, modeling, applied math, control, and system integration.

The final breakdown of the workshop participants was as follows: seven scientists in biochemical systems, 13 scientists in bioMEMS/nanofabricaton, 14 scientists in control, 14 scientists in measurement and modeling, 11 scientists in MEMS fabrication, nine scientists in nanofabrication, and 14 scientists in unspecified disciplines. Including the program managers from the NSF, DARPA, and AFOSR, as well as the committee members, the total attendance was 95. A list of the participants and a summary of their interests and research accomplishments can be found at the workshop Web site [4] under the headings “Participants” and “Quad Charts,” respectively. Each quad chart summarizes the goals, potential impact, approach, accomplishments, and open research questions for each of the participants. The quad charts provide an overview of the research areas represented at the workshop, and they form a snapshot of the types of developments underway in miniaturized systems. Topics include microencapsulation and drug delivery (Allison Rice-Ficht, Texas A&M), DNA sensing (Joe Gatewood, SeiraD), implantable MEMS devices to monitor brain activity (Jack W. Judy, UCLA), control of atomic force microscopy (AFM) probes (Metin Sitti, CMU), bacterial microfluidics (Kenny Breuer and Tom Powers, Brown University), nanostructured Origami (George Barbastathis, MIT), and modeling of nanofluidics (Narayan Aluru, University of Illinois at Urbana-Champaign).

Events and Discussions

The key goal of the workshop was to foster collaboration between control and micro-/nanoscale systems researchers, and the workshop program was designed to facilitate this goal. Events at the workshop were organized as follows.

Monday Morning: A Crash Course

Monday morning, 29 March 2004, was used to provide the participants with a crash course on miniaturized systems and the six themes of the workshop. Ken Wise from the University of Michigan spoke about challenges in creating closed-loop, self-contained, integrated microsystems. Experts in each of the six theme areas provided a 20-minute overview of research approaches and challenges in their respective areas: Martin Schmidt from MIT discussed research directions in MEMS; Jun Jiao from Portland State University reviewed nanofabrication efforts and challenges; Bill Tang from the University of California at Irvine covered the area of MEMS for biomedical applications; Costas Maranas from Penn State spoke about challenges and opportunities in biological systems analysis and design; Panagiotis Christofides from UCLA presented an example on control of thin film microstructures; and Terry Conlisk from Ohio State University gave an overview of modeling transport in micro- and nanofluidic systems. The same basic challenges were noted repeatedly in all of these talks: modeling for design, dealing with uncertainty, system integration, technical culture and language barriers, and training the next generation of interdisciplinary scientists and engineers.

Monday Afternoon: Discussion Groups

On Monday afternoon, workshop participants formed six smaller groups to facilitate discussions within their respective theme areas; each participant attended the discussion that best matched his or her area of expertise. The goal of this session was to identify and flesh out a set of research and education issues that must be addressed within each of the theme areas to enable control and system integration of miniaturized systems. Recognizing the broad nature of the question, attendees were asked to strike a balance between breadth and depth, finding a path between the extremes of discussing only one topic for the entire session and treating a large number of topics superficially. Each group was assigned three panelists to moderate the discussion. One panelist was to act as a theme representative by subsequently reporting on the discussion to the main audience, while another was required to act as a scribe by keeping track of the points that were raised.

Different dynamics developed within each of the discussion groups. The controls group split its discussions according to on-chip control, in which the device and control system are integrated onto the same chip, and off-chip control, where an external control system is used to improve the fabrication of a miniaturized system or to regulate a micro- or nanoscale process. Recommendations included: control design for fast time scales necessitating analog rather than digital control; creating control-ready models across disparate time and length scales; and dealing with geometric, parametric, and dynamic uncertainty.

By comparison, the nanofabrication group organized its discussion by focusing on fabrication methodologies, unknown physical phenomena, and education issues. Issues addressed by the group included: fabrication bottlenecks; the interactions of different materials across nanoscales and microscales; direct and in-situ characterization; packaging and system integration; and training and education of the next generation of students. The nanofabrication group provided a list of research and education challenges: better control of existing fabrication processes and control of self-assembly; real-time feedback on the short time scales found in nano systems; stochastic modeling and control to achieve overall system reliability when using unreliable components; and the creation of integrated, interdisciplinary curricula for training future students.

