MEMS-based Educational Laboratory

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Abstract
The advent and widespread utilization of micro and nanotechnologies necessitates the development of innovative instructional and research tools that will educate the next generation of engineers and scientists. Teaching micro and nano scale technologies is often challenging and expensive due to the cost and complexity of typical systems that are utilized to access the micro and nano realm. In this work we discuss the Class on a Chip System, which has four main components: packaged Microelectromechanical Systems (MEMS) chip, driver board/control electronics, graphical user interface, and laboratory experiments. The system provides a relatively low cost MEMS experimentation platform which can be utilized through a reasonable contingent of laboratory tools (microscope and personal computer) available at most educational institutions to teach fundamental physics and engineering knowledge, as well as illustrate important micro and nano scale concepts which are accessible to students at many educational levels and in various disciplines and classes.

Introduction and History
Microelectromechanical Systems (MEMS) are ubiquitous micro-scale devices that are found in many consumer electronic devices including smart-phones, video displays, gaming controllers, and automotive safety systems. The most prominent devices are accelerometers, micromirrors, pressure sensors, and chemical sensors. Due to their diminutive size, their existence is usually overlooked, but their functionality has led to dramatic improvements in safety and system performance in the aforementioned applications.

A common thread connecting MEMS devices is microfabrication. Techniques initially developed for producing transistors have been co-opted to produce these micro-scale transducers. A typical
fabrication process includes repeated deposition, patterning, and etching steps. Transducers can be divided into two main categories: sensors and actuators. Because of severe device packaging requirements, directly observing the operation of the device is virtually impossible, especially for the sensors.

In a previous work\(^1\), we have described the evolution of a three-course MEMS sequence at Texas Tech University. The courses have morphed over the years to match current capabilities, interests, and opportunities. The initial course offerings included hands-on laboratory fabrication of devices, supported by a grant from the National Science Foundation. Once the relatively high level of funding ended, the courses emphasized finite element modeling software tools for predicting MEMS device performance. In 2004, the courses transitioned to design for fabrication using a commercial process with hands-on testing of exemplar devices. Eventually, an array of functional devices was possible that became known as the MEMS Education Chip. This chip is the cornerstone of a MEMS educational laboratory system.

It has long been recognized that the science and engineering fields are best learned by doing, especially when there is intellectual engagement\(^2,3\). Learning theory and equations are necessary, but true interest and even passion usually comes from interactive experiences that allow exploration and creativity. However, in this day and age, interactive experience is gained primarily through a computer, especially when dealing with complex, research grade
Providing exceptional laboratory experiences to college and high school students that prepares them for the intellectual and technical challenges is a daunting task that can require substantial investment in equipment and human infrastructure. The Class on a Chip System is capable of providing an important fraction of the curriculum needed to give students insight to the micro/nano realm.

**Class on a Chip System**

The Class on a Chip System has four core components: a microdevice chip containing an array of microdevices (MEMS Education Chip), a custom power supply, control software/GUI, and lab manual. Users need a suitable optical or digital microscope and computer to utilize the system.

Figure 1 shows the Class on a Chip System. The user controls a device with the GUI and watches the motion through digital video on a computer or directly when utilized with a standard optical microscope. The lower image shows the many devices that are packed on one chip. The chip is approximately 3 mm by 6 mm and normally has up to 16 accessible microdevices (examples shown in Figure 2). The chip is designed at Texas Instrumentation.
Tech University (TTU) and produced at Sandia National Labs using a fabrication process known as SUMMiT V. SUMMiT is a process for producing poly-silicon (poly-Si) MEMS, allowing a wide variety of device types to be realized, of which some are capable of significant motion. In the very small chip area (18 mm²) many experiments can be conducted that help teach important physics/engineering concepts such as force, displacement, velocity, acceleration, thermal expansion, metric system, scientific notation, gear systems, and electricity. The experiments can also be used to illustrate micro/nano effects. Table I provides a list of experiments that have been developed so far.

The chip is electrically packaged for use with a computer controlled power supply that applies user inputs of power to the devices. This circuitry is responsible for allowing the chosen device to be actuated, the appropriate voltages or currents to be set, and the ability to apply varying signal frequencies. National Instruments LabVIEW has been utilized to create the GUIs (Figure 3) for the system and the individual devices.

