Online Interactive MEMS Experiments and Web-Based Curriculum

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Abstract

This paper introduces the research done on providing interactive 2D and 3D content for micro-electro-mechanical systems (MEMS). MEMS is a multidisciplinary field, which uses exclusive lab equipment and high-end design/analysis software adopted from different fields, such as electrical, mechanical, chemical engineering and solid state physics. This multidisciplinary nature, in addition to the highly customized design software, makes it a challenging topic to deliver over the web. Many MEMS software programs lack modern presentation tools which makes it difficult for designers in industry and academics to communicate their designs with their colleagues and students. Authors of this paper have made an effort to bridge the gap between the design/analysis and presentation by introducing interactive tools that can mimic the behavior of the real MEMS devices and their outputs. By using the tools provided, students can learn about different fabrication methods and basic MEMS elements. They can also design their own device and analyze it using the free tools provided. Video of the real experiments are also at the website. Students can play with a simulator of the experiment remotely and obtain the simulated results that follow the behavior of the real experiment. Adobe Flash plays a crucial role in the website, whereas 3D content is delivered in Adobe Shockwave format. Analysis tools are also implemented as spreadsheet templates or interactive MATLAB GUIs. For using the multimedia content a student only needs a generic web browser and expensive engineering packages are not required. This technology pool empowers the instructors to deliver basic MEMS information and provide hands-on practices on MEMS while sharing the expensive MEMS experiments with the universities all over the country as well as their own institutions.

I. Introduction

Education is traditionally one of government's principal responsibilities within the past century. In particular, science and technology education is seen as critical by most countries if they hope to keep high living standards. Because of the distance, one of the effective ways to educate people within large countries, like the US, is through the Internet. Internet technology gives teachers opportunity to bring high level and well developed material to students who could not attend real classes. For example, Gramoll[1] is using interactive electronic books to teach in his solid mechanics classes and Perkins[2] uses online interactive simulations to teach physics. Similarly, this work is designed to use Internet connections to empower students and instructors to see results from MEMS experiments done miles away from where they live. While physical distance has no meaning in the Internet era, bandwidth is an important concept. The thinner the bandwidth one has, the further he/she is from getting high quality education. In the last decade Internet access has grown noticeably in US. This growth is shown in Table 1. According to Nielsen//NetRatings statistics[3] there were 212,080,135 Internet users until July 07, 70.2% of the population.

YEAR	Population	Users	% Pop.
2000	281,421,906	124,000,000	44.1 %
2001	285,317,559	142,823,008	50.0 %
2002	288,368,698	167,196,688	58.0 %
2003	290,809,777	172,250,000	59.2 %
2004	293,271,500	201,661,159	68.8 %
2005	299,093,237	203,824,428	68.1 %
2007	301,967,681	212,080,135	70.2 %

Table 1 Internet Usage and Population Growth[3]

The research done for this paper was a part of a National Science Foundation (NSF) CCLI Grant entitled, "MEMS Experiments With Web-Based Material for Solid Mechanics Courseware and Labs Nationally". The main objective of the NSF grant was to develop and provide through the Internet an all MEMS Experimental Lab with web-based curriculum for an undergraduate level education. An actual physical MEMS experiment and supporting website are developed as part of the work. The website[4] consists of the background information to do the experiment and also provides scientific background on MEMS. The website was designed to be interactive where students are able to use the simulators provided on the website to simulate results similar to the real experiments. The web-based content and technology is explained in this article. The website is a synthesis of different technologies brought together to serve the purpose of having an iterative and entertaining resource. Similar techniques can be used to develop interactive content in the MEMS field. Techniques described in this article can be used by designers to communicate their ideas with each other without giving out sensitive CAD/CAM data.

The website is designed in eBook form and is organized in seven sections, including Introduction, Fabrication, Basic Mechanisms, Parallel Plates, Comb Drives, Micro-Mirrors and Virtual Lab. The first three sections are basic background about MEMS. The last four chapters cover specific information about the actual experimental setup and equipment. They also provide theory about the specific devices and how they relate to the experiments. In all the sections in the eBook, animations, video and simulations assist the users in understanding MEMS as shown in Figure 1. All material is open and no access codes or passwords are needed. The site uses Flash, Shockwave and QuickTime browser plug-in to enhance the interactivity of the web pages. A number of different technologies have been used to develop the interactive content and deliver MEMS animations and simulations to the web; however, students only need a web browser in order to use the content and there is no need to install high-end engineering packages on their computers.