After this first round of discussions, workshop participants reconvened in the main auditorium. Following a seminar by Mike Ramsey from Oak Ridge National Laboratory on biochemical sensing, each of the theme representatives gave 15-minute presentations summarizing the discussions within their session. The same basic issues were raised across all six themes: uncertainty, modeling for design, system integration challenges, technical language barriers, and interdisciplinary education needs. In the discussion that followed the six presentations, the workshop audience pointed out some of the technical, human, and infrastructure realities that make it difficult to address these recurring issues. The audience also suggested some possible solutions. It was noted that students can form effective bridges between fields; a coadvised student can facilitate collaboration and assist faculty in learning about new fields. It was thus suggested that NSF focus more on funding interdisciplinary student programs. DARPA program manager Anantha Krishnan pointed out that, although DARPA is well aware of the crossdisciplinary basic science challenges and sees the same recurring issues within the projects that it funds, DARPA does not have the charter to address these issues. DARPA relies on agencies such as NSF and AFOSR to address basic science and education issues. Other audience comments ranged from frustration at how the tenure process fails to encourage collaboration (papers with joint authors are often frowned upon) to the problematic inability of group A to effectively use the results of group B even when those results have been explicitly created for group A. As an example of this difficulty, there was mention of MEMS modeling tools created for system optimization, but which are not being used by the MEMS community.

Even though it is clear to a majority of researchers that uncertainty, modeling for system design, system integration, technical language barriers, and interdisciplinary education are issues that must be addressed, there remains an insufficient amount of collaboration, infrastructure, and funding mechanisms to effectively address these issues. For example, the identification and control of the uncertainties that affect carbon nanotube fabrication require collaboration among modelers, controls researchers, and nanofabrication scientists for a number of years, working under a well-funded program with sufficient measurement and characterization resources to validate models and control schemes. This collaboration has not yet occurred even though the broad research need is clear.

Tuesday Morning: Reorganized Groups

The last day of the workshop began with a seminar by Anantha Krishnan on the design and engineering of bio-molecular nanodevices and systems. This seminar was followed by a talk from Metin Sitti of Carnegie Mellon University on the report from the 2003 NSF Workshop on Nanoscale Systems, Dynamics, and Control [5], which focused primarily on dynamics and control of AFM probes. After these two seminars, the workshop audience separated into six groups for the second and final round of theme discussions. In the previous round of discussions, all participants attended the discussion group that best corresponded to their area of expertise. In this second round of discussions, the audience attendance was intentionally randomized across themes. Now researchers in control, for example, were randomly reassigned to attend discussions in nanofabrication or biochemical systems. The goal of this reorganization was to inject discussion topics from one theme into another. Only the three theme panelists remained in their original theme group to provide topic continuity. In addition, participants were free to move between groups as the discussions progressed.

During this second two-hour discussion, the workshop participants were charged with prioritizing, expanding, cross-referencing, and finalizing the recommendations of the previous day. In particular, participants were asked to address the questions of: What cannot be done today? What are the bottlenecks that prevent it from being done? And, if all technical and human barriers could be crossed, what should be done? The target result was a bulleted list of two to four concrete items per theme that could then be expanded into a report outlining funding recommendations to the NSF. Across all themes, the most difficult task was to keep the discussions focused (the organizing committee had intentionally picked outspoken panelists whom it deemed would best keep the discussion on track) and to keep the level of discussion sufficiently specific. For example, all participants could agree on the importance of model reduction, but this recommendation was already known prior to the workshop. Rather, the participants made such recommendations as "research should focus on creating parsimonious (keep-essentials-only) models for specific subclasses of micro- and nanoscale systems," which was a recommendation made in the controls theme. This particular recommendation dovetailed with a recommendation made in the measurement and modeling group to improve diagnostics and develop detailed and comprehensive micro-/nanomeasurement techniques. When the discussions were completed, the representative of each theme gave a short presentation to the main audience outlining their group's prioritized list of recommendations. The recommendations were discussed in the main audience over lunch, and then the workshop was adjourned at 2:00 p.m. on Tuesday, 30 March 2004.

Workshop Report and Recommendations Relevant to Control

The final report from the workshop, which details the funding recommendations made to NSF, can be found online at the workshop Web site [4]. There are two versions of the report: a short version (a 400-kB PDF file), which contains the text of the recommendations only, and a much longer version (a 172-MB PDF file), which includes the workshop program, the speaker abstracts, and the participant quad charts. The report includes research recommendations from a broad spectrum of researchers as well as funding recommendations to NSF agreed on by a group of 90 experts in the areas of micro-/ nanofabrication, biological and chemical systems, measurement and modeling, and control and system integration. Since the report is aimed at a diverse audience that includes scientists in micro-/nanofabrication, modeling, control, and biochemical systems, an attempt was made to explain concepts that are standard in one theme to researchers in other themes. For instance, statements concerning the prevalence of feedback in complex robust systems are included for the benefit of researchers in fabrication, while statements on the necessity of keeping device fabrication yield high are included for the benefit of controls researchers.

