Accommodating the Diverse Technical Interests of Foreign Exchange Students through Participation in MEMS and Micro-Robotic Research Projects

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Abstract - **Foreign student and faculty exchanges are an excellent vehicle for training a global engineering workforce. The high degree of technical specialization of engineering laboratories, however, often leads to inability to attract a large cohort of foreign students due to their diverse technical interests, and therefore, limits the impact of the exchange program. This paper describes an innovative use of micro-electromechanical systems (MEMS) and micro-robotics research as an educational vehicle attracting students from all engineering disciplines. Several recently developed projects and courses developed at the University of Arizona and the Swiss Federal Institute of Technology (ETH-Zurich) are described. These include design and fabrication of a pressure and force sensors, development of micro-robots with a bio-compatible coating, and optical cantilever-based gas sensor. The broad spectrum of these projects provided ample opportunities for involvement of students and faculty of almost any technical background. Recent examples include 13 Japanese students from Toyota Technological University attending a summer hands-on course at the University of Arizona, a French student applying diffusion-reaction models to a micro-robot coating process, and a visiting professor from Tuffs University participating in the development of software for control of the micro-robots at the ETH – Zurich. Opportunities to engage students with traditional engineering interests such as solid mechanics and fluid dynamics are also described in the context of the three projects via evaluation of the typical mechanical engineering curriculum in US.**

Index Terms – International Exchange Student, Mechanical Engineering, MEMS, Pressure Sensor

I. INTRODUCTION

Engineering is an activity involving the harvesting the three main resources—energy, materials, and information—in order to create tools and technologies in service of the human race. Consequently, engineering activity has a global impact, as most of these resource are shared, or their utilization has implication for the entire civilization. Consequently, engineering education has the objective of not only presenting the scientific principles, i.e., engineering science, but also of teaching students how to apply them judiciously, without adverse impact on the environment. Furthermore, the rapid growth of communication and the development the Internet resulted in a globalization of the engineering discipline. For example, in the 1960s only 7% of the US industry was subject to international competition, while in the 1980s that number had increased to over 70%. Similarly, the developed European nations are exposed to labor-market pressures from the new economies of China, India, and Eastern Europe. Therefore, there is a need for training a globally-engaged workforce of engineers, capable of interacting and competing with their peers abroad. In response to this demand, many engineering programs in US are exploring innovative methods for incorporating international education in their curriculum. Recent examples include joint programs in mechatronics [1], joint freshmen engineering course [2], an international graduate degree in civil engineering [3]. In 2006, the US government (through NSF) also launched a new program titled Partnership for International Research and Education (PIRE) that is designed to foster such activities. However, there are several obstacles hindering the growth of the international collaboration in engineering education. These include difficulties in scheduling and coordinating courses at the two partner institutions, the lack of suitable technical elective courses and opportunities for the students to maintain uninterrupted graduation schedule, insufficient time for completion of a joint project, and of course, limited financial resources at most institutions. Therefore, a successful international exchange program needs to leverage existing projects when hosting foreign students. This paper provides several examples based on Micro-Electromechanical Systems (MEMS).

MEMS have acquired a history of over 30 years of development. Many successful commercial applications have emerged, such as switches, display, pressure sensors, accelerometers, gyroscopes, inkjet printer heads, and lab-on-a-chip chemical detection systems. These success-stories inspired not only the industrial world, but also sparked interest among academic institutions in incorporating MEMS into their curriculum [4-7]. A distinguishing feature of educational programs focused on MEMS is their interdisciplinary nature stemming from the need to design and integrate electrical, mechanical, optical, or chemical sub-systems into a functional device. Therefore, such programs provide ample opportunities for participation of foreign exchange students and researchers with various technical backgrounds. In this paper we describe our experience in

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providing opportunities for international student exchanges based on the use of micro-mechatronics and MEMS.

II. EXAMPLES OF MEMS PROJECTS WITH PARTICIPATION OF FOREIGN EXCHANGE STUDENTS

The following projects have been derived from the two collaborating institutions: Advanced Microsystems Laboratory (www.ame.arizona.edu/research/memslab) at the University of Arizona; and the Institute of Robotics and Intelligent Systems (www.iris.ethz.ch) at the Swiss Federal Institute of Technology.

