PROJECTS FOR TEACHING MECHATRONICS AT MIT

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Abstract

The purpose of this paper is to describe current projects for teaching mechatronics at MIT. Two established efforts include the 6.270 robot contest, for which the popular handy board microcontroller was developed, and a senior elective in 2.737 Mechatronics. Our most recent project is the development of ActivLab labware for teaching undergraduate dynamics in course 2.003.

1 Introduction

The large volume of recent literature indicates that many universities in the U.S. and abroad have recognized the importance of teaching mechatronics (Acar & Parker 1996), (Acar 1997), (Bergh et al. 1999), (Habetler et al. 2000), (Murray & Garbini 1998), (Van Brussel 1996). Many authors note that there is a growing need for "work-ready" graduates who can design mechatronic systems (Hsu 1999), (Murray & Garbini 1999), (Yurkovitch et al. 1998), (Arkin et al. 1997). The experiences described include capstone (senior-level) design projects and competitions (Rizzoni et al. 1998), (Craig 2001), (Carryer 1998) as well as laboratory courses on specific skills such as electronics, sensors and actuators, and signal processing (Auslander 1998), (Craig 1999), (Luecke 1999), (Pham et al. 2000), (Field et al. 2000), (Kurfess & Witzel 2000). Universities have also begun offering classes to develop such skills in the freshman (Rizzoni et al. 1998), (Bradbeer 2001) or sophomore (Kurfess & Witzel 2000), (Peyton et al. 1996) years.

In MIT's mechanical engineering department, we now include lab experiences that teach mechatronic principles beginning at the introductory (second-year) level and continuing through intermediate (senior-level) and graduate-level instruction. At the sophomore level our introductory dynamics course has been restructured to provide an experimental component aimed at developing a stronger intuition about first- and second-order dynamics as well as a foundation in electronic circuits and controller dynamics. We feel such course work adds motivation to the underlying analytical material, and better prepares students for later mechatronic experiences. This paper outlines some of the current projects underway at MIT to teach skills in mechatronics.

The remainder of this paper is organized as follows: First, we provide some brief examples of relevant work at a number of institutions. Then we discuss two well-established projects in teaching mechatronics at MIT: the 6.270 autonomous robot contest and 2.737, a senior-level course in mechatronics. Next we describe our current ActivLab project to restructure the 2.003 sophomore-level dynamics course to include a mechatronic viewpoint. We describe each of the mechanical and electrical experiments which comprise the 2.003 ActivLab projects for teaching introductory dynamics, giving the goals of each assignment and presenting details about our choices in designing and selecting experimental hardware. We conclude the paper by appraising the results of these projects and provide links to further information for anyone wishing to adapt the materials outlined to their own needs.

2 Mechatronic teaching at other institutions

Many universities are incorporating mechatronics more broadly into their engineering curricula. For instance, mechatronics now provides a focal point across many core classes in the mechanical engineering department at Colorado State University (Alciatore & Histand 2001). Georgia Tech has instituted an interdisciplinary approach to mechatronics, teaching a variety of courses (for instance in robotics and manufacturing) in a mechatronic lab facility (Arkin et al. 1997). The University of Washington has an extensive mechatronics curriculum (Murray & Garbini 1999). The mechatronics program led by Kevin Craig at RPI is a well-known model program for other universities (Craig 1998). Space limitations prevent listing the other intriguing projects for teaching mechatronics currently underway at other institutions. Below, we focus on a few examples of mechatronics labs which relate to our newest project of teaching dynamics from a mechatronics viewpoint.

Stanford has recently developed a series of laboratory experiences which integrate mechatronic design into an introductory dynamics course. In Fall 2000, an undergraduate course (ME161: Dynamic Systems) was experimentally restructured (by Cham et al. 2001) around a cleverly designed hopping robot called the *dashpod*. The dynamics of the dashpod provided a unifying theme upon which to build a sequence of laboratory exercises that cover such topics as first- and second-order system response, simulation of nonlinear dynamics, time and frequency response, stable and unstable behavior, coupled dynamics and state-space methods. The course concludes with a contest to modify the dashpod to hop forward as fast as possible. Presenting the students with this design goal provided motivation to the students for learning the course material.

