

IREE: Collaborative Research and Education in Nanomechanical Cantilever Biosensors

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ABSTRACT: This IREE research utilizes nanotechnology, the science of building and manipulating objects as small as a single atom, to create miniature devices (in the form of micro- and nano-cantilever beams) that are able to detect small biological species such as E. Coli bacteria, DNA and proteins. Such biosensors operate through the adsorption of species on the functionalized beam's surface, and hence molecular recognition is directly and specifically converted into measurable micromechanical responses. This research approach, through a unique collaborative effort between Clemson University, Denmark Technical University and the Max Planck Institute for Polymer Research (Germany), involved the creation of microscopic components (or "beam") that can actually record the impact of how a particular particle or molecule interacts with a foreign substance. This interaction is conducted through the binding of molecules or particles directly on the surface of the microcantilever. Insert a one-paragraph abstract of this report.

INTRODUCTION

NSF Award Number: CMMI-0238987 (Supp. Award #: CMMI-0637135)

Principal Investigator: Dr. Nader Jalili

Institution: Clemson University

Background: While microcantilever-based sensors have been successfully applied in different fields in recent years, the activities reported in the US are in their early stage of development. Therefore, this international collaborative is innovative in that it educated US students as to how microcantilevers are used in microbial mass sensing and molecular recognition. The primary objective of this collaboration was to enable students to learn state-of-the-art measurement and fabrication instrumentation that explores and tests new concepts at the edge of what is technologically possible. Research was undertaken at the Max Planck Institute for Polymer Research, Germany and 2) Denmark Technical University, Department of Micro and Nanotechnology, Denmark. Figure 1 provides an overview of the relevant research areas, the counterpart overseas institutions and their

roles. A new graduate course designed around this student-driven research effort is scheduled to be offered in Spring 2008 at Clemson University with a specially-designed module in nanomechanical cantilever sensors.

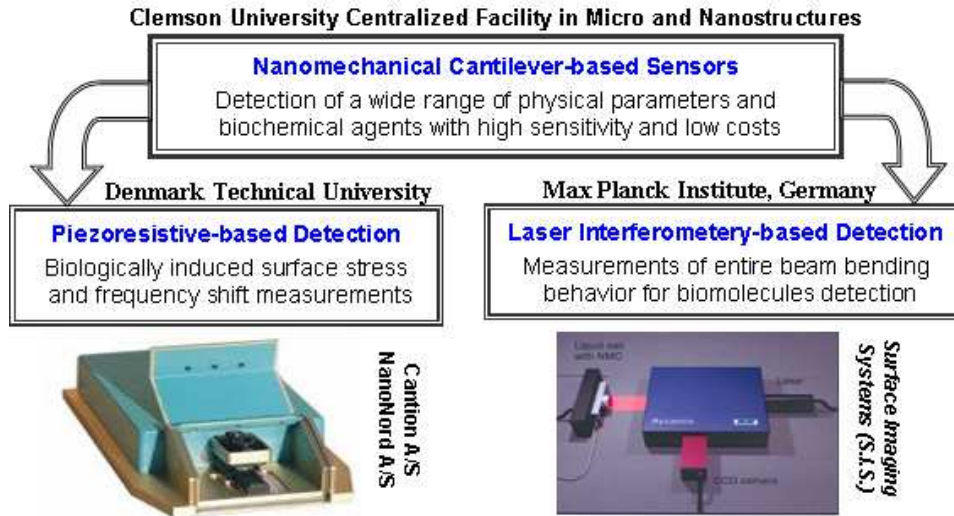


Figure 1. The schematic integration of collaborative research and education in nanomechanical cantilever biosensors.