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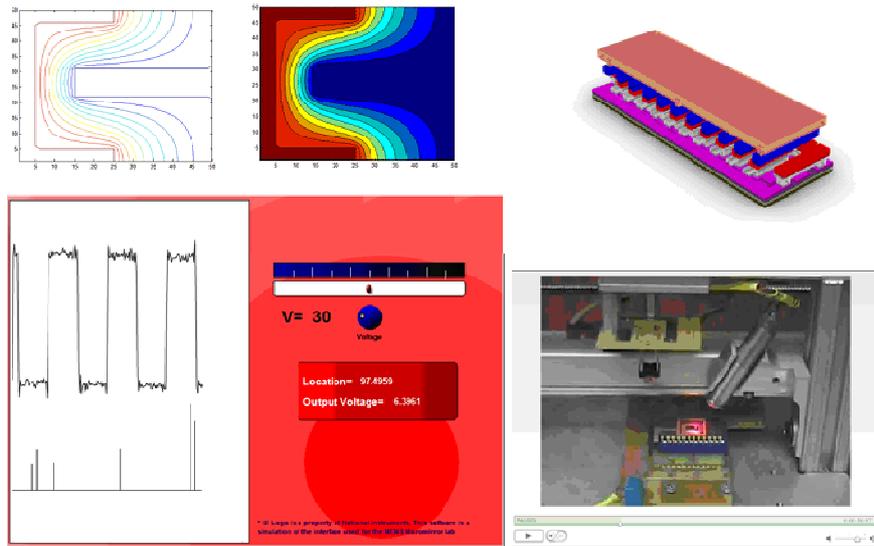

Figure 1 Examples of Simulations, Videos, and Graphics Used to Demonstrate MEMS

Over the last several years, MEMS has become important in industry and thus an increased need to introduce MEMS into undergraduate courses. However it is well known that most engineering programs do not have space in their curriculum for a full MEMS course. To help solve this issue, this project proposed to use the traditional mechanics course and lab to introduce MEMS. In other words, use a simple MEMS experiment to demonstrate both mechanics (i.e. beam bending) and MEMS concepts electrical induced force on beam).

To enable other institutions to benefit from the actual experimental process done at the University of Oklahoma, a website with information and a virtual lab was developed. A typical page of the website is shown in Figure 2.
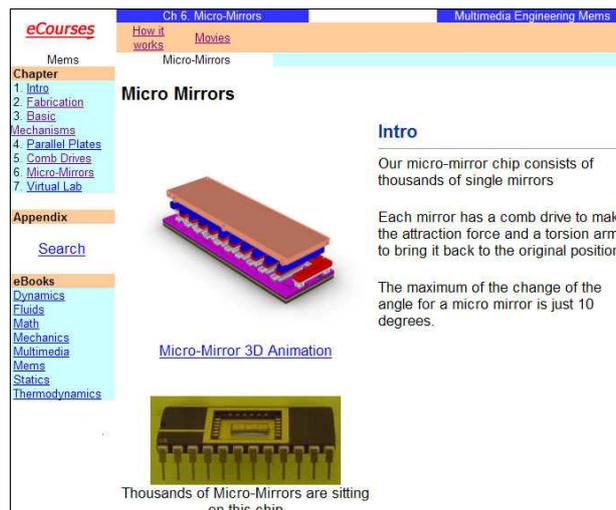

Figure 2 The Layout of the MEMS Website

One of the goals of the NSF grant was to make the MEMS experiment more portable by developing web-based material. Consequently, a virtual version of this experiment was developed so students can become more familiar with the real experiment[4]. Students can use the virtual lab at home or in the school computer lab. They can also review videos about the real test unit and how it is different from the virtual unit and the way they work. Animations about the micro-mirrors can be viewed in 3D virtual reality space[4]. The results of real computer simulations can be also seen. They can play animations made by sophisticated software not knowing how to do complex modeling and analysis with these software packages.

Excel spreadsheet experiments have been included in the website as well. And if students want to obtain a feeling how an engineer designs a MEMS device they can launch their excel spreadsheet and do some analysis on electrostatic field of their own MEMS devices.

