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INTEGRATING MICRO-NANO LEVEL INTERDISCIPLINARY MANUFACTURING ENGINEERING EDUCATION FOR MEMS DEVELOPMENT

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Abstract

MEMS or Micro Electro-Mechanical Systems are miniaturized mechanical, electrical, and biological devices and systems with a dimensional range within a few micrometers. They represent a novel multidisciplinary technology field with unlimited potential for a wide variety of markets including automobiles, health care, telecommunication, information technology, medicine, defense and space. The current level of development of MEMS is comparable to what the Integrated Circuit or the IC industry achieved three decades ago. Future innovations and advancement are critically dependent on the integration of knowledge from different engineering and science disciplines. Creating and sustaining a work force having requisite interdisciplinary knowledge and skills in engineering, science and micro-fabrication is a major challenge faced by the academic community. The objective of this paper is to summarize the emerging need for incorporating a MEMS based micro-nano level interdisciplinary manufacturing engineering curriculum. The current level of MEMS based education available within various U.S. universities is also analyzed.

I. Introduction to MEMS/Micro-Electro-Mechanical-Systems

MEMS or Micro Electro-Mechanical Systems are devices that have a characteristic length of less than 1mm but more that 1µm, and combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and/or novel techniques extended from IC processing. These 'smart' devices including micro-sensors and micro-actuators have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale[1-4]. The acronym MEMS, for Micro-Electromechanical Systems, was coined in the United States to describe novel, sophisticated mechanical systems on a silicon substrate, such as micro electric motors, resonators and gears. These miniaturized machines or systems are popularly known as Micro-machines in Japan and MST or Microsystem Technology in Europe. The worldwide market for MEMS based micro-system technologies is already a multi-billion dollar business annually and various market analysis studies show that it will grow rapidly and become one of the major industries of the 21st century reaching more than $50 billion by 2005 [5-6].

The nature of MEMS requires the integration of different disciplines of engineering such as mechanical, electrical, chemical, biological and different sciences. The development of a work force consisting of engineers and technicians with diverse skills as well as hands-on laboratory experience poses a real challenge for academia. Most universities with an engineering program will have to incorporate MEMS based education within a few years. The objective of this paper is to discuss the emerging need as well as different aspects for incorporating an interdisciplinary micro-nano level manufacturing engineering curriculum for the development of MEMS.

Figure1. Market analysis for Micro-Systems 2000– 2005 (Nexus Task Force Report)[6]

II. MEMS Applications

Micro System or MEMS is still an emerging technology and has not yet come close to reaching its full commercial potential. However, there have been a number of micro-machined systems capable of operating on electronic, mechanical, fluidic, optical and radiative signals being developed and commercialized for a wide range of markets. Some of the applications are listed below:

1) Automobile Industry [7-10]

- Internal navigation sensors
- Brake force sensors & suspension control
- Accelerometers
- Airbag sensors

2) MEMS for Medical and Health Care applications [11-13]

- Blood Pressure Sensors
- Implanted Pressure Sensor
- Muscle stimulator and drug delivery systems

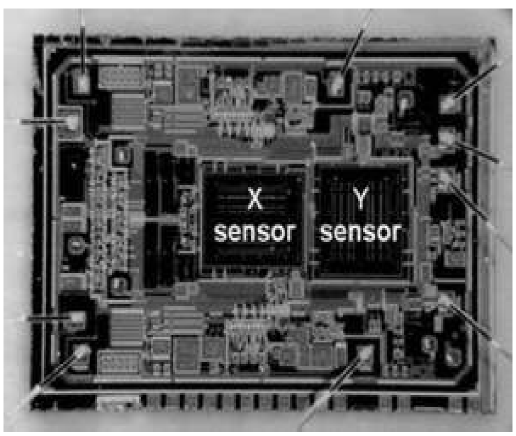
3) Telecommunications and Wireless Technology, MOEMS and (RF) MEMS [14, 15]

- Fiber-optic network components
- RF relays, switches and filters
- Projection displays in portable communications devices and instrumentation
- Voltage controlled oscillators
- Splitters and couplers, tunable lasers

Some commercially successful MEMS products are described below:

1) Automotive Sensor
The automotive industry was one of the successful earlier markets for MEMS based pressure sensors and accelerometers for a variety of applications such as engine control systems, power train, suspension, braking as well as air bag displacement that ensure the safety of the passengers[7-10].

