Enhancing Engineering Interest and Skills in Community College Students through a Project Based MEMS Design Competition

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Abstract

This paper will showcase an innovative approach to creating interest in microsystems engineering processing and design at the community college undergraduate level. This project based curriculum begins to address some of the economic competitiveness issues raised in the recent National Academy of Sciences report "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future," and the National Academy of Engineering's "Engineer of 2020." Common points raised include the students' lack of interest, motivation, knowledge and skills required to compete in the global economy. By leveraging the Sandia National Laboratories University Alliance and its MEMS Design competition, Central New Mexico Community College (CNM) has enabled undergraduate Manufacturing Technology MEMS (Micro Electromechanical Systems) students to compete with graduate and undergraduate engineering students across the nation from Universities including: Texas Tech, Oklahoma State, University of North Carolina, and the University of Illinois. The CNM design teams finished first or were runners up over the last three years resulting in many students realizing that they too were capable of pursuing an engineering career. Due to the high placement within the contest, all CNM designs have been fabricated at Sandia National Laboratories Micro Engineering Sciences Applications laboratory. These prototypes are now utilized at recruiting events for high school students as well as teacher workshops as MEMS student designed examples. The competition requires the students to productively work as a

team, design to a specific process, complete tasks under a strict deadline, locate and apply information from a variety of sources, document and present their work to complete a successful project. This results in a prototypical engineering mindset to be a creative collaborator while taking on a systems approach.

Motivation

For many years a variety of commissions and committees have issued reports decrying the state of education in the United States at all levels[1-3]. In recent years these concerns have been especially pointed with respect to education in what are known as STEM fields –Science, Technology, Engineering, and Mathematics – at the K-12 grades and in regard to engineering education at the postsecondary levels. The underlying rationale for this repetitious cycle of hand-wringing and consternation is the low production of engineers and scientists of U.S. extraction in U.S. universities as compared with the output of similarly educated workers by other nations. Within the context of economic globalization and an increasingly competitive global marketplace where success is critically dependent on technological prowess, these trends are indeed disturbing. As noted in "The Gathering Storm," distance no longer protects much of our intellectual product as the internet has made physical separation largely irrelevant. Moreover, from a very coarse big-picture perspective, the number of workers available in the U.S. is falling away from the number required to maintain present economic growth rates over time[4]. In order to counter these trends, the U.S. must increase the pipeline of students reaching the conclusion of 12th grade with the basic preparation needed to pursue a STEM degree, and retain more of those students with an expressed interest in such careers as they progress through baccalaureate programs and beyond. Given that one-third of students declaring the pursuit of an engineering degree quit before completion, there is significant opportunity for improvement.

Experiential education is one frequently suggested method of retaining a greater proportion of those entering an engineering path through to completion of the degree. In addition to the commonsense logic of immersing the student into an environment more closely resembling the workaday world to put theory into context, there are distinct benefits to addressing the variability in students' learning styles. The Myer-Briggs Type Indicator profile is a widely recognized and implemented tool for understanding individual proclivities. One key aspect of the behavioral model underlying the MBTI is that whereas some students will intuitively grasp concepts illustrated on a classroom whiteboard, other more sensing-oriented students need hands-on experience to plant those concepts within their minds. Research in engineering education supports the use of the MBTI and its effectiveness as a predictor of benefit from experiential education[5,6]. Indeed, among the key recommendations of the National Academy of Engineering's Engineer of 2020 project is to begin experiential training of engineers as a serious endeavor within the first year of college[7].

Another benefit of an experiential approach toward technical education is in the development of emotional intelligence and social skills[8]. Most engineering jobs demand greater and more effective social interaction and teamwork than a typical academic engineering program. The stereotype of an engineer who has virtually no social interaction skills is probably exaggerated, but there is no question that important "Emotional Intelligence" skills areas are given short shift in favor of individual and isolated theoretical learnings. While we do not advocate deeply delving into psychology within technical coursework, the critical "E.Q."skills of empathy, influence, persuasion, and conscientiousness in regard to collaboration are all clearly bolstered by internships and group/team projects.

Within the context of technologist education we have found through the widely recognized WorkKeys job evaluation process that actual job skills requirements may differ greatly from the expectations of engineering managers or academicians[9,10]. For example, the three highest-priority skills for Microsystems Technologists are Observation, Locating Information, and Listening, whereas Applied Mathematics ranks 8th. While these top priority skills can be incorporated into classroom exercises, clearly the most effective means of building these skills is through their actual use.