One of the main objectives of the website was to make the content as entertaining as possible so students can learn about MEMS while they are having fun with the online materials. Additionally, the simulation results with high-end and more costly analysis software have been included in the form of easy-to-use animations in addition to some basic software and codes that have been developed for students to do some experiments on their own computers with no need to have a high end and complex software on their computer. The web site was designed to present all materials with an easy to understand approach using movie clips, 3D animations and flash simulations in addition to the drawings of the actual MEMS devices in the AutoCAD software, Excel worksheets for basic calculations and MATLAB codes for more advanced labs. The website was constructed to serve as a textbook. Students should be able to read the introductions, play with some of the MEMS structures in a 3D environment, calculate the forces between the plates and finally play with an instrument simulator all on the Internet without needing additional software. Amusement was important as well. The authors made a strong effort to stay focused only on MEMS so there is no topic about Fast Fourier Transforms (FFT) for calculating electrostatic field or finite element basics, even though they are used in the tools to provide understandable animations and simulations. The major audience of the website is undergraduate students who have had basic courses in physics and mathematics. The content is portable and cross-platform thus students with different operating systems can benefit from web-based material.

II. Implementation and Development

The website is organized into different sections as follows:

1. Intro (*Introduction to MEMS, History and Introduction*)
2. Fabrication (*Fabrication Processes, Czochralski Growth Process, PVD*)
3. Basic Mechanisms (*Introduction, Column, Cantilever, MEMS Bridges*)
4. Parallel Plates (*Introduction, Theory, FEM, Finite Difference, Lab*)
5. Comb Drives (*Intro, Theory, FEM, Finite Difference*)
6. Micro-Mirrors (*Intro, How it works, Movies*)
7. Virtual Lab

An introduction to MEMS is provided in the first section. History of MEMS is not complete without starting from the history of transistors and that is why a brief history of transistors and microchips is presented at the first section. In this section a definition of a MEMS system is also introduced. The main goal for this chapter is to prepare a base for the next sections. Section two consists of fabrication processes and talks about two of the main processes, Czochralski (CZ) crystal growth and Physical Vapor Deposition (PVD). Some online videos from the other institutions demonstrate the actual process and how it is done in the industry. Many MEMS books start the mechanical engineering sections with talking about basic mechanical structures in MEMS systems and that is why chapter three consists of different sections on basic structural elements (parallel plates, cantilever beam, column and bridge); Figure 3 illustrates a parallel plate system illustrated in Carrara (a 3D modeling and animation program) which is explained in section three of the website.
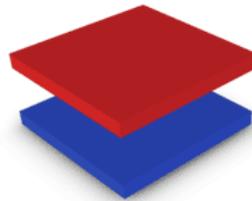
Figure 3 Hot and Cold Parallel Plates
(Rendered in Carrara 4 using VET Rendering)

Finite element analysis of parallel plates are briefly introduced in this section, however the main point of the analysis here is to give the student a visualization of how electric potential and energy lines are perpendicular to each other. And precise numerical analysis was not the main intention of the FEM sections in the book. Figure 4 is an illustration of the FEM results for a parallel plate system.
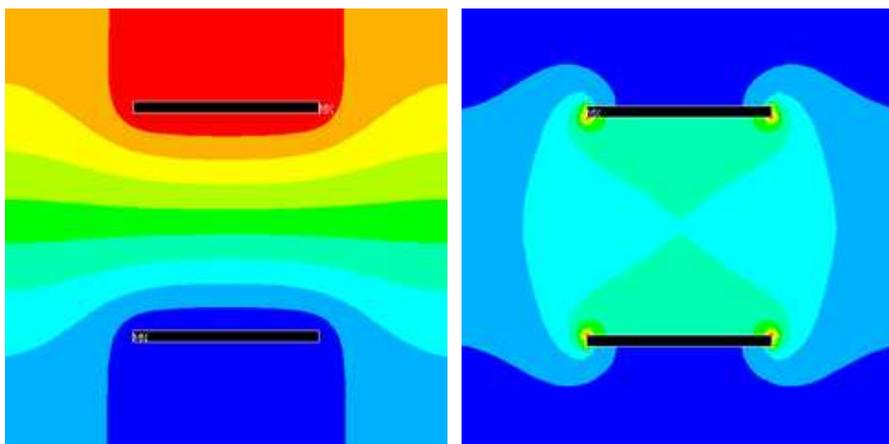

Figure 4 Visualization of the Electric Potential and Field around the Hot
and Cold Electrodes in a Parallel Plate System.