II.1 Cantilever Micro-Sensor for Detection of Organic Vapors (University of Arizona)

Microfabricated cantilever sensors are one of the earliest examples of the use of mechanical structures for chemical detection. The early sensor examples were based on mass-induced mechanical resonance shift [8]. However, due to relatively complicated detection scheme and the need for external excitation, these sensors did not result in a wide-spread use. An alternative detection mode is the surface stress based detection scheme, which uses the optical lever technique to amplify the cantilever displacement [9]. The first such demonstration was pioneered by a research group at IBM in Zurich, which demonstrated that a change in a single base-pare (bp) in a 12-bp sequence can be detected with chemically functionalized cantilevers [10]. Since then, a broad effort emerged to develop other sensors using this technique including metal-ion detectors (Hg, Cu, As) [11] and organic molecules [12].

The project described here is based on the preliminary work by Berger et.al. [9], which demonstrated sensitivity of alkenethiols using a commercial atomic force microscope (AFM) scan head and Au-coated cantilevers. The experimental setup is shown in Figure 1. A fixed volume chamber is used to expose the Au-coated cantilevers to the vapors of alkenethiols, during which, a well-known reaction between organic thiol groups and the Au-coated surface results in a densely packed layer of self-assembled alkanethiol molecules (SAM). The resulting surface stress, $\Delta\sigma$, produces a cantilever curvature R, given by the Stoney equation

$$\frac{1}{R}=\frac{6(1-\nu)}{Et^2}(\Delta\sigma), \qquad (1)$$

where E, t, and ν are the Young's modulus, the thickness, and the Poisson ratio of the cantilever, respectively. Assuming constant curvature, the deflection angle $\Delta\theta$ at a distance L from the base of the cantilever is

$$\Delta\theta=\frac{L}{R}. \qquad (2)$$

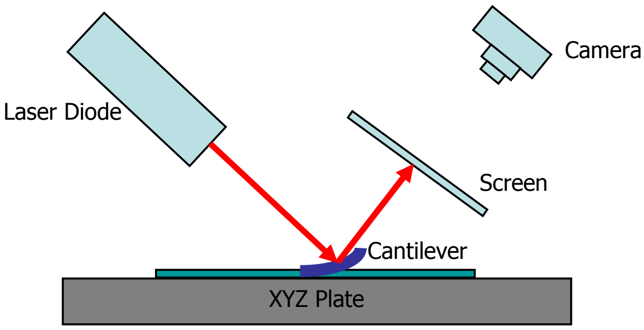

FIGURE 1
SCHEMATIC OF MICRO-CANTILEVER SENSOR EXPERIMENT

The deflection angle is then amplified using the "optical lever" technique, i.e. by monitoring the position of the reflected laser beam illuminating a position sensitive detector at a distance d from the cantilever

$$\Delta x = 2d\,\Delta\theta=\frac{12dL\Delta\sigma(1-\nu)}{Et^2}. \qquad (3)$$

The optical detection system was developed as a senior capstone design project which included the design and fabrication of the micro-cantilevers with a 1-mask process [13]. The resulting array of cantilevers is shown in Figure 2. The cantilever deflection was measured with an optical detection system comprised of a diode laser, focusing optics, positioning stages, and a position sensitive detector (PSD).

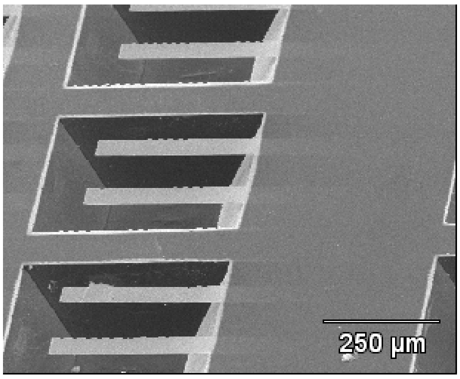

FIGURE 2
ARRAY OF MICRO-CANTILEVER SENSORS

The completed demonstration system consists of 635 nm laser diode with beam shaping optics (Edmund Optics NT59-080), a *x*- *y*- and θ positioning stage with sample holder, a post with the position sensitive detector (Hamamatsu S5990-01), and a syringe for dispensing the alkenethiols (see Figure 3).