An example of a system which requires nonlinear modeling is the behavior of a spinning coin (Euler's disk) as it loses energy (Moffatt 2000), (Engh et al. 2000), (Stanislavsky & Weron 2001). Many other good examples can be found among the collection of short papers written and assembled by Kirt McDonald of Princeton University. They analyze a range interesting dynamic systems including the Levitron (a levitation toy) (Fascinations, Inc. 2000), rolling motion of a half-full beer can, magnetic repulsion due to eddy currents, and the physics of the laundromat (McDonald 2002).

Professors are also teaching mechatronics in professional programs outside the university. In the Netherlands, Jan van Eijk has organized in-house courses on mechatronics for engineers at Philips. Over the past 13 years, over 1000 people have completed the 11-day program. One system studied in the course consists of a DC servomotor which activates a two-mass system. One mass is attached rigidly to the motor shaft. A flexible shafting made of thin hexagonal stock couples the motor to a second mass. This hardware can be used to analyze fourth-order system dynamics and multi-variate control. It demonstrates the common problems that occur in mechanical systems because of the finite stiffness of all machine parts. (personal communication Jan van Eijk 2001), (Philips 2001)

3 The 6.270 autonomous robot contest

Among the most popular design projects for teaching mechatronics are robot competitions (Jones 1999), (Arkin 1997), (Carryer 2000), (Gardner 2000), (Field et al. 2000), (Kurfess 2000), (Manseur 1997). Autonomous robot contests often use for control either the BASIC Stamp (Parallax, Inc. 2002), a microcontroller based on the PBASIC interpreter chip manufactured by Parallax, Inc., or the popular *handy board* (Martin 2000), which uses the Motorola 68HC11. The handy board emerged out of a project in the early 1990's to develop a microcontroller for the annual 6.270 autonomous LEGO robot contest at MIT. The name *6.270* ("six-two-seventy") derives from the inspiration for the contest: the popular Mechanical Engineering design class *2.70* ("two-seventy") developed by Prof. Woody Flowers.

The 6.270 contest was developed by a group of LEGO-fanatical students in the Electrical Engineering and Computer Science department who include Fred Martin, Randy Sargent and Panjak (PK) Oberoi. They put together the hardware, software and funding necessary, and the contest has continued as an annual event in January at MIT ever since. Many universities and high schools now use the handy board for similar robot competitions. Related research at the MIT Media Lab to create the Programmable LEGO Brick (Epistemology and Learning Group - MIT Media Lab 1998) inspired the development of the LEGO Mindstorms robotics line (The LEGO Group 2002).

Handy board specifications include 32K of static RAM. There are inputs for 7 analog and 9 digital sensors, and an expansion bus makes additional digital I/O latches possible. The board operates on internal (NiCad) batteries with built-in recharging circuit and uses two L293D motor driver chips capable of driving a total of four 9-volt DC motors. The boards facilitate teaching higher level design skills particularly well due in large part to the Interactive C (IC) programming language, developed for the 6811 by Randy Sargent (Newton Research Labs, Inc. 2002). IC compiles into pseudo-code (p-code), which is then interpreted by the machine language. As a result, users do not need to wait for lengthy compiles and can test code at the command line. This makes the environment particularly useful for learning higher level skills, so that robot-builders can focus on algorithms and good design practice rather than on details of low-level implementation. The handy board can be purchased from several retailers; more details about the board can be found at the website http://handyboard.com

4 Project labs for mechatronics (2.737)

Two classes teaching mechatronics at MIT include 6.199 Advanced Mechatronics Project Laboratory, a capstone design class taught by Prof. Steve Leeb in the Electrical Engineering and Computer Science Department, and 2.737 Mechatronics, an elective course in the Department of Mechanical Engineering taught by Prof. Trumper. Both courses are at a level appropriate for seniors and first-year graduate students. 2.737 focuses strongly on practical, hands-on laboratory experience in the integration of controller design, electronics and electromechanical components. Over the past eight years, we have developed a collection of laboratory projects for 2.737 which fall into two broad categories: (1) close-ended laboratories which demonstrate some well-defined skill sets related to electromechanical systems and control and (2) open-ended design projects.