Background

Central New Mexico Community College (CNM) has had an Associate of Applied Science Degree in Manufacturing Technology (MT) for many years. This degree has evolved through the years to remain current with the needs of the region and nation now including several courses in MEMS (micro electromechanical systems) and SMT (semiconductor technology) fabrication and design. Six MEMS courses where initially developed with funding from a NASA (National Aeronautical Space Administration) CIPA (curriculum improvement partnership award) grant awarded in 2002 and later further improved in part due to the NSF ATE DUE award 0402651 which established the Southwest Center for Microsystems Education in 2004. Table I represents a listing of the MEMS and Semiconductor manufacturing courses offered at CNM. Several of these courses require the students to participate on team projects.

Throughout the history of the Manufacturing Technology program, Sandia National Laboratories has been a valued partner and contributor. They have provided technical expertise through contact with subject matter experts, short course offerings in MEMS design and fabrication, provided visiting faculty positions and student internships. Sandia National Laboratories has provided access to their MEMS SUMMiT V (Sandia Ultraplaner Multilevel MEMS Technology) process to United States industry, government and academic organizations. This access is provided through two programs, the SAMPLES™ (Sandia Agile MEMS Prototyping Layout Tools, Education and Services) and the University Alliance programs.

Table I. CNM MEMS and SMT course listings, elements of the Manufacturing Technology AAS degree.

Course Name	Description
MEMS1001 Introduction to MEMS	Overview of MEMS Applications, Fabrication, Commercialization and Design
MEMS2001 MEMS Manufacturing Process	Lecture/lab course covering fabrication processes culminating in the fabrication of a micro pressure sensor in a class 100 cleanroom at the University of New Mexico Manufacturing Training and Technology Center (MTTC)
MEMS2005 MEMS Design I	Introduction to MEMS design concepts.
MEMS2010 MEMS Design II	Advanced MEMS design culminating in participation in the Sandia National Laboratories University Alliance MEMS Design Competition.
MEMS2015 MEMS Manufacturing Technology Theory	Advanced MEMS manufacturing topics
MEMS2092 MEMS Manufacturing Technology Lab	Applied MEMS fabrication laboratory including process characterization
SMT2001 Semiconductor Manufacturing Technology Theory	Overview of Semiconductor Manufacturing processes.
SMT2002 Semiconductor Manufacturing Technology Lab	Fabrication processes and actual manufacturing of semiconductor transistors.

Details of the University Alliance Program can be found on Sandia National Laboratories website: http://mems.sandia.gov/ua/index.html . There are currently nineteen members, four of which are community colleges. Members of the program have access to the SUMMiT V software including 2D and 3D visualizer tools and access to Sandia's design rule checker, training at two MEMS short courses, a complete set of instructional materials from three short courses, as well as the opportunity to participate in the Sandia National Laboratories University Alliance MEMS Design Competition.

Design Course Concepts

The MEMS Design I and II courses are taught utilizing two MEMS design software packages, CoventorWare™ and SUMMiT V™. The SUMMiT V software package is designed specifically for the processes used at Sandia National Laboratories and operates in conjunction with standard AutoCAD. The students cannot change the process. CoventorWare is a commercial product that includes a large variety of options including finite element analysis (FEA) and full control over the process utilized in the design. Each software package has visualization tools to provide immediate feedback and enable the students to perform rapid iteration of their designs. This rapid visualization feedback utility is a requirement for students to stay fully engaged.

The design students are required to have completed MEMS1001 and at a minimum, be concurrently enrolled in MEMS2001 (see Table I) and have had some exposure to computer aided drafting software. It is critical that they understand the fabrication processes used in manufacturing MEMS and Microsystems. In the first design course, the students learn how to manipulate the software, the interrelationships between design and fabrication processes, and create simple MEMS device components such as rotating gears, shuttles, hinges, valves, and cantilevers. The majority of designs are done based on surface micromachining process flows.