Rationale for International Collaboration and Research Activities: Such international collaboration for research opened opportunities for advancement outside of what would ordinarily be achievable. The executed international cooperation between Clemson University's SSNEMS (Smart Structures and Nano-Electrical Mechanical Systems) Laboratory, Max Planck Institute for Polymer (MPI-P) Research and Technical University of Denmark's Department of Micro and Nanotechnology (DTU-MIC) and facilitated by 2007 NSF IREE program resulted in a collaborative effort conducted on the following research areas; 1) use of microcantilevers for determining mechanical properties of thermally sensitive polymers, 2) fabrication of silicon nitride microcantilevers with intergraded gold strain gauges, 3) determining a relationship of static bending to natural frequency shift, 4) finding new methods of comparing SU-8 cantilevers to their silicon counterparts, 5) dual cantilever arrays for reference corrected mass sensing, as well as 6) groundwork for future projects. More specifically and through this initiative, new research and ideas have been generated for future research that will combine the resources and capabilities of these three groups.

Plan of Visit and Coordination: The following U.S. researchers were involved in this IREE program. 1) Daniel Elis (undergraduate student): Travel time between May 11, 2007 and Aug. 21, 2007; 2) Calvin Bradley (graduate student): Travel time between May 29, 2007 and Aug. 21, 2007; and 3) Dr. Nader Jalili (Advisor): Travel time between June 3, 2007 and June 14, 2007.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

Activities of US Researchers at Max Planck Institute for Polymer (MPIP) Research: During the course of the project, the researchers prepared NMCS using functional coatings such as polymers. Typical preparation techniques included plasma deposition, drop coating, self assembly or direct synthesis of the polymer onto one side of the cantilever. Absolute values of the bending, i.e., the radius of curvature of a NMCS can be determined by an interferometer setup which was recently developed in cooperation with Surface Imaging Systems (S.I.S.) GmbH.

Calvin Bradley's research project at MPI-P was to utilize microcantilevers to observe properties of thermally sensitive polymers in various configurations. For this, different cantilever configurations were considered and the effects of hydrophobicity transition on the mechanical stress of the polymer on the beam was observed (see Fig. 2). Daniel's time at MPI-P was mainly spent developing a system to measure natural frequency shifts in microcantilevers as a function of bimetallic, temperature-induced static deflections. The goal of this project was to find a highly sensitive relationship between the static deflections – measured with interferometric fringe analysis – of a cantilever and the corresponding resonance shifts – measured with a laser-based system. Figure 3 is an illustrated the laser-based resonance system built by Daniel at MPI-P.

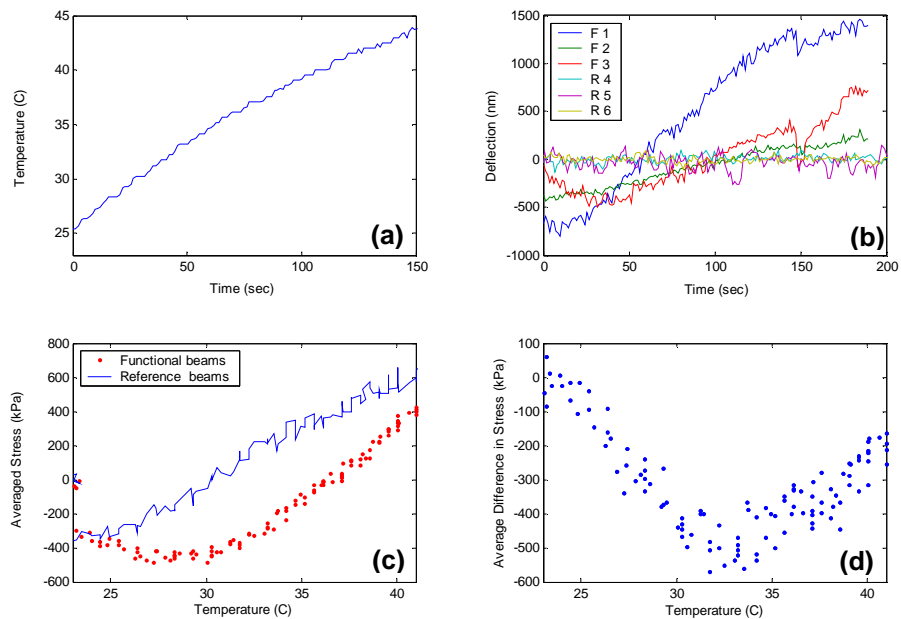


Figure 2. Surface stress measurement by thermal sensitivity of polymer; a) temperature variation throughout the experiment, b) deflection of both functionalized (F) and reference (R) beams, c) averaged surface stress variation with temperature for both functionalized (F) and reference (R) beams, and d) averaged relative (difference between functionalized and reference beams) surface stress variation with temperature.