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<td>Pop-up Mirror</td>
<td>Micro Hinges</td>
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<td>Trigonometry</td>
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<td>Chevron actuator + spring</td>
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<td>Ohm’s Law</td>
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* Torsional Ratcheting Actuator (TRA) – rotational drive
Educational Laboratory Use

In order to provide the context for how the Class on a Chip System is utilized, the following is a brief overview of the components of the MEMS I course. The coursework for MEMS I includes: a literature review report on a student selected MEMS technology (i.e. digital micromirrors, accelerometers, gyroscopes, etc.), a design project using the AutoCAD based SUMMiT V process (design a micromirror), a finite element model and simulation (electrothermal actuator), and a group final design project. Two to four person groups choose a device to research, design, and simulate, thus incorporating the primary aspects of the three previous projects. The final project involves proposal and final presentations, as well as a journal-style written report. Due to the long timeframe involved in device fabrication, the students’ device designs can’t be fabricated during the current semester, and certainly can’t be empirically tested. Because of this, it is important to augment the theoretical work with the hands-on utilization of the Class on a Chip System.

Anywhere from three to five experiments are conducted in MEMS I using the System. The number has varied based on the number of students in class. In the most recent offering of MEMS I in the Fall of 2013, approximately 50 students were enrolled. To accommodate this relatively large number of students, multiple lab times were scheduled and three to four Systems were set-up to minimize the number of students sharing an apparatus. Since the microscope image is displayed on a standard computer monitor, three to four students can readily be accommodated on each System. Each student is encouraged to find the appropriate device through the microscope and operate it using the graphical user interface (GUI).

Appendix A provides the first experiment that is typically conducted. The lab emphasizes familiarization with the technology and helps to calibrate the students’ thinking about the size
scale and the devices they will be exploring. Through this experiment and subsequent ones, the students should gain the empirical knowledge of the technology that will help guide their final design project. Almost all final projects will incorporate one of the actuators explored experimentally. Knowledge of the actual performance limits of the actuators tends to improve designs, *i.e.* un-realistic implementations are minimized. Students are also able to provide realistic testing scenarios for their devices if they do get fabricated eventually. They will know the approximate voltage and frequency ranges that their device can be operated at and expected performance.

In the second course of the MEMS sequence at TTU, MEMS II, students harness the knowledge and skills gained in MEMS I to produce a MEMS design that is suitable for entry into Sandia National Lab’s annual university MEMS design competition. The device can be a design begun in MEMS I or a new device idea. In either case, the device should represent a well-thought out concept that has had important aspects simulated. If a similar device exists in the TTU MEMS device inventory, then it is tested. Historically, Sandia has fabricated winning designs for free and supplies the chips to the participating schools for testing and characterization. The incorporation of more laboratory experiences into the MEMS I and II courses has led to more successful device designs. TTU design teams have won first place in the competition 7 out of 9 years. Some of these and other devices fabricated through the design competition have been utilized for various research projects including microstages$^{5,6}$, micromirrors$^{7,8}$, microactuators$^{9,10,11}$, microgrippers$^{12}$, microsensors$^{13,14}$, and microtribology$^{15,16}$. 

![Figure 4. Class on a Chip System in use at University of Utah Nanofab.](image)
In order to extend the benefits of the technology to other universities, a commercialization effort was begun in 2008 and came to fruition in 2010. To date, approximately 20 other universities have acquired the Class on a Chip System, along with two national labs. Some of the universities have used their systems extensively in their own MEMS courses and activities (Figure 4). The University of Utah has used the System for courses and demonstration and has designed their own SUMMiT chip to be used with the Class on a Chip power supply and software.

For the first few years of using the SUMMiT process, our students relied exclusively on electrostatic actuators for moving components. The first attempt at using electrothermal actuators relied on designs that were only simulated. Testing revealed that the simulations overstated the displacement that would occur. In a subsequent chip, the electrothermal actuator designs were corrected. Since then, we have included numerous electrothermal actuator examples on our education chip. Students are armed with important empirical data that helps them better design their own devices that rely on this actuation method.