Surface micromachining processes evolved from standard CMOS (Complimentary Metal Oxide Semiconductor) fabrication methods whereby micro circuits are made layer by layer through the alternating steps of thin film deposition, photolithography resist patterning and subsequent etching away of exposed material. This process requires a pattern for each layer and the sum of the layers and patterns result in a completed part. Each pattern is projected onto a photosensitive material using a reticle or mask image, analogous to the negative in classic photography. Each mask typically consists of a chrome pattern on a quartz plate. The mask pattern is only one layer of the design; it takes many layers to construct a device or component. Once the photosensitive material is exposed to light based on the mask pattern, it is developed. In other words, the exposed photo resist is dissolved and the remaining material protects the underlying layer from the subsequent etch process. This sequence of deposition, patterning and etch is repeated multiple times with a variety of materials.

In surface micromachining there are essentially two types of materials, structural and sacrificial materials. The structural materials will make up the moving parts while the sacrificial layers provide the scaffolding between the structural layers as the devices are being fabricated. The sacrificial layers not only provide spacing between structural components but also provide paths (holes) to connect parts from one layer to a previous one as well as anchors to the substrate. At the end of the fabrication process, the structural layers are dissolved releasing the layers so they can move.

The SUMMiT V process allows the designer to create four structural, moving layers and one non-moving ground layer, all made of polycrystalline silicon. Interleaved with these five structural layers are sacrificial layers of silicon dioxide. The silicon dioxide layers are dissolved at the end of the process in a solution containing hydrofluoric acid. Altogether, there are 14 masks which can be used to design and fabricate the MEMS devices utilizing the SUMMiT V process.

Understanding the interaction of the process with the design is critical for the students to be successful. Layer to layer alignment tolerances are finite, sidewall profiles are not always 90 degrees and if a device is drawn with a specific dimension, process variation results in a range of sizes. Materials thickness variation also comes into play as does vertical spacing. These interactions result in a clear set of design rules which must be followed.

The two design software packages were chosen as they provide two different design approaches. With CoventorWare, the students can create any type of process they desire. There are virtually an unlimited number of materials, layer thicknesses, etch profiles allowed for any given layer as well as an unlimited number of layers the designer can employ. The design rules can be as loose or tight as the designer deems necessary. The designer can create anything he or she desires on the computer and can disregard any real world constraints (*e.g.*, cost). The SUMMiT V design process requires the students to design to a specific surface micromachining process. The students cannot change anything about the process, only the pattern on the mask. These constraints include real world design rules ascertained through years of iterative cycles of learning. This is closer to the real world, especially for technician level designers. As taught in all of CNM's MEMS design classes, if the student desires to change a process step in the "real world," this will result in large cost increments and time delays as the new process steps are being characterized and implemented. Increasing complexity and options will result in a greater probability of catastrophic yield loss.

Throughout the Design I class, the students are continuously encouraged to work together, helping each other through problems and sharing ideas. At the end of the initial MEMS Design I class, the students have a keen understanding of the process and design interactions, what design rules really mean, how to effectively manipulate the software and enough trust from their classmates to ask them for input. They are then ready to apply this set of skills and knowledge base to a real project.

MEMS Design II – Project Based MEMS Design Competition

Sandia National Laboratories offered the University Alliance MEMS Design Competition to all members for the first time in spring of 2005. This was a golden opportunity for Dr. Pleil and his MEMS Design II students to participate in a real life experiential learning opportunity.

The students worked as a team to complete the project under strict submission time constraints. The course begins in mid January and the submission of the final project is during the first week of April. The students must also complete assignments which also prepares them for the competition. They now take what they have learned in the first course and begin assembling systems – incorporating hinges, hubs, pinjoints and springs into small devices such as flip mirrors and gear trains. This is done in small groups whereby the students create individual components and combine these components into working sub-systems. Along the way in these assignments, they have to:

- Read and understand the SUMMiT V design manual
- Utilize the Sandia Component Libraries
- Use the 2D and 3D visualization tools to continuously check their work
- Submit designs to the DRC – Design Rule Checker – for verification
- Combine Pin Joint, Hubs, Gears, Sliders and Hinges into small functioning subsystems

Once they have gained the skills needed to produce small, discrete parts which pass the design rules of the process, the students are required to begin designing for the competition. Several brainstorming sessions are facilitated to come up with ideas which meet the competition goals. Currently, there are two design categories – 1) Novel and 2) Charecterization/Reliability/Nanoscale Phenomena. The CNM students generally elected to participate in the Novel Design Competition which allowed them the greatest latitude.