Activities of US Researchers at Denmark Department of Micro/Nanotechnology (DTU-MIC): In the proposed project, US researchers conducted fabrication and initial characterization of piezoresistive cantilevers with piezoresistive read-out. These devices were designed so that they fit into the electronics box from NanoNord, A/S, which will facilitate their testing and characterization after fabrication. The researchers (grad student) working in the cleanroom facilities at MIC focused on developing improved micrometer sized cantilevers for surface stress detection. These devices were realized in either polymer or Si-based materials. The cantilevers were improved by optimizing the built-in strain gauge and/or by improving the design of the cantilever (see Fig. 4). After fabrication, the researchers (undergrad student) characterized the device with respect to sensitivity and noise. Finally, the sensors were used to detect sample molecules such as thiols on a gold-coated cantilever, which is known to generate large signals.

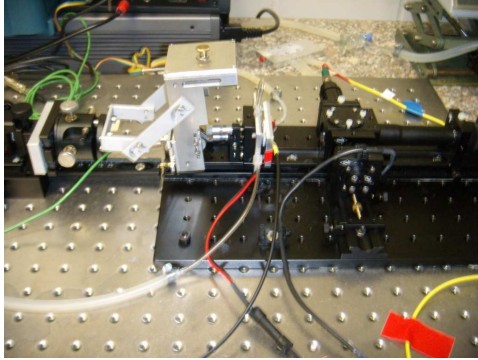


Figure 3. Schematic of the interferometer system, built and tested at MPI-P.

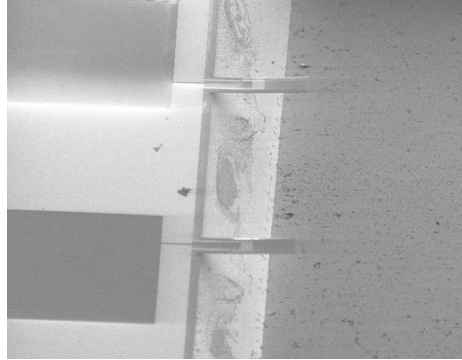


Figure 4. SEM image of dual cantilever with integrated strain gauge readout.

BROADER IMPACTS OF THE INTERNATIONAL TRAVEL

Impact on Research Activities: The proposed collaboration has substantially enhanced the engineering research program at Clemson University by moving the very advanced materials processing program into the more highly funded arena of active microstructures and nanostructures fabrication and characterization. As detailed here, this collaborative project has impacted the research of a current NSF CAREER awardee, and two graduate and undergraduate students. No Clemson research facility has the necessary type of fabrication and measurement instrumentation that is available at DTU-MIC or MPI-P. Each group within this collaboration has different strengths. The SSNEMS group has strength in dynamics and controls of MEMS and NEMS with its unique experimental characterization and analysis instrumentation. MPI-P has superior experience in applied uses of microcantilevers for sensing, while DTU-MIC has extensive fabrication facilities. The combination of these three capabilities has spawned ideas for new research to be undertaken within SSNEMS group.

Along this line, a project combining the resources of both SSNEMS and MPI-P has already begun. More specifically, utilizing a focused ion beam at MPI-P for extremely small mass deposition and self-actuated cantilevers from both MPI-P and SSNEMS as well as a newly-awarded NSF MRI, the Microsystems Analyzing (MSA-400) from Polytec, research into the dynamics of actuated microcantilevers will be pushed further

than either of these groups could have achieved separately. Such collaboration can lead to more efficient research and spread knowledge across international borders.