The workshop was originally initiated in the hopes of increasing collaboration between controls and micro-/ nanoscale researchers. In this respect, the workshop was a success: the number of applicants from both the controls and the micro/nano research communities reflected the willingness of these two groups to interact; discussions and exchanges at the workshop informed each group about the research challenges faced by the other groups; and the author is personally aware of a number of collaborations that were initiated at the workshop.

Below is a summary of the report recommendations that are relevant to the controls community. Readers who are interested in recommendations made for the other themes of micro-/nanofabricaton, biochemical systems, and modeling and measurement can download the complete report. The report discusses only research directions that require collaboration between at least two theme areas; research directions that can be addressed by controls researchers alone are not included. Recommendations are organized according to three subjects: system integration, system control, and education and infrastructure needs.

Micro/Nanosystem Integration Recommendations

In the current context, system integration refers to combining micro/nano components to form integrated systems, such as implantable drug delivery systems, micromachines like artificial insects or miniaturized surgical robots, and biochemical pathogen detection systems. The development of improved micro-/nanoscale diagnostics and characterization tools to enable system characterization and integration was one of the two major recommendations in this area. Although controls researchers can contribute to this research direction, the topic requires collaboration between the modeling/measurement and the micro-/nanofabrication communities.

The creation of parsimonious models was the other major recommendation within the system integration subject. This research issue requires collaboration between the control theme and the measurement and modeling theme. The necessary models must be carefully chosen to contain enough physics to be predictive while remaining computationally tractable to enable system optimization and control design. It was noted that the creation of parsimonious models can be achieved by physical insight, which is required to recognize and include only the dominant physical phenomena, and by model reduction techniques, which can be used to reduce the dimensionality of first-principles computational models. Methods are also needed to determine the point in the modeling process at which models become adequate and to validate such models using the available experimental data. Controls researchers, with their expertise in model reduction and system identification, are in a position to contribute to advances in parsimonious modeling and model validation.

Micro/Nanosystem Control Recommendations

Control research recommendations covered three areas: control of micro-/nanofabrication techniques including micro/nano manufacturing processes and nano self-assembly methods; on-chip and off-chip control issues; and recommendations on learning control from biological systems. With respect to the last item, it was noted both that living cells build better control systems than the control engineers and that newly created micro- and nanoscale cell sensors can be useful for examining, understanding, and perhaps replicating biological control capabilities.

Fabrication process control was recommended as an enabling technology. Currently, it is difficult to achieve reproducible fabrication results at the nanoscale. Jun Jiao from Portland State noted that, when fabricating carbon nanotubes, "we repeat the same procedure and get different results each time." Real-time process monitoring and feedback control provides an opportunity to regulate uncertainties and to improve nanodevice yield.

AFM probes can be used to push, pull, cut, indent, and lithographically deposit nanoscale objects. Research recommendations for this kind of nano-assembly control and object manipulation were consistent with those found in the 2003 NSF workshop report [5] and are not repeated here.

On-chip control refers to integrated miniaturized systems where the control algorithms, sensors, and actuators are included as part of the system. The AFM control mentioned above is an example of off-chip control. On-chip control is required for miniaturized systems such as implantable drug delivery platforms, micro sense-and-report systems, and, eventually, microrobots like artificial insects. Enabling these types of systems requires research in: 1) optimal placement of sensors and actuators inside meso-scale volumes, 2) analog, as opposed to DSP, controllers to deal with the fast time scales found in micro- and nanoscale systems, and 3) methods to deal with sensor and actuator failure as well as a significant degree of physical and parametric uncertainty.

Micro- and nanoscale systems involve an interplay between continuous and discrete dynamics; for example, microfluidic devices have continuum flows but often contain discrete objects such as cells or DNA chains that display stochastic behavior. There is also coupling between disparate time and length scales and crosstalk between interfacial and bulk phenomena. As a result, there is a need for modeling and control tools that can address complex heterogeneous systems. Although this area is already receiving attention within the controls community, it was judged that, for applications to micro- and nanoscale systems, closer collaboration between control and micro-/nanoscale researchers is desirable.