The student teams competed in 2005, 2006 and 2007. The 2006 team won the Novel Design category. The teams received honorable mention both in 2005 and 2007. All three years resulted in the fabrication of the students' design. These teams were self directed and only mentored by Dr. Pleil. This allowed for the greatest range of student creativity. As a result, several very unique components and systems where designed over the three years including what may be the world's smallest man made chain, each link being only 11um in length. Other components include a polysilicon belt, orthogonal gear, thermal actuated lever, pre-stressed cantilevers, a number of micro-grippers, a micro fan, and several other out of plane structures.

The chain designed in the first year was one of the most interesting and challenging components to design. This chain was utilized in subsequent design competitions by CNM students. The following figures not only show the design graphical 2D and 3D outputs but also a scanning electro micrograph (SEM) of the fabricated Sandia National Laboratories fabricated chain. The students learned that the chain easily came off of its gear track as a result of 0.2um slop per link (the gap which allows the individual links to rotate).

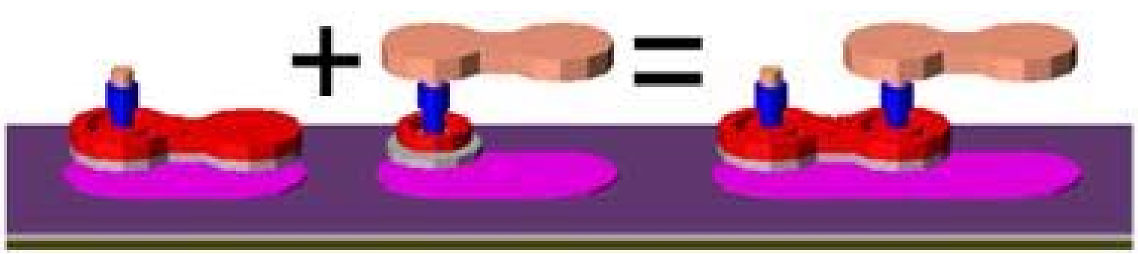

Figure 1. Design schematic of the chain link designed by student. The different colors indicate different process layers.

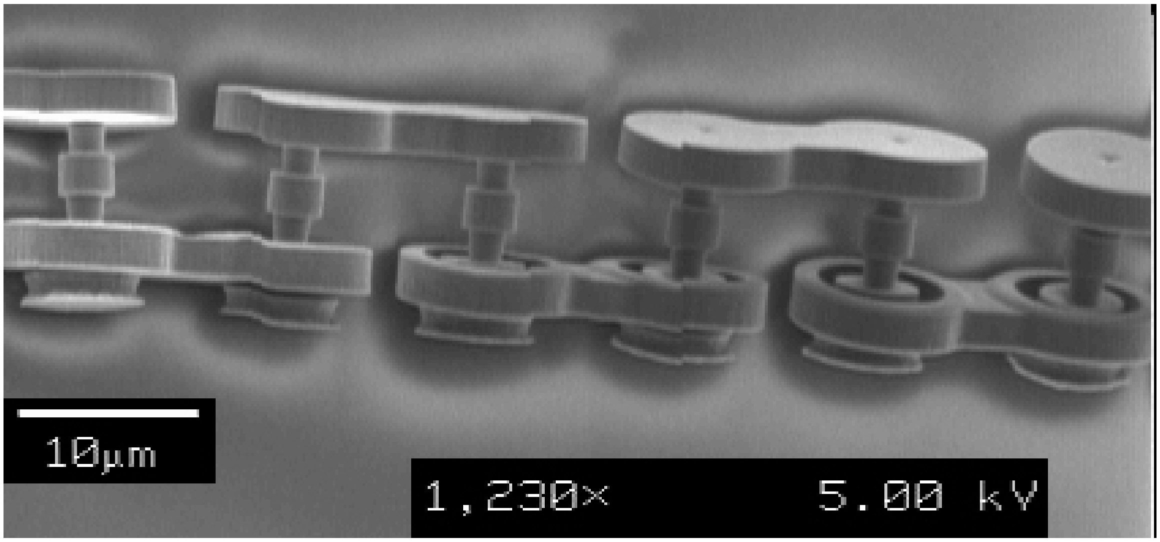

Figure 2. Scanning electron micrograph of the fabricated chain design. Image courtesy of Sandia National Laboratories.