Also finite difference results are illustrated in this section and Microsoft Excel is introduced as an inexpensive solver for these equations. For better understanding excel worksheet templates

are also provided for downloading. For example calculations for a parallel plate presented in the Figure 5 are done in Microsoft Excel and the data visualization is done in MATLAB.
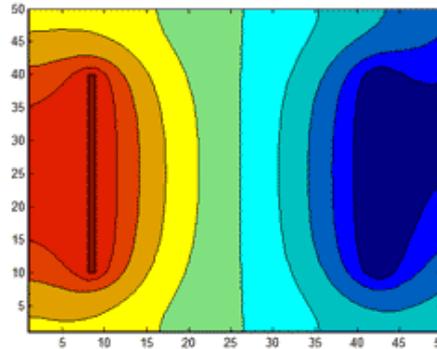

Figure 5 Finite-difference Solution for the Electric Potential Around Parallel Plates.

For parallel plate calculations, a graphical MATLAB program is presented in this section of the eBook. The GUI functionality versus the command line code empowers the student to experiment different geometries and settings and see the results as plots immediately. The source code is available for the students to download and view. This empowers the students not only to learn about parallel plates but also to learn about how to write their own graphical programs for similar calculations and experiments. Figure 6 demonstrates the interface of the code for the parallel plates.
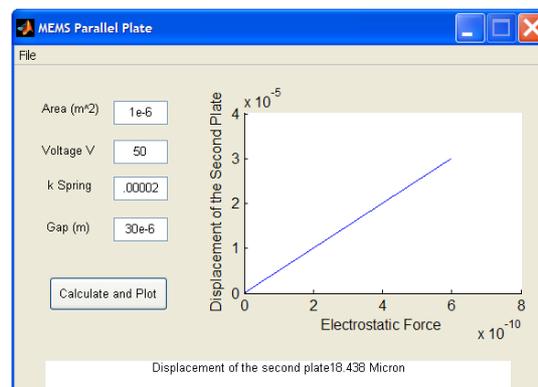

Figure 6 Visual Program to Help Students Understand Parallel Plates
(source code available on the website[4])

In section 5 of the eBook, comb drives are introduced as another basic element in designing the MEMS chips and the theory of comb drives is presented. Also videos of the comb drives help support the theory and demonstrate their movements. A particular high torque comb drive is introduced in this section; this comb drive can be seen in Figure 7. Teeth with the geometry shown are easier to manufacture while giving a higher torque.

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Figure 7 Comb Drives Designed in AutoCAD and Exported to Carrara.

In addition to the animations, some videos are made using a digital video camera to show the different steps of the actual lab. Various Internet technologies have been used through out the website, including:

- Flash for video delivering
- MEMS SUMMiT V drawings for illustrations
- VET rendering style for animation rendering
- Freehand for drawings
- Flash for basic user interaction and simulations
- ANSYS for finite element analysis
- Digital videos and screen capturing technology

Flash video has been used for video media instead of QuickTime or Windows Media Video (WMV) because ease of use, good quality and cross platform compatibility. Flash video produces better quality on gradients while QuickTime gives better quality with solid colors. To produce Flash flv files the RIVA flv encoder was used to convert different video files to flash video (FLV) then the resulting file is imported to Adobe Flash and a Media Playback Component is used for controlling the movie. For solid color videos like FEM results the QuickTime video has more advantages over the FLV videos since it renders the solid colors better. Samples of multimedia component are shown in Figures 8.

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Figure 8 Media Playback Panel

To help students better understand the of MEMS design process, the actual CAD files for basic MEMS components are used. To draw the mechanisms, AutoCAD along with Sandia SUMMiT V were used. Students can change the drawing and prepare their own micro structures, copy and paste the basic elements that are provided on the website, and build more complex structures. One of the obstacles was to solve the integration problem of AutoCAD and the rendering software. After doing research on possible import/export methods, two ways were found to export MEMS 3D models to the 3D animators and simulators. These methods empower the designers to bring their engineering MEMS drawings to 3D animation and simulation systems (i.e. Flash, Director, Carrara, etc), and allows them to communicate better with other team members over the Internet or any multimedia infrastructure. These two methods are

