1 Introduction

Project-based courses have long been used to teach the fundamentals of engineering design. This hands-on approach is used at MIT to teach engineering students several fundamental principles of precision engineering:

(1) Flexure design   (2) Magnet-coil design   (3) Basic electronics/control
(4) Precision fixtureing   (5) Precision measurement   (6) Natural frequency and mode shapes
(7) Vibration isolation   (8) Thermal sensitivity/design   (9) Deterministic design practices

These fundamentals are taught in 2.000: How and Why Machines Work [01]. During this semester-long course, freshmen engineering students are tasked with two separate precision design projects:

(1) Nano-etch-a-sketch: Modeling, design, fabrication and characterization of a two-axis, macro-scale Nanomanipulator (a Nano-etch-a-sketch).
(2) MEMS accelerometer: Modeling, design and characterization of a MEMS mass-spring accelerometer.

The following sections describe the projects and philosophy/tools the students use to learn the preceding fundamentals. The curriculum which supports these activities is freely available. Contact culpepper@mit.edu with questions / requests.

2 Teaching philosophy

A failing of many engineering design courses is that they turn “technically impressionable” students into applied mathematicians with engineering knowledge. By this, we mean that most engineering courses present engineering theory and quantitative methods rather than a balanced set of theory, qualitative skills and quantitative skills. The approach taken in these projects, aims to make the students develop qualitative skills by helping them figure out the important characteristics of a problem and performance sensitivity to important variables before they delve into equations. They then use dimensional analysis to form relationships between the important variables/characteristics and performance. This often starts with analogy. For example, when the students are asked to design a mass-spring-damper system (see Section 5) with a particular natural frequency, they are asked to think about how a car’s suspension system characteristics affect its natural frequency. After several thought experiments, the students are able to determine that the mass and stiffness are the important variables. They then perform dimensional analysis to develop relationships between the design and performance parameters and run experiments to flesh out the relationships. Activities such as these build confidence in the student’s innate ability to understand what is important and then use this knowledge to solve an engineering problem. Once the students understand the important variables, they are taught the engineering theory in the classical, analytically intense manner.

3 CoMeT – A compliant mechanism/flexure design tool

The projects in subsequent sections rely on flexures and compliant mechanisms. We have developed a software package and curriculum which students use to understand, design, fabricate and integrate flexure-based machines into precision equipment [02]. This tool, CoMeT (Compliant Mechanism Design Tool), has also been used to
design R&D 100 award (2004) winning flexures and compliant mechanisms for Nanomanipulation equipment [03] for research projects. CoMeT is a Matlab™ script designed to enable:

Rapid concept evaluation – The GUI, shown in Fig.1, reads hand sketches of mechanism concepts (e.g. via pen on tablet PC) to automatically generate matrix based analysis models that use beam equations (i.e. no meshing). This is equivalent to having a smart “back of the envelope” which can help you optimize/explore designs.

4  Nano-etch-a-sketch contest

An example of a student-designed Nanomanipulator is shown in the upper right hand corner of Figure 2. The Nanomanipulator consists of an x-y flexure stage which is driven by two magnet-coil actuators. The steps follow as they design their device are shown in Fig. 2 and outlined below the figure.
The following steps trace the flow shown in Fig. 2:

**Step 1**: Students conceive of an x-y flexure stage design and model it using the CoMeT flexure design software.

**Step 2**: Students design the geometry of auxiliary equipment (actuators, sensors, fixtures) using a CAD program.

**Step 3**: Students design and build the electronics and the magnet coil actuators.

**Step 4**: Students use an abrasive waterjet to fabricate their flexure stage.

**Step 5**: Students assemble, test and calibrate their Nanomanipulators. At this stage, students learn to use precision measurement probes (capacitance probes) which they set up to track the motion of their Nanomanipulator. Students also equip their Nanomanipulator with a kinematic interface which enables them to quickly/repeatably dock and undock their Nanomanipulator to the capacitance probe fixture.

At the end of the course, students “race” their Nano-manipulators through a virtual 30x30 micron race track. The bottom left of Fig. 2 shows three teams lining up to race. To successfully complete the track, the student’s needed to design a Nanomanipulator which can move over a 30x30 micron range. Each Nanomanipulator must be capable of 50 nm resolution (to make the tightest turns). Students quickly learn not to “jump up and down” when they get excited during the race (some students design low-cost, but effective vibration isolation tables for their machines by supporting the Nanomanipulators with bubble wrap) In addition, design for thermal insensitivity is impressed on the students as they run experiments to determine the affect of temperature variation on their ability to drive the Nanomanipulator through the course. They quickly learn that they can not handle the Nanomanipulators without gloves (due to thermal energy transfer from their hands). Clever students lean how to integrate friction damping to limit the effect of vibration-based disturbances. To date 28 of 32 students have been able to successfully complete the maze with their machine.

5 **MEMS accelerometer project**

The 2.000 students are also tasked with designing and testing the hardware components of a MEMS accelerometer. The students are given targets with respect to natural frequency, size constraints, the CoMeT tool and material properties of single crystal silicon. The students then go through the thought experiments described in Section 2, to determine the important variables and relationships which relate stiffness and mass to dynamic performance. The students use the CoMeT tool to develop concepts and simulate their performance. After two weeks, they are required to hand in a DXF file of their design which is then transformed into a mask pattern. The course TA fabricates the devices in the MIT Micro Technologies Laboratory (see wafer in Fig. 3). Several examples of student designs are shown on the right hand side of Fig. 3. Students then use capacitance probes to measure the vibration properties (displacement vs. time) of their device, perform a FFT and determine the device’s natural frequency. To date, their calculations have matched measured data within 5%.

![Figure 3: 2.000 How and Why machines Work; MEMS accelerometer project](image)
6 Graduate student projects in precision engineering

During the Fall of 2004, Graduate students at MIT will take 2.76: Multi-scale systems design and manufacturing [04]. Multi-scale systems consist of components from two or more length scales (nano, micro, meso, or macro-scales) and thus require precision engineering to ensure proper design and fabrication. The students will be tasked with the design, modeling, fabrication and characterization of a STM which is capable of better than 0.5 nm resolution over a range of 500 x 500 x 500 nm³. Problem sets guide the design of each key component of the SPM. Figure 4 shows the original concept for the STM project.

![Figure 4: 2.76: Multi-scale design and manufacturing course project (STM)](image)

7 Acknowledgements

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8 References

[01] 2.000 Course web site: [http://psdam.mit.edu/2.000/start.html](http://psdam.mit.edu/2.000/start.html).


[04] 2.76 Course web site: [http://psdam.mit.edu/2.76/index.html](http://psdam.mit.edu/2.76/index.html)

[05] MIT iCampus web site: [http://icampus.mit.edu](http://icampus.mit.edu)