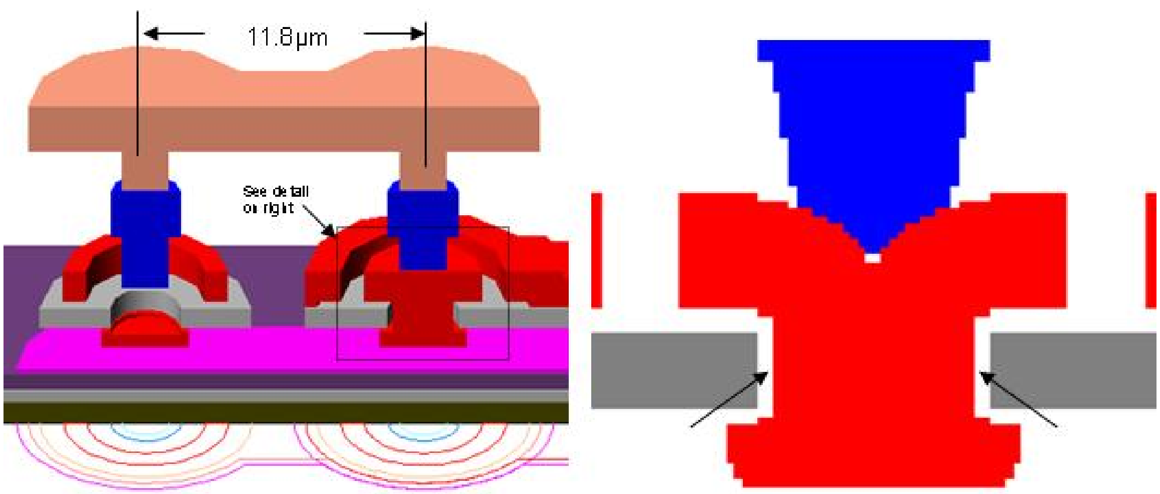

Figure 3. Detailed cut away showing the 3D and 2D visualization tools. Note how closely matched the visualization tool is to the actual SEM image shown above. Also note the 0.2µm gap per link.

Since the team had an honorable mention the first year, Sandia National Laboratories selected the design to be fabricated. As a result, the second year team discovered that the chain fell off of the gear guide teeth. This resulted in their designing of a chain tensioner as part of the subsequent submission. Another student also pursued the design of a polysilicon belt with the expectation that this would not have any slop associated with it. In order to test their designs, the team decided to leverage the rapid prototyping tool at CNM to view scale models of their more intricate designs. Two students took the responsibility of interacting with the technician in charge of the rapid prototyping tool in order to learning how to produce design models. One of the ideas from the brainstorming session was to create a micro car which would be able to run on a flat surface. One of the issues for creating such a vehicle was to design an orthogonal, self assembled gear system. A prototype and corresponding design is shown in Figure 6 below. The complete design submission is shown in Figure 7.

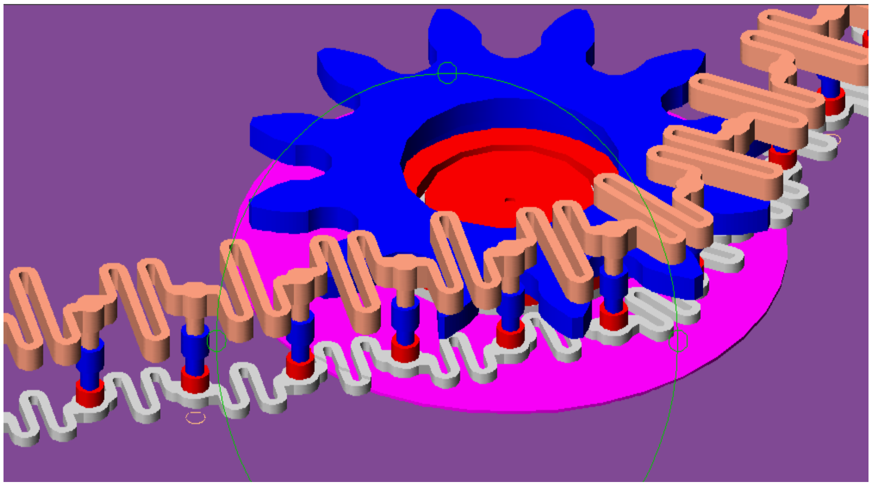

Figure 4. 3D image of the polysilicon belt design engaging with a standard gear. Each color represents a different structural layer.