Among the close-ended projects developed for the class are: (1) Analog (PI) feedback current control of a transformer with a varying inductive load, (2) Lead-lag compensation (implemented digitally using dSPACE/Simulink) of a DC servomotor (dSPACE 2002). Topics illustrated in this lab include integrator windup, A/D quantization and issues with structural resonance, and (3) a digital electronics project where students implement an encoder quadrature decoder. Topics covered here include Schmitt triggers, phase interpolation of sinusoidal encoder signals and circuitry debugging skills.

Two examples of open-ended design projects that students have studied include (1) Active vibration isolation using an 8-inch audio speaker (Trumper & Sato 2002), and (2) A laser light show, where students design controllers for a pair of galvanometers to achieve high bandwidth and produce laser-traced images. More details on many of these projects have previously been documented (Trumper & Ludwick 1999).

Students in 2.737 use dSPACE, Simulink, and MATLAB (The Mathworks, Inc. 2002) extensively for system analysis and controller implementation. This allows them to concentrate on higher level design issues so that learning about mechatronic systems serves as a vehicle for teaching good design principles more generally. The philosophy driving the class is that the experiences provided should not only motivate students in this particular field (e.g. mechatronics) but should also give them design skills which can be applied to whatever new fields of study they encounter (Roberge 1991).

5 ActivLab labware for teaching dynamics

We have coined the name *ActivLab* to refer to the set of hardware and experiments we developed during the summer of 2001 for 2.003 Modeling Dynamics and Control I. The course is an introductory required undergraduate course in our department that focuses on modeling linear time-invariant mechanical and electrical systems. Our lab projects have been developed as shareware; we are in the process of providing web-accessible documentation to allow instructors at other universities to adapt these labs to their own efforts (Hijmans 2001).

5.1 Philosophy for designing labs

The laboratories for the 2.003 class were designed with a few basic goals in mind. One particular concern was that the students should be able to directly observe the relevant dynamics in the mechanical systems. In these systems, it is also important that students are able to observe the linear effects of damping with a minimal amount of nonlinear friction. To achieve this, we use porous carbon cylindrical air bearings to implement both rotational and translational mechanical systems (New Way Machine Components, Inc. 2002).

We also believe the laboratory hardware and data acquisition should be as transparent as practical to the students. For this reason, we have avoided introducing tachometers, encoders or other sensor technology in the first two laboratories to allow students to observe dynamic systems which evolve on a human-perceivable time scale. The above ideas were catalyzed by discussions with Prof. Ely Sachs in our Mechanical Engineering Dept. (Sachs 2001)

For these reasons the labs utilize flexures and air bearings to constrain motion, as these behave in a near-ideal fashion. They allow time constants and oscillation periods on the order of one second, and thus at a time scale directly perceivable to the students. Finally, in the early labs, motion is measured with a video camera. Time resolution is taken by single-stepping through the video frames, which are typically acquired at 20 Hz.

Also, the equipment should be modular in nature, to allow extensions to the setups to be developed with a minimum of effort and to reduce the needed investment in space and money to develop a full set of laboratory hardware. All hardware is mounted on optical breadboard, which allows us to assemble the labs easily and to disassemble the components for efficient storage.