**Pedagogy Considerations**

Like any other course component, the key question is “if and how the Class on a Chip System affects student learning?” The considerations that have been most important to the instructor include: matriculation in the elective MEMS courses, quality of student device designs, understanding of micro/nano concepts, student attitudes, and dissemination of the technology to other programs. Many of these are somewhat subjective metrics, but provide a useful picture of how the technology has impacted student interest and learning.

A fundamental impact the technology has had on the MEMS courses is maintaining student interest in the courses. Since the courses are elective, students at both the undergraduate and
graduate level can easily choose not to take MEMS. However, the MEMS I class has been offered every fall since 2000, and every summer between 2008-2012. An average of almost 50 students per year has taken the class over the last four years that the Class on a Chip System has been utilized. Students report through end-of-course surveys that they enjoy the mix of lectures and hands-on activities.

Table II. MEMS I course enrollment 2010-2013.

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<thead>
<tr>
<th>Semester</th>
<th>Su’10</th>
<th>F’10</th>
<th>2010</th>
<th>Su’11</th>
<th>F’11</th>
<th>2011</th>
<th>Su’12</th>
<th>F’12</th>
<th>2012</th>
<th>F’13</th>
<th>2013</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>15</td>
<td>20</td>
<td>17</td>
<td>33</td>
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<td>39</td>
<td>50</td>
<td>54</td>
<td>50</td>
<td></td>
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<tr>
<td>Yearly Total</td>
<td>35</td>
<td></td>
<td>50</td>
<td></td>
<td>54</td>
<td>50</td>
<td></td>
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</table>

As was previously noted, access to actual devices has been important to device designs in both MEMS I and MEMS II. Most, but not all, students are able to take the empirical values determined through experiment and utilize in their own device development process. Students who don’t initially make the connection usually blame the oversight on compartmentalization of the course work.

Most of the students, especially the undergraduates, who enroll in the MEMS courses have little experience working with microscopic devices. Some graduate students enrolled in MEMS do work in micro/nano technologies, and thus, have an appreciation for micro/nano phenomena and concepts. Additionally, the System is frequently used for K-12 demonstrations with approximately 500 student/teachers viewing live demonstrations on the System in 2013. Aside from the graduate students and a handful of undergraduates, the MEMS technologies on display are outside the knowledge realm of most. There is much intrigue related to the microscopic motors that spin even smaller gears. The interest generated provides a favorable atmosphere for conveying information on the specific technologies and related ones (i.e. accelerometers, micromirrors).
Finally, the dissemination efforts have allowed ~20 Systems to go to other universities. To date, there has not been a formal evaluation of usage levels at the other institutions. Most information on use has come from the institutions that have used the Systems frequently. In general, the technology has benefited instruction in similar ways to the TTU experience and has allowed additional outreach activities.

**Future Work**

There are some new instructional devices that have made it through the prototype process and have been added to a new version of the MEMS Education Chip that is currently being fabricated. The new devices will emphasize forces and simple harmonic motion. A more formal evaluation of external use of the technology will be undertaken to better establish usage and hurdles to implementation.

**Conclusions**

The Class on a Chip System has developed into a key aspect of the MEMS courses at TTU and other universities. The relatively low cost technology has allowed hundreds of students at both the college level and below to visualize and experience microscale devices. The technology has led to improved student learning and design outcomes in the MEMS courses at TTU and opened up the eyes of many to the power of microscale technologies. Continued device and curriculum development will lead to more learning opportunities. The laboratory System is suitable for use with physics and other engineering courses.
Appendix A – Example Laboratory Experiment: What is Micro?