Figure 2 shows one of the most widely used commercial accelerometers for the airbag deployment system developed by Analog Devices Inc.



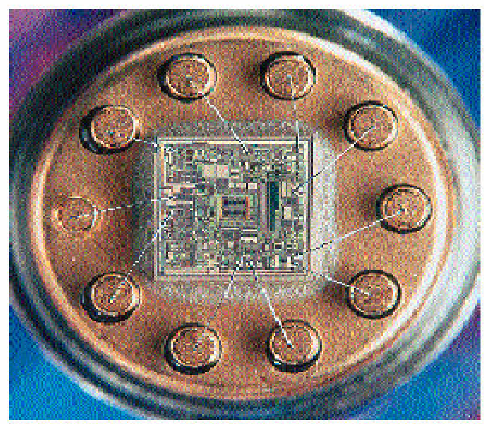


Figure 2. Analog Devices ADXL250 accelerometer chip and assembly (Analog Devices, Inc.)

The impact of a vehicle in a serious collision is detected by the two micro-inertial sensors, one is in the horizontal direction(x) and other is in the vertical direction(y). The entire chip assembly consists of two accelerometers along with the signal transduction and processing units with an approximate size of 3x2 mm.

2) Ink Jet Print Heads
Micro Ink Jet print heads first developed by Hewlett Packard HP are one of the largest volumes of commercialized MEMS devices which form an integral part of many ink jet printers. The device consists of an array of MEMS based heater elements positioned behind simple orifices. When the heater is turned on a bubble is formed in the ink which shoots ink through the orifice [16]. Figure 3 shows a comparison in size between a commercial ink jet print head and a coin.

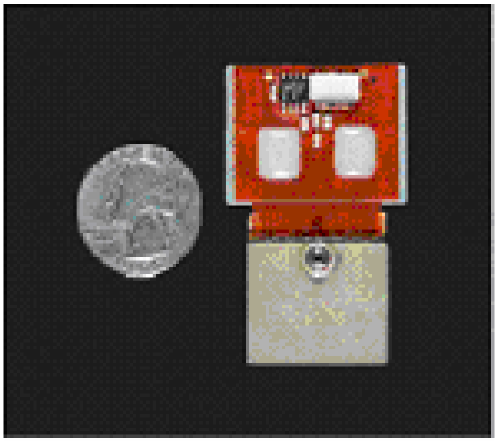


Figure 3 Ink Jet Print Head (Micro Fabrication Technologies Inc)

3) MEMS medical applications

MEMS devices and structures have been used in medical applications since the 1980's with the advent of the silicon micro-machined disposable blood pressure sensor. The medical applications market is estimated to grow by one billion dollars by 2006[17]. The incorporation of MEMS devices on surgical tools represents one of the greatest growth areas. Cardiac catheterization is a non-invasive surgical procedure in which specialized catheters are threaded up through the blood vessels in the arm or neck to an area of the body which needs treatment. The problem is treated from the inside of the blood vessel. MEMS pressure sensors are now commonly found on catheter devices to measure blood pressure in coronary arteries. Because of the tiny size of the pressure sensor chip, as shown in Figure 4, it can be inserted directly into coronary arteries to monitor blood pressure [18].

Figure 4 Pressure sensor chips
(0.1 x 0.1 x 1.3 mm) beside a 1 mm cannula needle (Silexmicrosystems)

III. MEMS-Interdisciplinary Nature and Curriculum Challenge

MEMS technologies and products are undergoing dynamic developments nowadays. Micro components through increasing minimization and intelligence have become an essential part of many novel products and different forecasts show an increasing role in a wide variety of diverse applications. Like any other technological development, proper education and training plans are essential for creating the ingenious brains indispensable in the areas of research, development and mass production of MEMS devices. Assimilating experts with different backgrounds is not necessarily the optimal solution, rather a new generation of scientists, engineers and technicians is required, with broad knowledge of different sciences and engineering, as well as of the basic principles of design, manufacturing and control. These experts need to be able to work together handling areas beyond their immediate expertise, and developing a common framework that will permit an integrated development of micro-scale devices and systems.