5.2 1st-order spring-damper translational system

The first lab in the course demonstrates a first-order response with position as the variable of interest. The hardware for this lab, shown in Figure 1, consists of a flat spring steel cantilever which is clamped at one end by an aluminum bracket and acts as a spring. An Airpot (Airpot Corporation 2002) dashpot connects the other end of the cantilever to a second, fixed aluminum bracket. Damping occurs as a piston forces air through an adjustable orifice in the dashpot. Figure 2 shows an Airpot with its protective, rubber coating removed to show the cylinder and piston inside. The dashpots used in the lab have a rubber coating to prevent

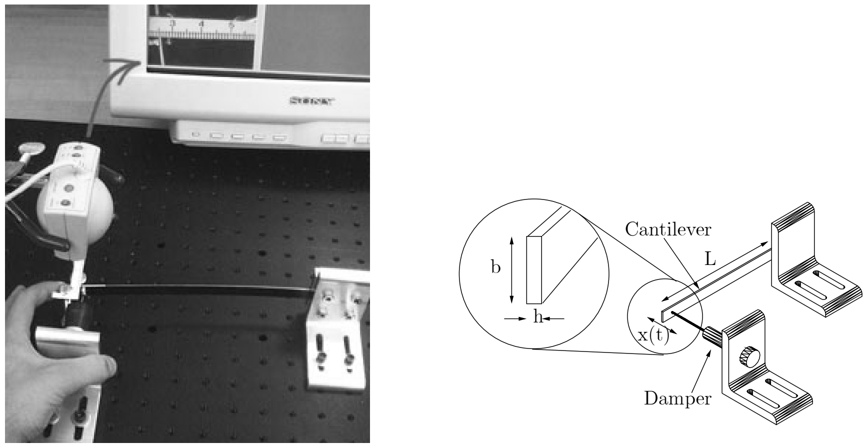


Figure 1: First-order spring-damper system

injury from glass shards if the glass cylinder shatters.

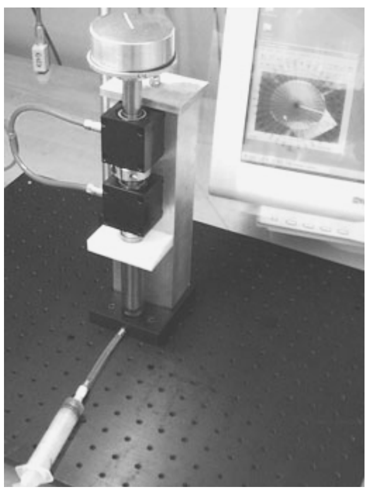
Figure 2: Close-up of Airpot without rubber casing

The data for the lab are collected using a digital video camera with a capture rate of approximately 20 frames per second. A scale is mounted above the cantilever to allow students to record the position of the cantilever manually in each frame. Students use MATLAB to plot these points and estimate the time constant of the system response. They are then asked to determine the damping coefficient empirically using the known spring constant of the cantilever which they calculate in the pre-lab assignment using the analytical result from beam theory.

A secondary effect is that the air-filled cylinder of the dashpot also creates a second, less-significant spring, which is ignored in presenting the model of the system to the students in this lab. The springiness of the Airpot becomes noticeable only as the orifice is adjusted to provide maximal damping. With high damping, the students should observe an unexpected result: the time constant is *not* identical (as predicted by the linear, first-order model presented) when the air in the dashpot is compressed versus being expanded.

5.3 1st-order inertia-damper rotational system

This laboratory explores the dynamics of a rotational 1st-order system. A shaft is mounted vertically within the air bearings and allowed to spin freely on a tungsten carbide flat as depicted in Figure 3. A cup at the base of the shaft holds honey to provide damping to the system. We use honey both because of its high viscosity and because it is environmentally benign. The level of the honey is adjusted during the lab exercises with a syringe attached at the base of the cup. An aluminum hub is mounted at the top of the shaft, and a brass ring can be put on or taken off to vary the inertia.