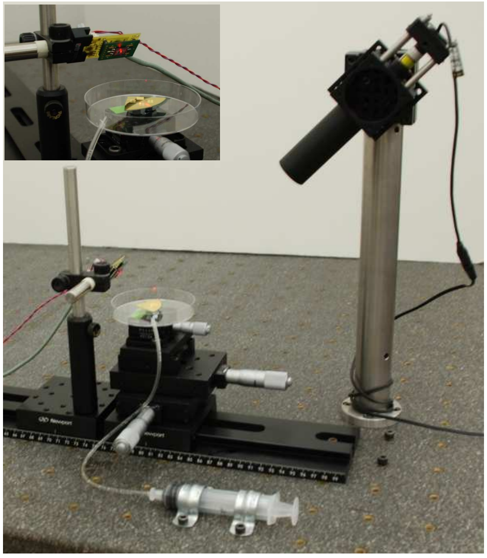

FIGURE 3
EXPERIMENTAL SETUP: LASER DIODE WITH OPTICS (RIGHT); SAMPLE HOLDER WITH ORIENTATION CONTROL(CENTER); PSD DETECTOR (LEFT)

A covered Petri dish containing Au-coated silicon nitride cantilevers was used to expose them to a solution of dodecanethiol (2 ml) using a medical syringe. The cantilever deflection was then recorded and converted to surface stress values using (1-3). Figure 4 shows typical experimental data.

While this project was developed as a demonstration project for domestic students interested in MEMS and micro-technology, it also proved very useful vehicle for offering short courses to visting foreign students. An example for this is the joint summer program between the University of Arizona and the Toyota Technological University, Japan. This summer program was initiated in 2005 and brings approximately 13-15 students to the University of Arizona for English courses followed by a hands-on laboratory experience offered by the College of Optical Sciences and the College of Engineering and Mines. The micro-cantilever project described here is one of the experiments described in this course. After a short lecture on MEMS and micro-technology, the students are asked to design their own cantilevers, test existing cantilevers sensors and produce a report describing the sensitivity of the sensor. More details on the technical content of the project can be found in [13]

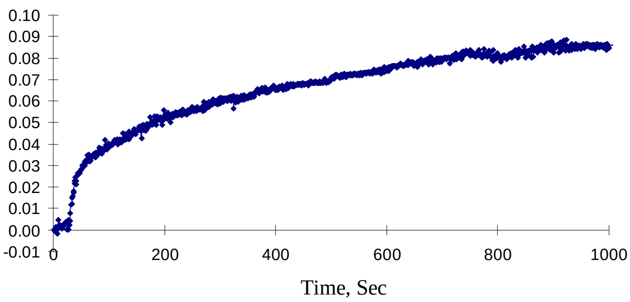

FIGURE 4
MEASURED SURFACE STRESS (N/m) AS A FUNCTION OF TIME

II.2 Magnetic Micro-Robot for Targeted Drug Delivery (Swiss federal Institute of Technology)

This project is aimed at demonstrating a micro-robot capable of autonomously navigating and delivering active pharmaceutical ingredients (drugs). The approach taken here is based on the use of an oscillating external magnetic field to trigger the release of the drug. Localized drug delivery is an exciting new alternative to systemic delivery, as it could reduce the undesirable side effects of many drugs [14]. In the core of this project is a sub-millimeter sized ferromagnetic structure (micro-robot), which is steered via the forces generated by external electro-magnets arranged as Maxwell and Helmholtz coils [15] (see Figure 5). The objective of the project described here is to develop a bio-compatible "skin", a coating that can carry the drug and a method to release it. A proof-of-concept device has been constructed via dip-coating the robot with sodium alginate (Na-Alg)-derived gel. The process follows the protocol of Saslawksi [16]. The alginic acid is a linear polysaccharide comprised of mannuronic acid (M) and guluronic acid (G) residues. These are chained in a repeated alternating pattern (GG-GM-MM-..). The negatively charged carboxyl groups of the acid residues are key to the formation of cross-linking bonds when the the polymer is exposed to multivalent metal ions such as Ca^{2+}. To control the permeability of the skin, the gel was further cross-linked using cationic polymers such as poly-l-lysine and polyethyleneimine. The triggering of the drug release was achieved by incorporating strontium ferrite micro-particles together with the model drug, (horseradish peroxidase, HRP) in the coating (see Figure 6 of two coated devices). Subsequent exposure to 0.4 T oscillating magnetic field resulted in a 10-fold increase in the release rate of HRP as shown in Figure 7.