MEMS is truly an interdisciplinary field of conventionally divided sciences and engineering. The importance of different sciences and engineering disciplines are listed below [19]:

- Scaling laws are essential which provide engineers with a sense for the scaling down of physical quantities involved in the design of miniaturized devices.
  At micro scale, objects have greatly reduced inertia, convection and momentum becomes negligible. The surface and interface properties of materials begin to play an increasingly dominant role in the behavior of structures.
- Molecular biology is very much involved in the design and development of BioMEMS based sensors and equipment.
- Quantum and molecular physics knowledge is necessary for the modeling of physical behaviors of materials and substances in micro-scales.
- Electro-hydrodynamic principles form the basis for the development of micro-fluidic applications such as micro-channels and conduits.
- Electro-chemistry is widely used in electrolysis to ionize substances in some micro-manufacturing processes.
- Mechanical engineering principles are used primarily for the design and packaging of components.
- Electrical engineering knowledge is essential for power supplies, signal processing circuit design and control.
- Chemical engineering applications are involved for different micro-manufacturing and micro-device packaging.
- Materials engineering plays a key role in development of chemical, biological and optical sensors.
- Industrial engineering principles apply for the mass production and assembly of micro-components.

The interdisciplinary nature of technologies at micro-nano scale domain poses a real challenge in the development of a curriculum plan for incorporating students from different disciplines. An educational system focusing on single discipline will not provide an adequate framework for the work force development. The interdisciplinary system needed is that once after the education, each individual will be still strong in their respective field, but at the same time they will have developed enough understanding and awareness of other disciplines such that they can capitalize their progress. The traditional method of curriculum will not impart cross-disciplinary knowledge. For example, it is common for graduate students in mechanical engineering to have no knowledge of solid-state physics, IC fabrication and micromachining pertinent to the micro-system development. Students with a science background lack the required engineering experience and skills for design and development. The root problem could be attributed to elementary level of US education system, which lacks an integrated approach to using science and engineering. The report "Before It's Too Late" [20] by The National Commission on Mathematics and Science Teaching for the 21st Century suggests that U.S. students are receiving only a superficial knowledge in science in today's classrooms. In secondary level of education, different sciences are treated separately each in its own compartment. At higher college level and in engineering education, there is little exposure to science, most engineering curriculum will not have modern physics including quantum mechanics which plays an important role at micro-nano scale. This fact is of great concern for the academics as MEMS development needs input from diverse fields.

Currently, most of the MEMS related courses are offered for higher-level graduates or Ph.D. students confined within different departments creating a gap for undergraduate and entry-level graduate courses. It is also recognized that graduate research programs alone may not be the efficient educational mechanism for further innovations and development of the field. In order to develop the adequate human factor with the required understanding, knowledge and skill to solve the technological challenges posed by the emerging science, MEMS introductory educational curriculum should be incorporated into mainstream undergraduate education[21,22]. Prerequisites for the courses shall be kept to a minimum to college level mathematics, physics and chemistry which allow the infiltration of MEMS and micro-fabrication technologies into other disciplines. Introductory level courses offered at the undergraduate level impart the flexibility that students can pursue education in other fields of interest at a higher level or in industrial units, thereby applying the skills achieved for unique applications in their respective technological areas.

The program should first introduce to students relevant basic concepts of related disciplines of science and technologies involved in the design, fabrication of micro level devices and systems. After students have gauged the interrelation between various related disciplines they should able to choose their field of research or application.

The goal of the introductory courses is to grasp the basic operation theories of micro-scale devices such as sensors and actuators and to bring the student to an adequate level of awareness irrespective of their technical background. Careful design of the syllabus is essential so that it suits the background of students in each discipline. For example, students from electrical engineering may have prior knowledge of the IC fabrication methods and solid-state physics when compared to others from biology or medicine. Individual attention from faculty members or laboratory assistants may be provided to quickly solve problems and questions.

A unique way of exploiting the interdisciplinary nature shall be through the formation of small learning teams or groups from different disciplines. Each team will be involved in various activities to share their knowledge, through discussion/teaching, identifying suitable MEMS design and fabrication projects. For instance, an area of rapidly increasing interest is the use of micro-fabricated BioMEMS devices and structures for drug delivery which requires expertise spanning across biology, chemistry, fluids, mechanics, electronics and signal processing. By selecting such unique projects as part of the curriculum, each student within the study team will get an opportunity to work in their own area of interest and also benefit from each other's experience. The team should also conduct different case study analyses of successful MEMS devices. Review of current journal and conference papers should also be an integral part of the curriculum to introduce the student to the latest developments in the field.