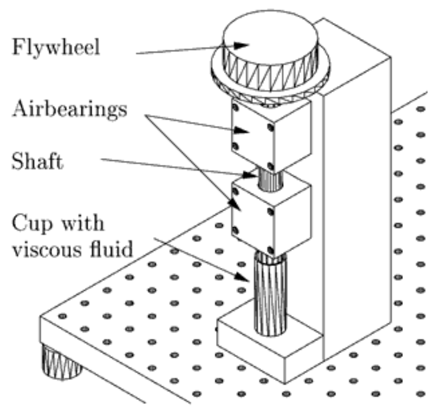


Figure 3: Rotary First-Order System

Students again use the digital cameras to record data. We have placed a radial line at the top of the hub to allow the students to record the angle at each frame in the recorded data. A clear plastic sheet with angular markings is later taped to the computer screen to facilitate this method.

The students record data for two or three levels of honey both with and without the additional inertia of the brass ring. They then use MATLAB to plot their data and use these plots to determine the time constant for each set of system parameters. As the students generally have not yet taken a formal course in fluid dynamics, we do not present an exact model of the viscous damping (e.g. as fluid shear between concentric cylinders). Instead, we focus on the system effects of changing both the viscosity and inertia of the system.

5.4 2nd-order spring-mass-damper translational system

Air bearings and steel shafting are again used in this lab, but they are now oriented to allow low-friction *translational* movement. Stainless steel welding rod (1.1mm dia) serves as a cantilever spring. The welding rod is mounted off-center of the axis of the shaft to allow the shafting to rotate slightly as the spring is deflected. This allows the spring to remain nearly linear over a deflection of approximately one centimeter.

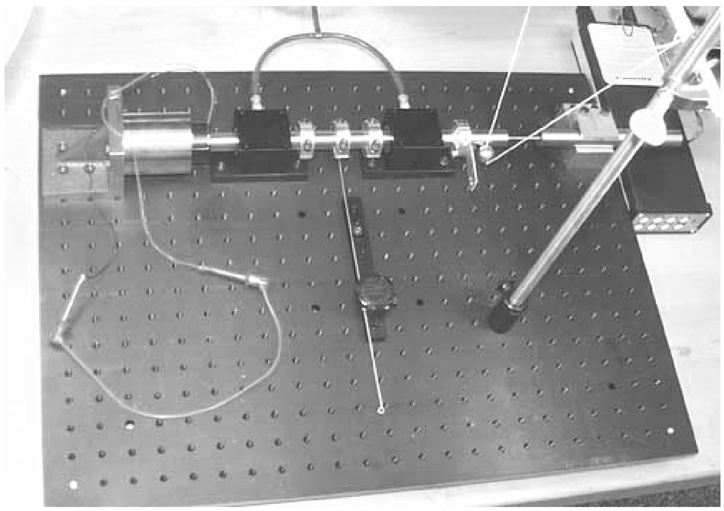


Figure 4: Second-order translational system

A voice coil actuator is mounted at the left end of the shaft as shown in Figure 4, and an LVDT (linear variable differential transformer) at the other end measures position. In this lab, the voice coil is not used as an actuator; it simply provides a variable system damping. The coil assembly is wound on an aluminum cup. Eddy currents are generated within the aluminum cup as it moves through the magnetic field of the actuator housing. This results in system damping. If the terminals of the actuator are shorted, a back emf is produced in the coils; the total damping includes both the eddy current and back emf effects.

Students vary both the damping and stiffness of the system in this lab and investigate the resulting system response. The cantilever spring is attached to the optical breadboard baseplate with an adjustable clamp to create a spring of any arbitrary length from about 5 cm to 16 cm. The system damping is varied between its two possible values by either shorting the voice coil with a patch cord or leaving the terminals open-circuited.

Students can deliver an impulse to the system by allowing a brass ball mounted on string to swing into an aluminum target plate. (Ball and target can be seen in the upper right of Figure 4.) Impulse response data collected with the oscilloscope can be saved to a floppy disk and then loaded into MATLAB. Students use their data to determine the system poles empirically. They can then replot their data against an ideal, second-order response to compare the two and verify their calculations. Initial position responses can also be taken by displacing the mass by hand.