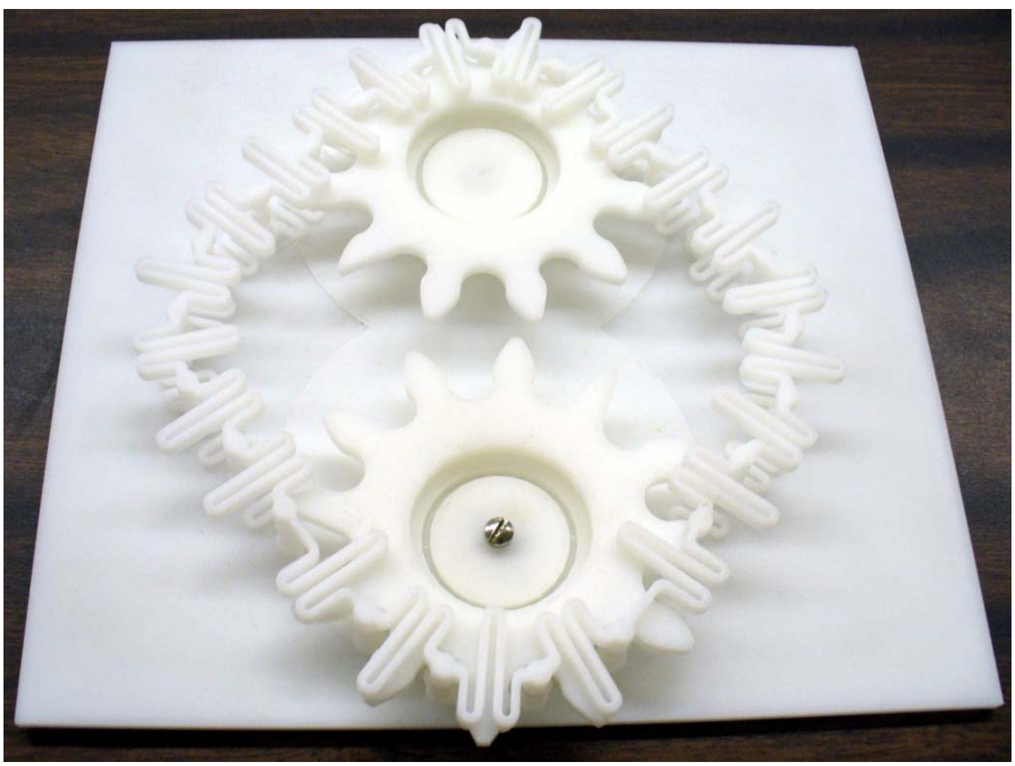

Figure 5. Rapid prototype of the Polysilicon belt design similar to the one shown in the previous figure.

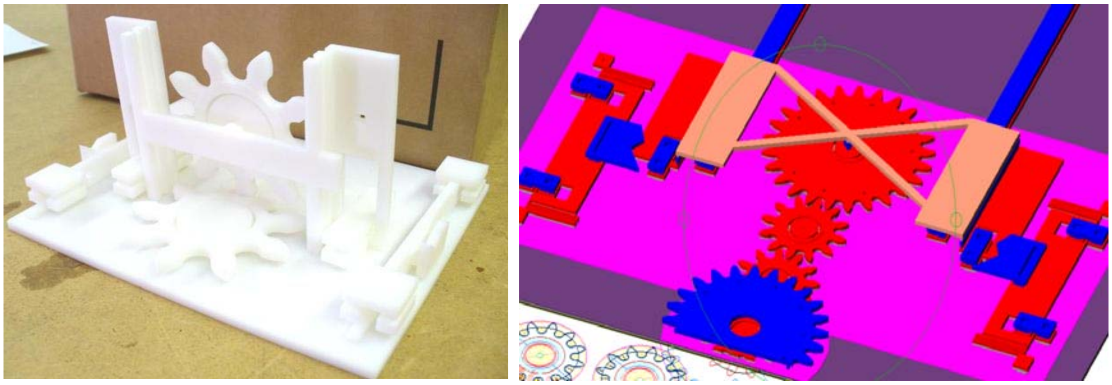

Figure 6. Rapid prototype model of any earlier orthogonal gear design revision (left) and subsequent final design (right).