The educational curriculum should be designed such that it addresses the following educational goals:

- Provide the ability for synthesis, processing and manufacturing of micro-system through various micro-fabrication or micro-machining techniques.
- Provide knowledge for the characterization and measurement of properties at micro-nano scales.
- Provide the required knowledge for the design, analysis, simulation, modeling of micro-systems and devices through special software and tools like MEMCad.
- Provide the facility for research and development of useful devices considering the economical and commercialization aspects.
- Provide courses focusing on different areas of applications, in particular biomedical, micro-fluidics, micro-sensors, biosensors, Radio Frequency (RF MEMS) and imaging devices, and space applications sensors.

The MEMS curriculum under development at the University of Illinois is a typical example for the interdisciplinary introductory course at the undergraduate level [23]. The curriculum consists of three interlinked, progressive course offerings covering MEMS theories, design and fabrication as shown in Figure 4. The main highlight of the curriculum is that teaching and research will strongly be coupled within the educational plan. The latest research will be incorporated into the teaching environment. Students will get hands-on experience through the development of unique applications and devices.

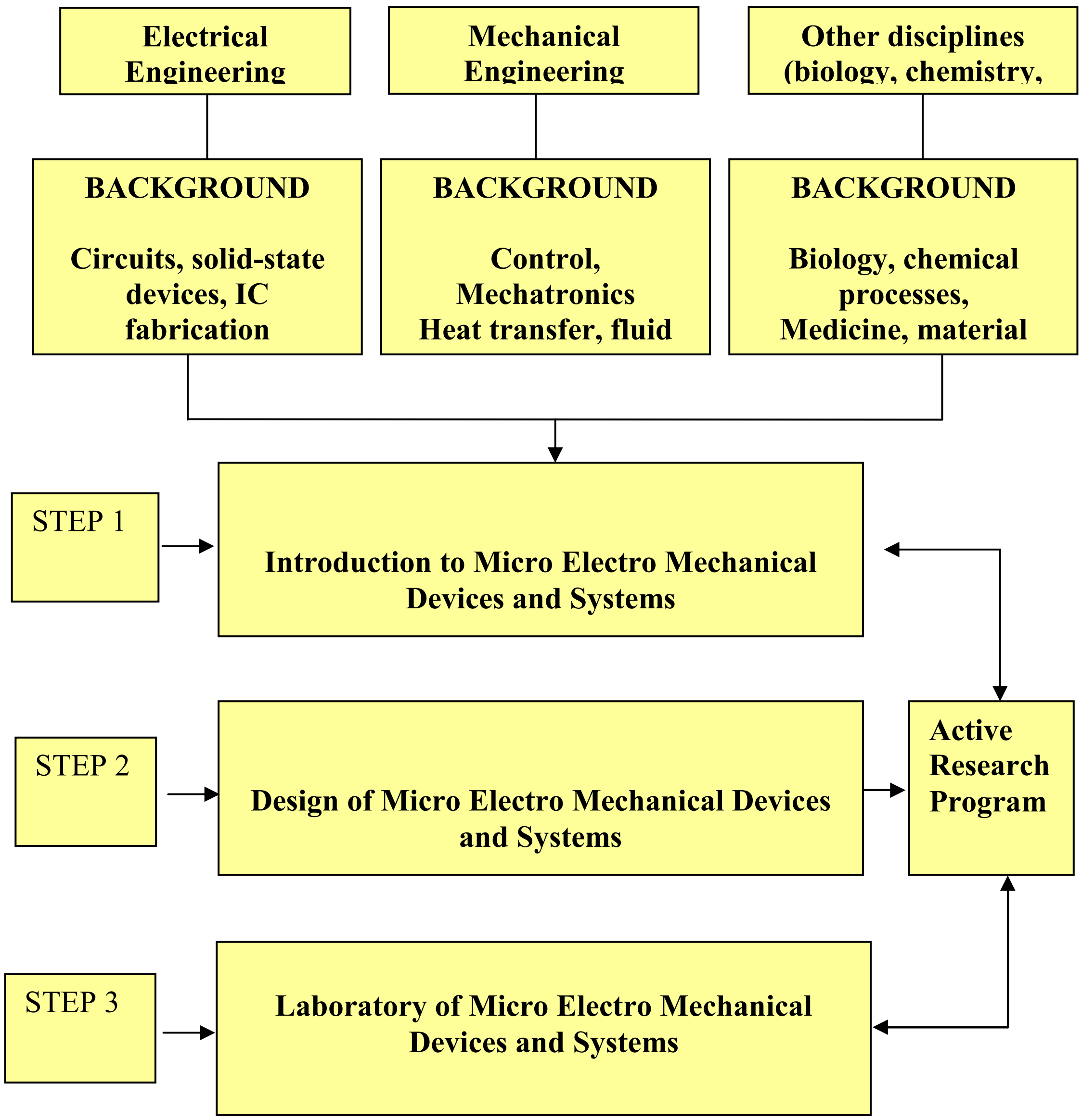


Figure 4. Anticipated background of students from several major targeted disciplines will be accommodated through a three step education plan.

IV. MEMS courses offered at U.S. universities

Several U.S. universities have already started offering MEMS courses for undergraduate and graduate students with different majors. Some of them are discussed below:

University of Minnesota started offering in the 1990's, a course entitled 'Design and Fabrication of Micro Electromechanical Systems' for undergraduate students of different disciplines. This course is believed to represent one of the first attempts in bringing hands-on MEMS fabrication into the undergraduate curriculum [24].

University Of Louisville has developed an integrated course plan to establish a comprehensive MEMS educational curriculum [25]. The curriculum was developed under a grant provided by the National Science Foundation with an emphasis on micro-fabrication principles for MEMS instead of traditional microelectronics. The goal of the course is to introduce micro-fabrication principles to a diverse group of undergraduate students and is divided into two separate courses, the first part is the theory based lecture and second part is a laboratory course for MEMS based projects. Students acquire hands-on micro-fabrication experience through the fabrication, testing and packaging of micro-sensors.

The department of Mechanical Engineering and Applied Mechanics (MEAM) at University of Michigan developed a course in microelectromechanical systems for mechanical engineering students which integrates courses from mechanical and electrical courses. The curriculum starts from the undergraduate level and finishes at the Ph.D. level [26].