In lab 4, the same hardware configuration is modified slightly to allow students to investigate the driven response of the system. Figure 5 shows these necessary modifications. The voice coil is now used as an actuator. A power

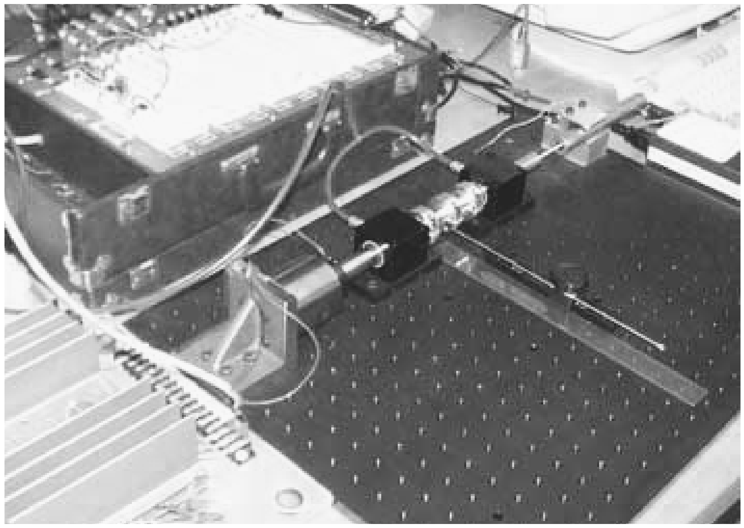


Figure 5: Driven response of a second-order system

amplifier (shown in the bottom left corner of Figure 5) drives the voice coil, using a signal from a function generator to create a step input to the system. Protoboards at each station (shown in the upper left corner of Figure 5) are used here to make the necessary connections to the oscilloscope and function generator.

5.5 First- and second-order electronic circuits

It is much easier to create a nearly ideal dynamic system using electronic circuits than it is to create a nearly ideal (e.g. low friction) mechanical system. In two laboratories on simple electronic circuits, we have our students create simple RC and LRC circuits on individual prototyping boards at each lab station. The data are again collected on an oscilloscope and then downloaded into MATLAB for further analysis. The previous mechanical laboratories have studied only the system time response. In these labs, we have the students analyze both time and frequency responses.

One of the goals of the lab is to illustrate how these first- and second-order system dynamics correspond to the dynamics of the mechanical systems the students have previously studied. Mechanical engineering students often find electrical circuits to be less intuitive than mechanical systems, so we have presented the mechanical versions first. In the circuit laboratories, we also begin to emphasize the link between the time response, frequency response, and pole locations of a system.

5.6 Op-amp circuit dynamics

In 2.003 we present three basic models to represent an op-amp: first, as an ideal element with infinite gain, so that a negative feedback connection mathematically forces the positive and negative terminals to be at identical voltages;

second, as an element with a finite (but very large) gain; and finally, as an integrator with very large gain (i.e. "G/s") (Roberge 1975). In this laboratory, we use this final model to represent an op-amp and ask the students to predict system dynamics for two elementary op-amp circuits, shown in Figure 6.

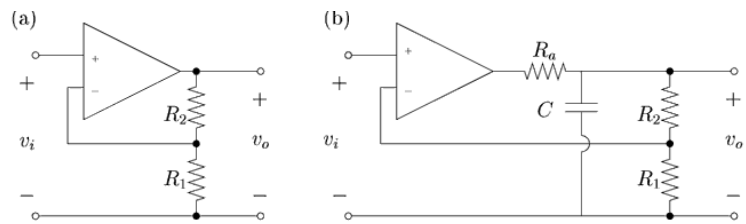


Figure 6: Driven response of a second-order system

The circuit at the left is essentially first-order, while the one at right results in a second-order response. Students predict the system pole locations and then experimentally determine the poles by performing a frequency response test by inputting sinusoids at each of several frequencies and recording the steady-state phase shift and amplitude at each frequency of excitation. The students are shown how to set the digital oscilloscopes to display amplitude and phase directly to expedite this process.