- SUMMiT 3D model generator and AutoCAD 3DS exporter
- Generic SAT files

These procedures bridge the gap between the MEMS drawing tools and the multimedia presentation/interactive tools which allow the engineers to present their drawings in a more interactive style. The first method for exporting models from AutoCAD is to use "Generate 3D Model" tool in SUMMiT V. After generating the models with the above tool, the models have to be read again with AutoCAD using "Load/View 3D Models." One can view 3D model in isometric view or any other view that is needed. Figure 9 is a 3D model rendered inside AutoCAD using its rendering capabilities. Afterward, 3D Max models can be generated and be imported to many of the 3D animation and simulation tools. 3DS format can be exported into Adobe Director (interactive 3D program) and Carrara as well as much other software that supports the 3DS format.
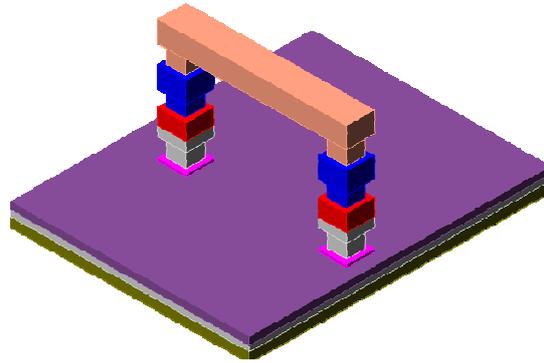
Figure 9 Bridge Built with SUMMiT and Rendered in AutoCAD.

The second method to export the 3D models into multimedia software is done by using generic SAT files. While the rendering capability in the AutoCAD lets the user view a 3D model in the AutoCAD, it is intricate to export it to a useful format. Additionally, AutoCAD is slow when rendering a 3D impression of a MEMS device. As a result, by generating a 3D model in AutoCAD and saving it as an easy to read format, the user will not have to repeatedly go through the same time-consuming process. Exporting MEMS models from AutoCAD and Sandia SUMMiT V to Carrara using the SAT file format can be summarized into the following steps

- The drawings are made in SUMMiT and AutoCAD
- A simple SAT model is exported from AutoCAD
- The SAT file is read in SUMMiT again
- A 3DS output is generated in AutoCAD

Using an SAT file format before exporting the whole drawing as a single 3DS file will preserve the properties of all the nitride and poly-silicon layers. This will help the 3D software to recognize the CAD model as a collection of different elements and layers. Figure 10 illustrates the MEMS column exported using SAT and rendered in Carrara using VET rendering.
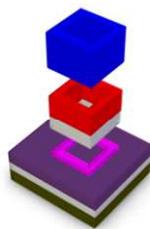

Figure 10 VET Rendering of a SAT Model

The procedure of converting the files into SAT data is done in the "SNL MEMS 3D Modeler" panel in the SUMMiT software. Figures 11 and 12 show the difference of two models rendered in AutoCAD and VET mode, and as seen in the figures, VET rendering offers smoother edges

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and superior shading. VET rendering in Carrara has been used to render still images. VET rendering produces beautiful images and eye catching shadings around the MEMS Micro-Mirrors. The simple look of the VET rendering makes this style an appropriate rendering technique for educational content. Models rendered using VET are simple and bright and all the details are shown properly therefore it makes it an ideal tool for educational purposes. Figure 12 is a Sandia Micromirror rendered in VET, the shading around the mirror makes it stand out.
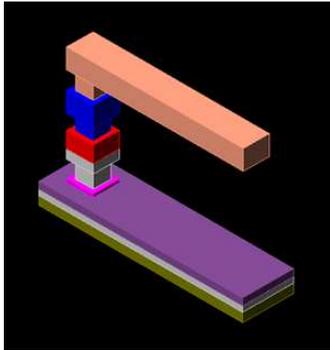

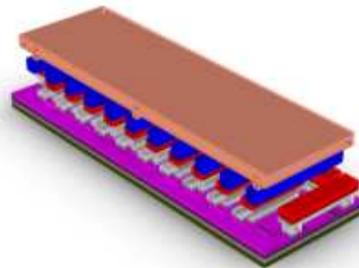**Figure 11 A MEMS Cantilever rendered in AutoCAD**

Figure 12 3D Model Generated by VET Rendering

A number of animations in the eBook have been made using direct screen capturing from ANSYS output and by adding all the captured pictures in a single movie. Adobe Image Ready has been used to make QuickTime movies with 35 key frames. Apple QuickTime has some advantages over Flash FLV in solid color animations. When less key frames were necessary, the timeline capability in Adobe Flash was used to put all the frames together and make an animation sequence. In this case FLV was not a suitable choice of movie file-type since it is not capable of rendering solid colors and it makes the solid colors blur.