<table>
<thead>
<tr>
<th>Objectives</th>
<th>1. Teach concept of microscope with respect to macro objects</th>
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<tbody>
<tr>
<td></td>
<td>2. Teaches small units (millimeters and micrometers)</td>
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<td></td>
<td>3. Gain familiarity with Class on a Chip System</td>
</tr>
<tr>
<td>Device</td>
<td>TRA with micromotor</td>
</tr>
<tr>
<td>Apparatus</td>
<td>Ruler or meter stick</td>
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<tr>
<td></td>
<td>MEMS Education Chip</td>
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<td></td>
<td>Microscope</td>
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</table>

**Introduction**

Most of our daily life involves manipulating and interacting with objects which are considered to be macroscopic. A pencil is approximately 20 cm (0.2 meters) long. A tall person is 100 cm (2 meters). Figure 1 depicts a typical metric ruler with major units in centimeters (cm) and minor units in millimeters (mm). This ruler is good for measuring some macroscopic objects. Figure 2 shows an expanded view of test followed by a period 1 mm with a diameter of ~1 mm. This ruler can only really measure something down to this size. Smaller objects will need to be measured with an even smaller ruler while being imaged using a microscope.

**What is micro?**

An optical microscope uses a series of lenses to produce a larger image of an object. A good optical microscope can be used to image objects to ~1 micrometer (μm). For imaging objects in this size range and smaller, an electron microscope needs to be used. The Scanning Electron Microscope (SEM) is an important instrument that has been used to produce some of the images used throughout this lab manual. A good SEM can image objects down to 1 nm in size.

We will use a standard optical microscope in this experiment to determine the size of structures on a micro size gear. The gear is a widely used mechanical component for transmitting rotational motion. Figure 3 shows smaller gears found in a watch. The gears in the watch are only 5 mm in diameter. However, much smaller gears can be made using microfabrication processes. We will utilize some very small gears as we begin to explore microscale mechanisms.

**Procedure**

1. Place the MEMS Education Chip under the microscope (note: depending on the microscope you are using, some of these procedures may be different – always check with your instructor if you have a question about the available hardware.)
2. If necessary, turn on light for the microscope. The chip has to be illuminated from above.
3. Focus the microscope to that object on the chip surface can be seen.
4. If possible, adjust the magnification of the microscope so, cover in and out to see overall view of the device as well as small features.
5. Locate the rotational drive (See note 1A for additional information regarding the Torque Ratcheting Actuator [TRA] and gear shown in Figure 4. The rotational drive is the larger, circular device with a lot of features. The diameter of the T56 is 100 μm.)

**Figure 3.** Gear are containing variety of devices, including driving wheels and actuators.

**Figure 4.** Electron microscope image of a T56 and gear.

**Typically, the uncertainty in a measurement is directly related to the measurement tool that one is using. State how you determined the size of the spots and what the uncertainty in the measurement is and what causes it.**

Size of spots on gear = ______ μm ± ______ μm

**Notes:** (Hint for Question 7 on page 11)

1-a) The Torsional Ratcheting Actuator (TRA) was developed at Sandia National Laboratories and is used for producing circular motion to spin gears and drive linear rods. The TRA uses electrostatic force to ratchet the outer gear ring producing circular motion. Figure 6 shows a close up view of some of the structures. Pulses voltage is applied to opposing capacitive comb fingers (the detailed features in the middle of the device). One set of comb fingers is fixed, while the other side is mounted to a spring. When voltage is applied, the fingers approach each other, but do not come into contact. This motion causes a ratcheting pawl to move and produces one “click” of rotation. When the voltage is dropped back to zero, the pawl returns to its rest position. The TRA can be actuated to spin at a rate from 1 – 1100 rpm (rotations per minute). At high frequency, operations and high input voltage, multiple ratcheting is observed.

1-b) The dark spots on the surface of the gear are actually holes that go all the way through. Gears and other structures need these holes because of the fabrication process used to make them. The holes allow an aqueous etching solution to remove a sacrificial layer of silicon dioxide that is below the gear. Four etch-release holes can be seen in Figure 6.

**Figure 5.** Electron microscope image of gear. Based on the diameter of the gear determined in Step 6, determine the size of the dark spots (What are they? See note 1-b below) on the gear. Some uncertainty will be involved in this measurement. When stating the value, use the "±" symbol to quantify the uncertainty. As an example, an answer can be stated as 55 mm ± 5 mm if one has determined that the measurement falls in the range of 50 – 60 mm.
References


3 “Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology. (NSF 96-139), National Science Foundation.