5.7 Effects of zeros in a mechanical system

Many undergraduate courses in dynamics do not give much (if any) coverage to the effects of zeros in system response. In this laboratory, we add an additional mass and spring to the translational spring-mass-damper system described in Section 5.4. An aluminum blade and a steel mass mounted at its end provide the additional stiffness and mass (as shown in Figure 7). Students observe that the lightly-damped pole pair created by the second spring and mass becomes a lightly-damped complex pair of zeros when both the driving force and position measurement occur at the first mass.

We have the students perform an automated swept sine frequency response using a Simulink model and accompanying MATLAB software which we have developed to run on the dSPACE 1102 boards on the lab computers (Lilienkamp & Trumper 1999). Voice coil actuation and LVDT measurement each occur at the larger (shafting) mass. Thus, the transfer function is measured from a voltage input to the voice coil to an output of shaft position. The position of the second mass is not measured directly in this lab.

The students use their experimental frequency response plots to determine the complex poles and zeros of the system. They then generate a theoretical Bode plot to verify their idealized (4th-order) model. Bode plots of both the experimental data and the idealized system model are given in Figure 10. It is clear from the phase difference between the two above 10 Hz that the idealized, 4th-order model misses some system dynamics. As a peripheral exercise, we take

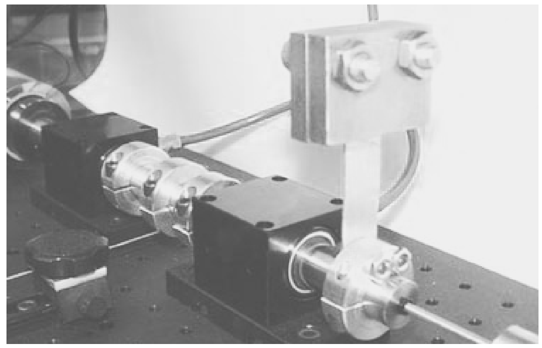


Figure 7: Fourth-order (2-mass) dynamic system

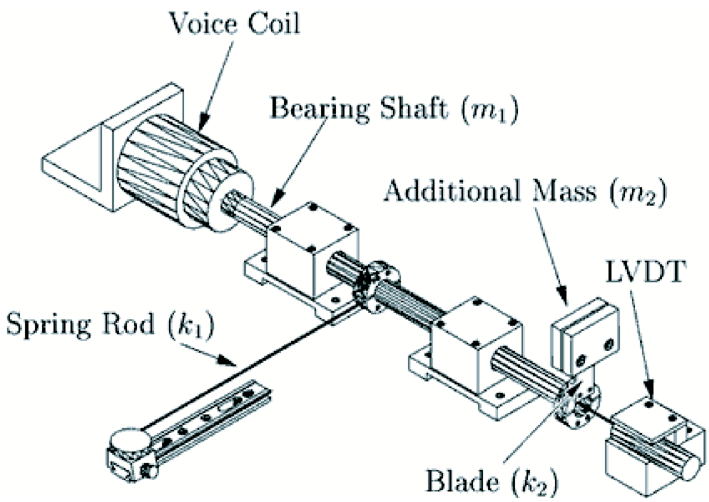


Figure 8: Schematic of the 2-mass laboratory hardware

advantage of the unexpected (and unmodeled) system dynamics to illustrate to the students the importance of verifying ideal models with experimental data. By including an additional, real-valued (stable) pole at around 30 Hz, students can obtain a much closer fit to the experimental data. In fact, what is really missing is a model of magnetic diffusion in the steel core of the voice coil magnetic circuit, although we do not expect students to have the background in field theory required to understand this effect.