One of the more challenging aspects of this work was the design and development of the simulation program. This program is a simulation of more expensive hardware used to acquire the information from the test unit. This simulation allows the students to do the experiment without having the actual hardware and the cost of the MEMS chips. A Fourier series, with additional random noise, is used to simulate the signals coming out of the National Instrument data acquisition board. In addition, data from the real experiments has been stored in the code to empower the simulation to mimic the behavior of the real instrument. A random .05% error is added to the data and every time a student does the experiment they will see different results. Figure 13 demonstrates the interface for the lab simulator.
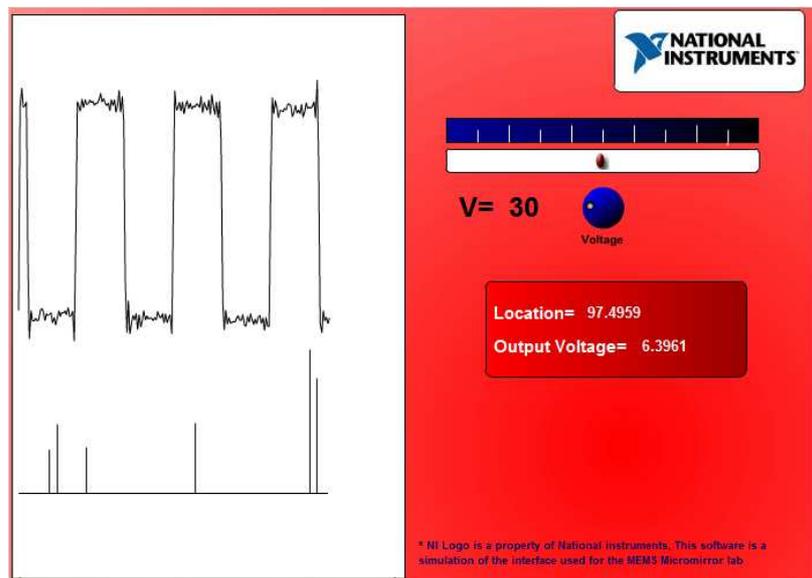
Figure 13 Simulation Software Written in Adobe Flash

Some electrostatic effects, the fringe effect in particular, cannot be derived from the elementary parallel plate equations. The finite element method is a popular tool to visualize the fringe effect on the edges. ANSYS and its coupled field analysis toolbox are used for simulation movies in this project. Its remarkable power of coupled field analysis[5] (structural and electrical domains) allows the user to do different crucial numerical simulation, especially comb drive and parallel plate simulations. Image conversion capability in ANSYS lets the user import the results into the movie making software and make movies with the screen captures. Figure 14 illustrates one of the frames that were used for the movie. Sharp solid colors can be handled in the Adobe Image Ready software. The results are exported as Apple QuickTime movies directly from the Adobe Image Ready. Three ANSYS elements such as Solid 122, 123 and Plain 121, have adequate electrostatic qualifications while still being fairly simple for students to use.
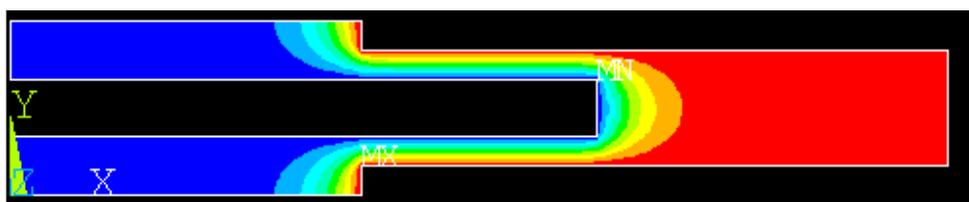

Figure 14 ANSYS Output, Electric Potential for a Comb Drive

Although ANSYS can offer fast and accurate results, it has a steep learning curve, especially for undergraduate students, in addition to being more costly. To overcome these issues, some of the simulations are presented in excel format using a finite-difference method. The main equation, the Poisson PDE, is solved by Successive Over Relaxation (SOR) method, however it can also be solved via Fast Fourier Transformation (FFT) more rapidly, and with less nodes. But FFT is harder to implement in Excel and it is difficult to understand for the students, while the relaxation method consists of some simple averaging between nodes[6]. Figure 15 illustrates the ability of excel worksheets in calculating the electrostatic field. Figure 16 is the visualization of the solutions done in MATLAB (MATLAB has better graphic capabilities and that is the reason