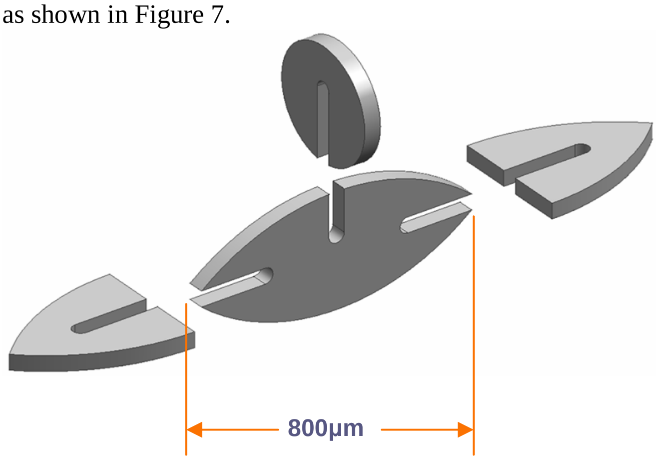

FIGURE 5
STRUCTURE OF THE MAGNETIC CORE OF THE MICRO-ROBOT

As in the other examples, this project also requires knowledge in electro-magnetism, material science and chemistry, semiconductor processing, control theory, and mechanics. The wide spectrum of disciplines involved allowed researchers from three institutions to collaborate in a complementary fashion. The robot's skeleton and electromagnetic positioning system was developed by the robotics group at ETH (IRIS), the bio-compatible coating was developed by Enikov from the University of Arizona, while a new version of the electronic control interface was implemented in Labview by a visiting professor (at ETH) from Tuffs University. Student exchange is also planned for the summer of 2007 between the University of Arizona and the Ecole Nationale Superieure de Mecanique et d'Aerotechnique (ENSMA). The French student will analyze and model the cross-linking process and, subsequently, the drug release properties of the micro-robot coating.

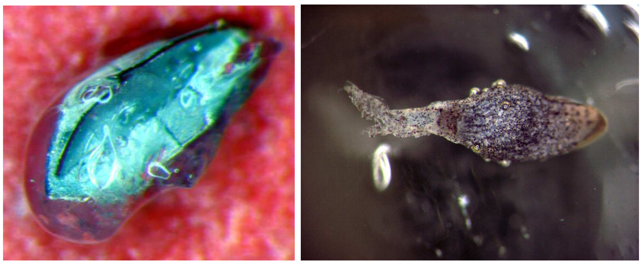

FIGURE 6
COATED MICRO-ROBOTS: CALCIUM ALGINATE ONLY(LEFT); CALCIUM ALGINATE AND STRONTIUM FERRITE MICRO-PARTICLES (RIGHT).

II.3 Piezoresistive Pressure/Force Sensor (University of Arizona)

Pressure sensors are now well-established application of MEMS and, therefore, represent an essential element of most curricula on micro-electromechanical sensors. Most pressure sensors utilize a deformable membrane with integrated strain- or displacement-sensing elements.

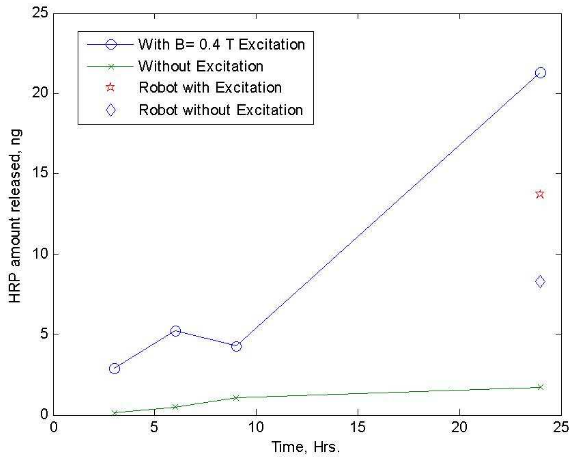

FIGURE 7
HRP RELEASE FROM CALCIUM ALGINATE BEADS (2MM DIAMETER). ASTERISK AND DIAMOND SHOW THE RELEASE FROM MICRO-ROBOTS WITH AND WITHOUT MAGNETIC EXCITATION, RESPECTIVELY

The classical Si pressure sensor was first developed by Kurtz and Goodman in the early 1970s [17]. It is based on anisotropic etching of Si, which results in a truncated pyramid forming the cavity of the sensor (see Figure 8). The pressure is measured by (typically) four piezo-resistive elements, placed at the location of highest stress and forming a Wheatstone bridge (see Figure 8).