A new multidisciplinary industry-oriented curriculum was developed at Ohio State University (OSU) through the NSF-CRCD (Combined Research-Curriculum Development) program [27]. The NSF Center for Industrial Sensors and Measurement (CISM) provides the course framework for interaction among scientists, engineers, students and business leaders. A three-course sequence for senior undergraduate and starting graduate students covering basic scientific and technological principles, computer simulation and modeling of sensor arrays, and a laboratory experiment leading to the fabrication of a sensor probe including probe design, packaging and testing is offered. These courses are being designed from a multidisciplinary approach and are team-taught by faculty members from a wide range of disciplines. An essential component of the group projects will be industry internships thus providing students an opportunity to work on research relevant to industry.

Another course worth mentioning is the nation's first doctoral degree program in nanotechnology which is closely tied to other science disciplines developed at the University of Washington's Center for Nanotechnology[28]. Nine departments from the three colleges, College of Arts and Science, Engineering, and Medical School are taking part and students will earn concurrent degrees in nanotechnology and in a discipline of science, engineering or medicine.

Table 1 shows a list of some other U.S. universities offering MEMS based courses.

UNIVERSITY	COURSE TITLE
University of Rochester	ECE234/434 Microelectromechanical Systems
University of Pennsylvania	550 (EE 550) Design and Modeling of Micro-Electro-Mechanical Systems
Stanford University	EE321 MEMS Design
Carnegie Mellon	18-724 Microelectromechanical System Design
Case Western Reserve University	EEAP 434, Micro fabricated Silicon ElectromechanicalSystems EEAP 527, Advanced Sensors
University of California, Davis	EEC 289L-Design of Microelectromechanical Systems
University of California, Berkeley	EE 245 Intro to MEMS Design
University of Illinois	ECE 371 & MIE 393-Introduction to Micro Electromechanical Devices and Systems (MEMS)
University of Cincinnati	ECE-641 Semiconductor Microfabrication lab for Microelectromechanical Systems
University of Kentucky	EE 599 Microsensors and Microelectromechanical Systems
Dartmouth College	ENGS 265: Science and Technology of Micro Fabrication
Northeastern University	ECE 3642, Microelectromechanical Systems
Boston University	MN500 MEMS: Fabrication and materials
University of Texas A and M, College Station	ME 489 Introduction to Nanoengineering and MEMS
University of California at Santa Barbara	ME 141 MicroElectroMechanical Systems I
University of Texas at Arlington	Course EE 5349/4328 Introduction to Microelectromechanical Systems (MEMS
University of Louisville	EE 500 Microfabrication
John Hopkins University	520/530.487 Introduction to Microelectromechanical Systems
University of Minnesota	Microelectronic Fabrication, EE5171