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it is used in this report, note that the same plots can be made in Excel conversely with less exquisiteness). Excel and other generic spreadsheet tools are affordable substitutes for electrostatic MEMS analysis tools similar to ANSYS and COMSOL.
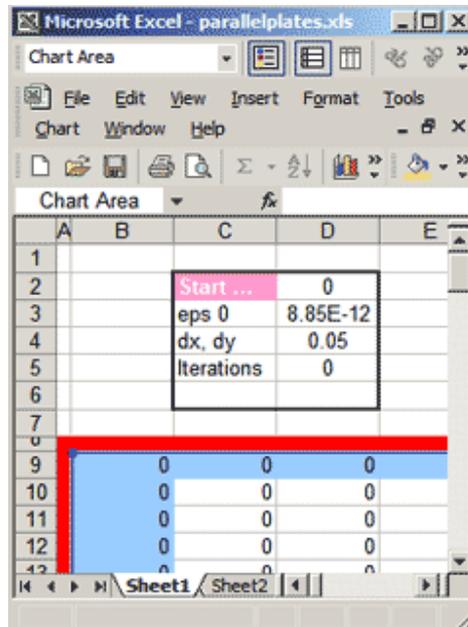

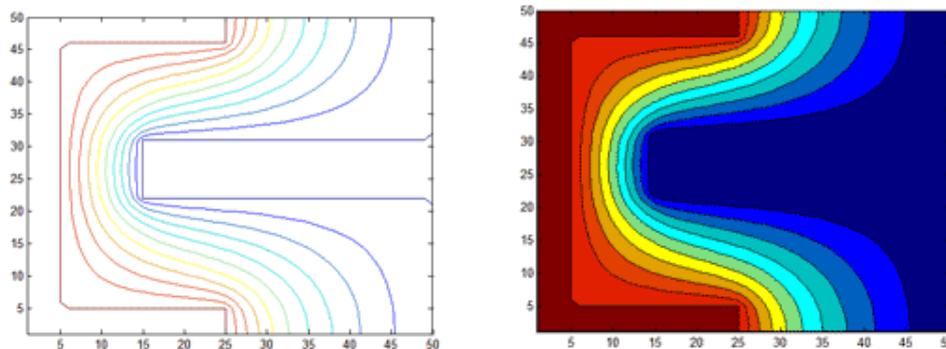**Figure 15 Finite-Difference Template**

Figure 16 Plotting Finite Difference Results in MATLAB

In 2006 the eBook is used for junior level students in Solid Mechanics Lecture course (AME 3143) and Solid mechanics Measurement Lab (AME 3112) at the University of Oklahoma. In these courses nearly 70 students learned about applying the fundamental theories of solid mechanics to design and analyze basic MEMS devices. They used the project to learn how MEMS can influence their everyday life in addition to learning about the history of MEMS and understanding the background theory and design and analysis methods[7].

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III. Summary

MEMS is a fairly new field and is still in development. Lack of easy-to-use tools makes it difficult for beginners to enter and explore this new world. In order for schools to provide basic MEMS experimental lab courses, they would need to equip their labs with the costly facilities needed. As an alternative to experimental labs, the Internet can help schools provide virtual MEMS experiments to their students with a relative low cost. This allows students to work with MEMS simulations without their schools being concerned about maintaining hardware lab facilities. This would help students explore this new MEMS field and it would help develop future engineers with a better understanding about MEMS. In this research various technologies for delivering MEMS content were examined and some of the best alternatives are identified. The following methods have been developed to bring the visual information from high-end software packages to web-based tools. The following conversion methods were developed and documented:

- ANSYS to Adobe Flash (Macromedia Flash at that time)
- ANSYS data to QuickTime
- SUMMiT and AutoCAD drawings to Flash
- SUMMiT and AutoCAD drawings to Director
- SUMMiT and AutoCAD drawings to CARRARA 3D tool

Using the above methods, MEMS designers can communicate their drawings and designs with each other over the web. Also, converting the original CAD and ANSYS models to these web-based systems helps the designers to protect their intellectual properties. It also eliminates the need of having a high-end software package at the viewer side. Designer can share their drawings without being worried about giving out sensitive measures and details. The level of details can be changes by including different layers and changing the settings.

IV. Acknowledgement

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