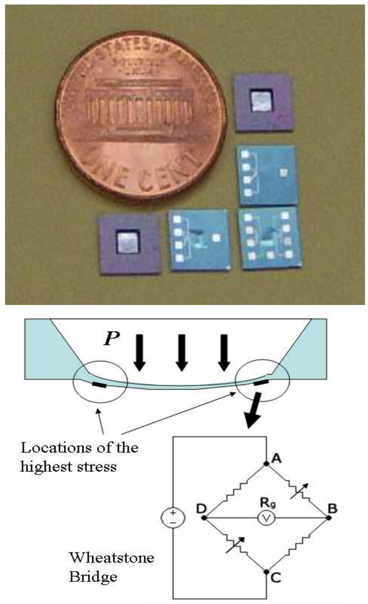

FIGURE 8
TYPICAL SI PIEZO-RESISTIVE PRESSURE SENSORS

For a square diaphragm with size $a \times a$ and thickness h, the change of resistance, ΔR, as a function of the applied pressure, p, can be calculated through

$$\frac{\Delta R}{R_0} = -\frac{1}{2}\pi_{44}\sigma, \qquad \sigma = 0.0513 pa^2 \frac{12}{h^2}, \tag{4}$$

where π_{44} is the piezo-resistive coefficient. Typical values of π_{44} for lightly doped Si are -13.6 Pa^{-1} and 138.1 Pa^{-1} for n-type and p-type Si, respectively [18]. Due to its high temperature sensitivity, the piezoresistors are almost always connected in a Wheatstone bridge configuration to reduce the effect of temperature variation. In this case, the output voltage of the bridge is a function of the input voltage through

$$V_{out} = V_{in}\frac{\Delta R}{2R_0} = -0.0513 V_{in}\pi_{44} pa^2 \frac{3}{h^2}. \tag{5}$$

The resolution of the sensor, however, is determined by its noise level, which is a function of the value of the resistors. The lowest discrimination value is typically twice the root mean square (RMS) of the thermal noise [19]

$$V_{out}^{\min} = 2v_{rms} = 2\sqrt{4kTR\Delta f}\ , \tag{6}$$

where $k = 1.38 \times 10^{-23}$ W-s/K is the Boltzmann's constant, T is the absolute temperature, and Δf is the frequency bandwidth of the amplifier used to amplify the signal. Therefore, using (5) and (6), one can estimate the ultimate pressure resolution for a given sensor design.

The pressure sensor project is also part of the MEMS curriculum at the University of Arizona. It provides hands-on experience for both domestic and foreign exchange students. Furthermore, the use of an established processing technology allows students to confidently explore its creative use. Examples of learning projects based on the current device include

- Design of micro Pitot tube for airspeed velocity measurements in a micro air vehicle (MAV) (undergraduate level);
- Design of altimeter (undergraduate level);
- Design of temperature compensation circuitry (graduate level);
- Analysis of the hysteresis and non-linear effects in the response (graduate level).

III. MECHANICAL ENGINEERING CURRICULUM THROUGH MEMS PROJECTS

The three projects described here provide ample opportunities for short-term projects of visiting researchers. While it is clear that chemical, optical, and electrical engineering students can successfully participate in these projects, we also investigated the opportunities for mechanical engineering students with interests in classical disciplines such as solid mechanics, thermodynamics to participate in MEMS-based research. To this end, we have analyzed the discipline-specific courses in the undergraduate mechanical engineering curriculum at the University of Arizona, and have identified specific technical tasks that could be used to illustrate each course. These are summarized in Table I.

TABLE I
DISCIPLINE SPECIFIC COURSES LEADING TO A BACCALAUREATES' DEGREE IN MECHANICAL ENGINEERING AT THE UNIVERSITY OF ARIZONA: THEMATIC CONNECTIONS TO THE MEMS PROJECTS.