Educational and Societal Impacts and Relation to Research: Forming a unique multidisciplinary team, such as that implemented between Clemson Mechanical Engineering Department, DTU-MIC and MPI-P offered unprecedented opportunities to create relationships among physics, mathematics, chemistry, biology and engineering faculty while promoting education at the interface between these disciplines. Personal growth is also an important part of the international experience that should not be ignored. Working in different countries demonstrated that there exist different ideals for methods and work environments. Intangible growth for the individuals occurs when similarities and differences between cultures are experienced, such as development of interpersonal skills for a global cooperation.

DISCUSSION AND SUMMARY

The opportunity to conduct research outside of the United States has enabled personal and academic advancement for those involved. With continued efforts these advances will be shared beyond the limited scope of only those involved through the publication of results in journals and conference proceedings.

Personal growth from travel abroad is commonly talked about. It is a learning experience in many ways. However, the U.S. students were never exposed to a real opportunity to do real research abroad before this experience. Due to scheduling demands of traditional engineering undergraduate classes combined with co-op work spending time to study abroad is a near impossible thing for undergraduate students. However, given this chance as a graduate student was a truly amazing experience for the undergraduate student as he was so thrilled to have been given this time. It will probably have a huge effect on his life. For the undergraduate student this opportunity was Daniel's first exposure to a real research environment. The lessons he learned abroad have already found application through current research at Clemson as well as affecting decisions for future research and educational opportunities.

Academic advancement was found in the research accomplishments and future work possibilities. In Germany alone work for at least one journal paper was accomplished in the area of polymer physics using microcantilevers. On top of this, joint research was initiated by conducting mass deposition on self actuating piezoelectric microcantilevers. Also, research being conducted at SSNEMS was presented to a large audience at MPI-P. In Denmark, microcantilevers were fabricated and lanes were opened for providing SSNEMS with a means of attaining custom cantilevers. Also, original work for mass sensing with integrated strain gauges with compensating reference cantilever was done and an abstract for a conference paper has been submitted and already accepted. Through these publications, the impact of the work done during this period will impact more than just the three research groups involved.

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BRIEF BIOGRAPHIES OF RESEARCHERS

Nader Jalili received the B.S. and M.S. degrees from Sharif University of Technology, Tehran, Iran, in 1992 and 1995, respectively, and the Ph.D. degree in mechanical engineering from University of Connecticut, Storrs, in 1998. He is currently an Associate Professor of Mechanical Engineering and Director of Clemson University Smart Structures and NEMS Laboratory. Dr. Jalili is currently the Associate Technical Editor of IEEE/ASME Transactions on *Mechatronics* and Associate Editor of ASME Transactions, *Journal of Dynamic Systems, Measurement, and Control*.

Calvin Bradley received his Mechanical Engineering B.S. degree summa cum laude from The University of Tennessee in Knoxville in May of 2006. While at Tennessee he completed 5 co-op engineering terms with Eastman Chemical Company in Kingsport Tennessee where he received a patent for packaging and packaging techniques. He is currently pursuing a master's degree at Clemson University with an expected graduation in spring 2008. He is a research scholar in the Smart Structures and Nanoelectromechanical Systems Laboratory in the Department of Mechanical Engineering at Clemson University. His research interests are sensitivity enhancements, fabrication, and novel applications for microcantilevers. While pursuing his degree at Clemson University he has also worked at Max-Planck Institute for Polymer Research in Mainz Germany and Denmark Technical University in Lyngby Denmark. He is a member of numerous honors societies including Tau Beta Pi.

Daniel Eils is an undergraduate student who will receive a B.S. in Mechanical Engineering from Clemson University in December 2007. He began his research in microelectromechanical sensors in spring 2007 through the Calhoun Honors College Departmental Honors Undergraduate Research Program at Clemson University. Research interests include microfabrication and characterization of microcantilevers for biosensor application.