Table 1. List of U.S. universities offering MEMS courses

V. Key issues influencing MEMS manufacturing education curriculum

1) Experimental facilities and infrastructure requirements

Technological education would not be complete without laboratory based practical experience. So, as far as MEMS based manufacturing education is concerned there should be a continuous exposure to the state-of-the-art fabrication and characterization facilities. The higher capital cost of acquiring this equipment within each university presents a considerable financial challenge. Shared infrastructure facilities acting as geographically distributed centers among universities, profit and non-profit organizations and governmental research firms seem to be a plausible solution. Some of these U.S. facilities are listed below

- National Nanofabrication Users Network-NNUN [29] created by National Science Foundation is a shared micro-nano technology facilities resource open to users from across the country. NNUN consists of Penn State, Cornell University, Howard University, Stanford University and the University of California at Santa Barbara. Through NNUN the NSF supports micro-nano fabrication user's facilities at each of these locations.
- MCNC MEMS Technology Application Center [30]
- Ohio MEMSNet [31]

2) Curriculum research with industry involvement

Commercially successful MEMS products and devices are few compared to the numerous research based structures. This facilitates for a multifaceted partnership involving academia, government, national laboratories and industries. The objective is to integrate the latest research development into the students' curriculum and train students with projects in collaboration with allied industries. The program will give industrial experience to the participants through different stages from conducting market research to the commercialization of the product. The industrial partnership for the multi-disciplinary research at the NSF Center for Industrial Sensor and Measurement (CISM) at Ohio State University (OSU) provides the student and faculty with the opportunity to work on research relevant to industry[27].

Another instance for this approach is the curriculum research work done at NJMEMSI or New Jersey MEMS initiative, a comprehensive research, development, commercialization, and education program through the NJ commission on Science and Technology [New Jersey MEMS]. It consists of several academic institutions including New Jersey Institute of Technology and Rutgers University in cooperation with MEMS based industries to develop an innovative educational program that attempts to couple training in leading edge technological innovation with methodologies of entrepreneurship.[32]

3) Use of web based approach and multimedia

Multimedia supported education material prove to be useful medium for teaching basics, applications and designing aspects belonging mainly to the area of MEMS.
These modern educational software tools can provide up-to-date information, and 3-D visualization of MEMS structures through appropriate software and application specific examples of the subject. The availability of the course material through the internet and compact discs for other communities including universities and industries will help the easy content up-gradation. These electronic learning tools for self-study will certainly be a part of the education. Figure 4 shows 3D demonstration animation of a MEMS cantilever which provides improved visualization [33]

An example for the multimedia based education is the interactive compact disc "The World of Micro-systems" released recently by the FSRM, the Swiss Foundation for Research in Microtechnology [33]. Entrapping the full use of the power of modern multimedia clearly demonstrates the current developments, fabrication techniques, challenges and uses of micro-systems technologies.

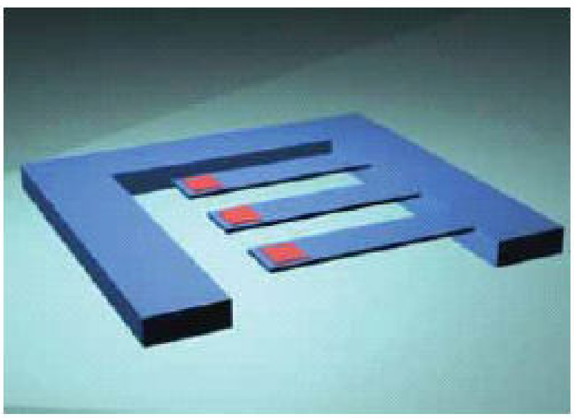


Figure 4 A 3D demonstration animation of the MEMS cantilever system (MST News)