Finally, participants in the biochemical theme noted that emerging micro- and nanoscale diagnostics techniques are, for the first time, providing detailed measurements of signaling pathways and intra- and intercellular processes in living organisms. These advances allow control researchers to learn control from biological systems whose functionality, robustness, and complexity can exceed that of synthetic systems.

Education and Infrastructure Recommendations

Not surprisingly, the same education and infrastructure concerns were raised in all of the themes: educating the next generation of cross-disciplinary students, technical language communication gaps among research areas, lack of sufficient collaboration among disciplines, and the incompatibility of modeling, analysis, and design tools across themes. There are historical reasons, vested interests, time constraints, and funding realities that make it difficult to address these issues. For example, faculty in aerospace and mechanical engineering departments have a difficult time convincing their colleagues that aerospace and mechanical students should be taking courses in chemistry and biology.

Workshop participants tried to find specific ways to improve the education and infrastructure situation. Recommendations relevant to the controls community include the establishment of funded cross-disciplinary student exchange programs, which will allow control students to spend a summer at a MEMS or a biochemical research group. Second, it was suggested that funding mechanisms be created to encourage the co-advising of students by faculty in different fields. Third, it was recommended that NSF provide support for summer workshops in micro/nano research topics such as AFM, microfluidics, nanofabrication, and bio-systems. This support would enable researchers in control to receive focused, technically detailed courses in specific areas of micro/nano research. It was suggested that these workshops follow the Gordon conference model, where a small number of scientists interact in a relaxed setting with a large amount of time set aside for informal discussions. Fourth, cross-disciplinary curricula should be developed at both the undergraduate and graduate levels. Finally, there should be mentoring of junior faculty by senior faculty in other fields, as well as funding mechanisms to encourage faculty to take sabbaticals in areas outside their main expertise.

The above recommendations are addressed to NSF and to the research community in controls, micro/nano systems, modeling, and biochemical systems interested in developing integrated miniaturized systems.

Conclusions

Throughout the organization of this NSF workshop, and in subsequent conversations with colleagues in control, the author has found a number of people who are expanding the role of control into new areas, including miniaturized and biological systems. This expansion can benefit the community at large since new subject matters can lead to developments in control theory, and exciting applications can attract the next generation of top students to the area of control.

The match between the area of micro-/nanosystems research and control is timely and is of benefit to both communities. Micro- and nanoscale fabrication techniques are moving from components and devices to integrated systems. In fact, researchers can benefit from controls and system integration tools that address the management of and design for uncertainty, component coupling, and system optimization and control. Controls researchers developing tools in distributed control can benefit from the distributed actuation and sensing opportunities afforded by miniaturized sensors and actuators integrated into mesoscopic volumes or scattered across large ones.

The hope of the NSF workshop organizers and participants is that, over the next few years, there will emerge a large number of workshops and conference sessions dedicated to control of miniaturized systems, along with meaningful collaborations between researchers in control and researchers in fabrication, modeling, and biochemical systems. Ideally, this increased collaboration will lead to improvements in the funding and education infrastructure while generating sufficient support and interest within the control community to enable the rapid development of control methodologies for micro- and nanoscale systems. We expect that micro- and nanoscale systems, such as miniaturized implantable drug delivery systems and autonomous microsurgical robots, will contain control as an integral part of their operation. The NSF workshop organizers and participants hope that the control community will be play a timely, pertinent role in the development of such micro- and nanoscale systems.

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this reviewer's perspective, this assessment is particularly true of the chapter on aerospace control, which presents an incomplete picture of some of the control problems studied. This comment is not intended as a criticism of the book, but rather to stress that the purpose of the book is not to treat the case study examples for their own intrinsic interest. Rather, the authors use the case study examples to expose the principles of application-specific Lyapunov-based adaptive control.

Several important topics are omitted from the text. Controllers that involve nonlinear estimators or observers are not treated. No model simplification approaches, such as singular perturbations or vector field approximations, are employed. Little attention is given to the geometric features of the control problems; this deficiency is most noticeable in the sections that treat attitude representations using quaternions. The focus on Lyapunov-based adaptive control means that many alternative nonlinear control methodologies are not treated. These omissions do not detract in a significant way from the narrower theme of the book.

The text treats a number of case study examples, illustrating the application of Lyapunov-based control methods. It is a welcome addition to the tutorial literature on applying Lyapunov-based adaptive control to engineering systems.

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