5.8 Introduction to controls

In the final laboratory, students explore the effects of proportional and derivative control action. Students should note that proportional control increases the effective stiffness of the controlled mechanical system and that derivative action adds equivalent damping. They can physically play with the spring-mass-damper system (shown in Figure 5) to feel the changes in springiness and damping that result as they adjust proportional and derivative gains. Control

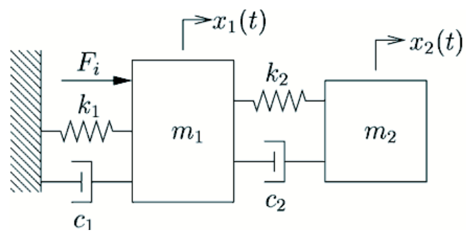


Figure 9: Idealized model of the 2-mass system

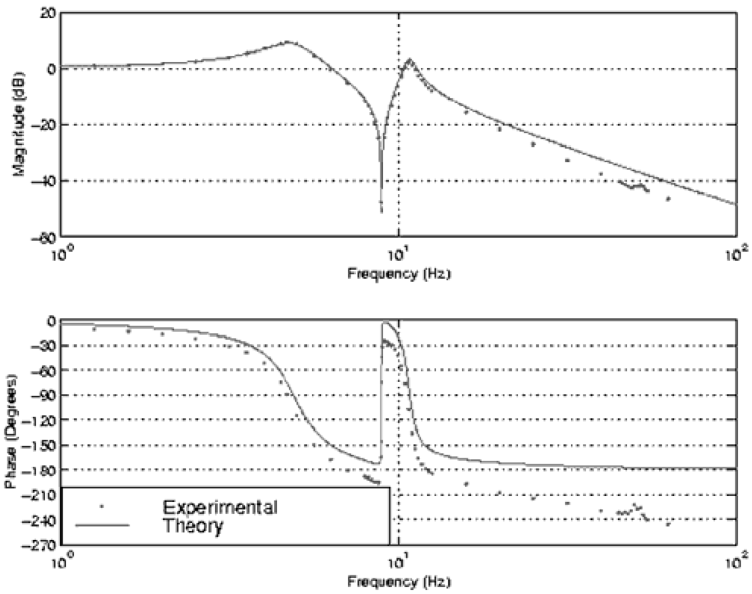


Figure 10: Theoretic and experimental transfer functions for 2-mass aystem

design is often an intimidating subject for undergraduates, and we hope this early hands-on experience will be an aid in developing an intuitive understanding for later control courses.

6 Conclusions

We have developed laboratory hardware and exercises to integrate the teaching of mechatronics into the undergraduate curriculum beginning in the second year. Laboratory projects in more advanced courses in mechatronic design and graduate-level digital control can then build on this early intuition. We hope that educators at other universities will find inspiration from both the ActivLab materials and mechatronic laboratories used at MIT. ActivLab labware in particular has been developed specifically as shareware. The concepts and equipment designs may be freely copied or modified for adaptation to a particular program or need.

Additional information about the laboratories for 2.003 can be found at the

ActivLab website:
http://web.mit.edu/2.003/www/activlab/activlab.html
The 2.737 website provides an overview of the mechatronics lab:
http://web.mit.edu/2.737/www

7 Acknowledgments

Firstly, we would like to thank Brit and Alex d'Arbeloff for their generous donation of funds for establishment of d'Arbeloff Laboratory for Information Systems at MIT, which houses the laboratory currently used for both 2.003 and 2.737.

The lab use of air bearings and our choice to keep the dynamics on a human-observable time scale were inspired by conversations with Prof. Ely Sachs of our Mechanical Engineering Department.

Many people have contributed to development of the lab projects for 2.003. Professors Gossard and Hogan taught lab sections during the first term (Fall 2001) in which the new laboratories were used. They have contributed substantially both to the overall success of the class and to the content of each laboratory project. Joe Cattell and Andrew Wilson invested several months' effort helping the authors design and build equipment for the class. Additionally, their assistance as teaching assistants during the fall of 2001 helped ensure the overall success of the laboratories.

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Willem Hijmans (of Delft University) created our ActivLab website in the Fall of 2001, documenting the 2.003 laboratory experiments. He also played an invaluable role behind the scenes to help the class run smoothly during the first offering of the course. We would like to thank Professor Jan van Eijk (also of Delft) for helping to arrange Mr. Hijmans internship at MIT and for his continued support and advice.

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