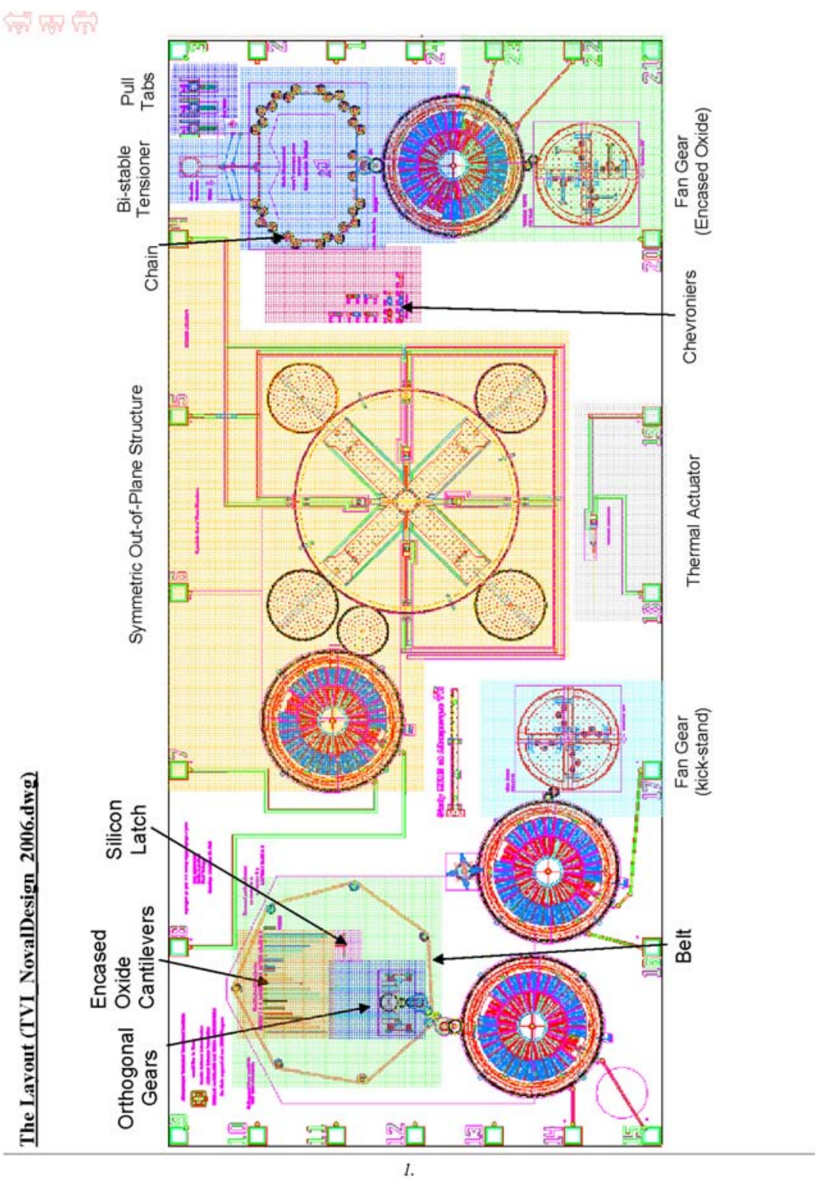

Figure 7. 2006 CNM winning MEMS design.

The third and most recent design competition team had ten students competing. They produced several additions including two variations of a micro gripper, a micro-sized memory game, a thermally actuated rotary micro engine, a miniature crane, a chain transmission and a self assembled micro fluidic capillary system.

In all, approximately 20 students over three years have participated in this competition. They all responded positively to the course, many stating that having to work together, stay on a schedule, and produce a refined, final project was well worth the time invested. One may ask, "What are the students doing now?" All are either working in a high tech field or continuing their education. They have used their team portfolios while interviewing for employment which has been very effective. This allows them to demonstrate their capabilities and express a coherent story encompassing not only their acquired knowledge in MEMS design and fabrication but also their ability to perform within the context of a design team at a level of engineer. Here are some examples of students who have kept in contact:

- Shannon C. – was working at a micro power company and is now working as an intern at Sandia National Laboratories while pursuing a Mechanical Engineering degree.
- Linda P. – working full time at a micro optical startup MEMS company and is currently completing her two year degree in Manufacturing Technology with a MEMS concentration. Linda was home schooled and now plans to continue her education in engineering with the ultimate goal of joining NASA and participating in future Mars missions.
- Brian S. – completing his two year AAS degree and plans to pursue a degree in engineering.
- Paul T. – completing a Manufacturing Technology AAS and a Photonics AAS. He is currently working in an advanced jet aircraft company.
- David F. – completed his two year Manufacturing Technology degree and is currently employed at an environment control company participating in design and fabrication of humidity and temperature control systems.
- Joe S. – augmented his technical education with MEMS courses, his company is now pursuing future business to support custom platform and packaging solutions for Microsystems components.
- Ben P. – retired air force analyst – is enjoying learning about these new technologies and advocates to the younger generation.
- Rory G. – completing his AAS degree this year.

In addition to the design competition leveraged in the MEMS Design II course, CNM also has built MEMS demonstration units for Sandia National Laboratories as part of three individual Manufacturing Concepts courses. These required the students to utilize each others skills and develop new ones including time management, process flow design, soldering, circuit board design, characterization, product testing, technical writing, and presentation while working as a team. In addition to the list from the design course identified above, the following list demonstrates further the value of project based learning:

- Rebecca – after being an intern at Sandia National Laboratories for one year, was hired as a permanent technologist. She has completed her AAS Manufacturing Technology degree, is completing a degree in Photonics and plans to pursue an engineering degree in the future.
- Brian A. – decided to forgo the AAS degree and is currently an engineering student at UNM.

Summary

An increased emphasis or outright re-introduction of experiential learning into STEM education is critically important to the national security and economic well-being of the United States. Whereas the common classroom mode of lecture, questions, and homework plays an important role in developing individual theoretical knowledge, individual and team project skills are critical to the development of practical STEM talent, and should not be overlooked or minimized by educational programs in those fields. Here we have shown that when properly integrated into a technology degree curriculum, a design competition can provide a focused goal leading to the formation of high-performing self-directed teams and a substantial positive impact on students' learning, with the added benefit of clearly documented participation in a complex and highly interactive team development project experience.

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Biographical Information

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Dr. Pleil is currently an instructor at Central New Mexico Community College in the School of Applied Technologies and Research Associate Professor in the School of Engineering, Mechanical Engineering Program at the University of New Mexico. Dr. Pleil is also the Principal Investigator for the Southwest Center for Microsystems Education (SCME), a National Science Foundation Advanced Technological Education regional center funded under the Department of Undergraduate Education grant DUE: 0402651. Dr. Pleil received his Ph.D. in Physics from Texas Tech University in 1993 having done original research in picosecond time correlated single photon counting applications. He has 12 years combined experience in Semiconductor Manufacturing as a senior process engineer, equipment engineer, manufacturing line supervisor, and engineering manager at Texas Instruments and Phillips Semiconductors. While in industry, he worked in several areas including photolithography, metrology and yield improvement. Dr. Pleil's current areas of interest include STEM education, K-12 outreach, and Micro/Nano Technology education.

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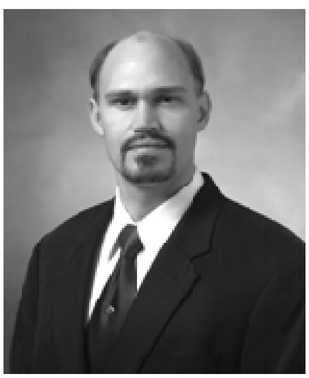

Dr. Osborn is Manager of Microsystems Outreach at Sandia National Laboratories and Executive Director of the Southwest Center for Microsystems Education. Thor received a B.S.E.E. from Washington State University in 1987, and his Ph.D. in Bioengineering from the University of Washington in 1994. Following a brief postdoctoral fellowship on a DARPA-funded portable microfluidic medical laboratory, he worked as a process engineer for AlliedSignal and then Motorola from 1995 to 1998 leading the development and integration of MEMS wafer processes for navigation and airbag grade accelerometers. Thor managed the development of MEMS optical scanning devices and subsystems for Microvision, Inc., from 1998 to 2001, and was Director of the MicroSystems Engineering Center at SRI International prior to joining Sandia in 2004. He holds three U.S. patents and has authored or co-authored several journal articles on the behavior of artificial cell membranes on silicon substrates, microfluidic separations, and MEMS optical scanning technology and business analysis.