Subject/ Curriculum Year	*MEMS Project and Activity*		
	Cantilever Sensor	Micro-Robot	Pressure Sensor
Prob. Solving and Eng. Design /Yr I	Demonstration only	Demonstration only	Demonstration only
Introductory Mechanics / Yr I	Cantilever beam theory	Newton's Second Law	Force vs. pressure,
Fund. Tech. Of Chemistry Yr I	Molecules and surfaces, adsorption isotherm	Beer's law of absorbance. Concentration measurements	Anisotropic Etching of Si.
Introduction to Electricity and Magn. / Yr II	Light as EM radiation. Absorbance, reflection, and diffraction	Magnetic forces and torques. Magnetic circuit analysis.	Piezoresistive effect.
Introduction to CAD Design/ Yr II.	Photomask design.	Photomask design.	Photomask design.
Statics / Yr II	N/A	Mechanical equilibrium under magnetic excitation.	N/A
Elements of Electrical Eng./ Yr II	Transimpedance amplifiers for PSD readout.	Electromagnets and driving circuits.	Bridge circuit analysis.
Thermodynamics I/ Yr II	Thermodynamic equilibrium. Addsorption isotherms.	Diffusion kinetics.	Kinnetic theory of gases. Gas laws.
Dynamics / Yr II	Vibrational modes. Thermal noise in cantilevers.	N/A	Modal analysis of plates.
Mech. Behav. Of Materials/ Yr III	Mutli-layered cantilever deflection analysis.	N/A	Stresses and strains in anisotropic materials.
Principles and Applications of Fluid Dynamics/ Yr III	N/A	Motion in low Reynolds's number environments.	N/A
Dynamics of Machines /Yr III	N/A	N/A	N/A
Instrumentation Laboratory/ Yr III	Laboratory exercise on laser diodes and photodetectors.	Laboratory experiment on control of electromagnetic field and its gradient.	Laboratory experiment on bridge balancing and readout.
Engineering Component Design / Yr III	Stress-strain analysis via ANSYS	N/A	Stress-strain analysis via ANSYS
Fundamentals of Materials for Engineers/ Yr III	N/A	Bio-polymers – processing and use.	N/A
Senior Laboratory/ Yr IV	Perform device test and analysis.	Perform device test and analysis.	Perform device test and analysis.
Capstone Design I,II/ Yr IV	Design/improve the sensor performance.	Design/improve the robot shape, and driving mode.	Design/improve the sensor performance. Develop multi-axis force sensor
Heat Transfer/ Yr IV	N/A	Use of heat diffusion equation to analyze drug elution.	Analyze self-heating effects
Control Systems Design / Yr IV	Implement automatic laser beam alignment system.	Implement closed-loop position control of the robot.	N/A

Based on the mapping between courses and project tasks, it is easy to develop activities for foreign mechanical engineering exchange students regardless of their area of specialization. For example, a student visiting University of Arizona in summer of 2007 from Ecole Nationale Superieure de Mecanique et d'Aerotechnique (ENSMA) traind in classical fluid mechanics is working on a new extrusion technique to better encapsulate the micro-robot in the alginate gel. Interviews with the student indicated that at ENSMA most of the curriculum is pre-determined and there is relatively little freedom allotted to the student in conducting independent research. During his work on the micro-encapsulation project at the University of Arizona, the student had to learn how to perform effective literature search, design and carry out several experiments in support of his project, and identify a mathematical model most accurately representing his experimental conditions. In contrast, the group of 13 students from Toyota Technological University participated in a lecture-based short course on MEMS, supplemented with hands-on exercises. The Japanese students appeared much less keen on participating in a question-and-answer sessions during the lectures, but demonstrated a great deal of interest during the hands-on sessions and lab tours.

IV. FACTORS INFLUENCING THE SUCCESS OF INTERNATIONAL COLLABORATION

The main constraints associated with visiting scholars arise from the limited duration of the visit (4-6 months), the lack of knowledge of the local institutional research culture and available resources. It is important, therefore, to provide access to knowledgeable members of the host research group, as well as to critically review the scope of the project and decide on a project scope that could be completed during the length of the visit. Proper documentation of prior work on a given project is also vital for the quick adaptation of the visiting researcher. Examples include access to online data base with presentations and research reports, participation in research group meetings and discussions, and attendance of seminars offered by members of the host institution. In the case of MEMS fabrication requiring access to specialized equipment, it is often more productive to ask a local super-user to perform the operation and allow the visitor to focus on the interpretation of the results. Therefore, the success of the visiting researcher is strongly dependent on the project organization at the host institution, the availability of staff able to assist them. A low-cost alternatives to a full-fledged MEMS fabrication project are the analysis and testing of existing devices from previous projects, the development of software interface for existing experiments, and the compilation of surveys of the state-of-the-art in a given application area. Finally, the projects should allow the visiting scholars to complete them and/or to use the results at their home institutions, for example in satisfying a degree a course requirement. An institutional agreement prior to the start of the project is a good way to formalize such arrangements.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the National Science Foundation under Grant Nos. DMI-0134585, CBET-0603198, and DUE-0633312.

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