Internet based education is gaining popularity nowadays compared to the conventional human knowledge based learning. The factors which pushes for the modern technique of knowledge-transfer such as multimedia and web based MEMS educational approach are listed below:

- Illustration of micro mechanical parts or dynamic processes, which form an integral part of most MEMS structure, is difficult without sufficient modeling or visualization applications.
- 3-D visualization of components for designing, packaging or testing of components supports easy understandability.
- A vast amount of knowledge sharing is possible between diverse groups and specific areas of specialization can be accessed.
- Imparting theoretical knowledge along with the presentation of industry-based projects updated regularly makes learning even more interesting.
- Self-paced learning is possible.

- Overcoming the geographical disadvantage.
- Easy feedback and contribution of additional materials.

Several universities worldwide as well as within the U.S. are developing internet based courses for micro-system based education.

- In the U.S., University of Maryland, College Park is developing internet based educational materials that describe the fundamental failure mechanisms in MEMS, their packaging and provide techniques for using this information to design MEMS and micro-systems that are less susceptible to failure by those mechanisms[34].
- Budapest University of Technology and Economics is working on a project called 'MEMSedu' for the development of a multimedia supported education material that teaches the theoretical background, application of microelectronics and packaging technologies in designing microelectromechanical systems for the next generation of intelligent systems. The department already established a web based animated teaching material 'SensEdu' for the teaching of sensor related technologies[35].

4. Combined MEMS and Nanoscience in curriculum

Nanotechnology is the application of science to develop new materials and processes by manipulating molecules and atoms[36]. It is a collective term for a set of technologies, techniques and processes rather than a specific area of science or engineering. Nanotechnology will be a strategic branch of science and engineering for the next century. One that will fundamentally restructure the technologies currently used for manufacturing, medicine, defense, energy production, environmental management, transportation, communication, computation, and education. A combination of MEMS and nanotechnology, both characterized by multidisciplinarity is predicted to play an important role in shaping tomorrow's world [37].

Two main aspects of the combination of the technologies are:
- Micro-systems applications or devices used as tools for accessing and analyzing the nanoscale dimension. For example, AFM (atomic force microscopy) is a MEMS development which is an essential tool for nanoscale object manipulation.
- Functionalities and properties based on nano-effects leading to new applications enabled through integration by use of micro-systems technology.

Micro-system technology will help the transition of nanoscience's path from a pure science to technology in many aspects. New developments in MST will contribute to solving the problem of bridging the length-scale interface that exists between nanoscale molecular assemblies and functional micro-scale and macro devices [38-39].

A commercially successful outcome of merging the micro-system with nanotechnology is the read heads of hard disks. Within ten years of the fundamental discovery of the new phenomenon of giant magnetoresistance (GMR) by IBM researchers, this nanotechnology development completely replaced older technologies for computer disk drive heads and it is already a multi-billion dollar business in the U.S. [40].

VI. Conclusion

The rapid growth of MEMS industry, worth billions of dollars, presents a big challenge in education. MEMS development is critically based on the integration of knowledge from different disciplines of science and engineering. An interdisciplinary curriculum which encompasses a broad understanding of sciences, engineering and information science pertinent to micro-nano scale incorporated into undergraduate education is essential for future development.

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VIII. Biographical Sketches

HARI JANARDANAN NAIR: Hari Janardanan Nair is a Master's student of Manufacturing Engineering program at the UMR. He is working as a Graduate Research Assistant at LAMP (Laser Aided Materials Processing) lab in UMR under the guidance of Dr. Frank Liou. His area of research concentration includes laser deposition of Functionally Graded Materials (FGM), laser micro-deposition , MEMS.

FRANK LIOU: Frank Liou is a Professor of Mechanical Engineering Department at the University of Missouri-Rolla (UMR). He currently serves as the Director of the Manufacturing Engineering Education Program (MEEP) at UMR. His teaching and research interests include CAD/CAM, nano-technology, rapid prototyping, rapid manufacturing, and augmented reality. He has published over 80 technical papers, and has research grants and contracts over $5M.