

# Take-Home Lab Kits for System Dynamics and Controls Courses

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**Abstract**—Laboratories are essential component of system dynamics and controls education yet traditional laboratories are costly and require considerable space. In this project we are piloting the concept of distributed laboratories in the form of kits that students take home and work on much like a problem set. Two kits have been developed, a mass-spring-damper system and an analog filter system. The home PC provides the needed computational horsepower for experiment control, data collection and analysis while an inexpensive microcontroller handles real-time control tasks. Twenty-five kits were constructed and piloted in an undergraduate systems course.

## I. INTRODUCTION

FOR engineering students in introductory system dynamics and controls courses who need to gain intuitive feel for physical systems, the distributed laboratory is a way to explore basic concepts through a hands-on experience that uses inexpensive, custom hardware and software kits. Unlike traditional laboratory experiences, the distributed lab kit is brought home by each student and tackled on a self-paced schedule in much the same manner as a homework assignment, thus allowing each student to customize the laboratory experience to his or her learning style.

The intent of this project is to pilot an innovative approach to system dynamics and control laboratories that incorporates proven hands-on learning principles to improve student learning. The long term goals are to create program-wide distributed labs using modular hardware and software components that students take home to do labs in their dorm room. The specific objective of this project is to pilot a distributed lab for system dynamics and control to understand the strengths and weaknesses of the concept.

Lab kits whose parts cost less than \$100 when purchased in lot sizes of 100 have been designed and tested in a pilot

project. The kits contain a controller board based on a standard microcontroller chip that implements real-time control and data acquisition software and communicates with a host over a serial port. The systems under study are hardware modules that connect to the controller board. The host computer is the student's home PC running a Visual Basic application for experiment control.

Traditional, centralized laboratories have limitations. On the programmatic side, labs require physical space, always at a premium in a university. Labs must be staffed by faculty or teaching assistants which is costly. Because traditional labs typically use high-performance computers and sophisticated plants to control, the number of lab stations is generally less than the number of students which means students work in groups. Lab hours are limited. When your scheduled two hours are up, you have to leave. Once in the lab, students cannot break the rules and try something with the equipment that is off task because the helpful lab assistant is always looking over their shoulder.

Distributed labs are a novel approach to giving students hands-on experience. Rather than relying on a central facility that students come to at a specified hour with fixed supervision, students can take the lab home to explore on their own terms in as much or little detail as they wish. Recent advances in integrated microcontrollers and sensing components, coupled with careful mechanical design make it possible to replicate hardware for each student at a parts cost of under \$100 per unit. Almost all students have powerful home computers that can be harnessed for supervisory control and data analysis. For the first time, laboratories can be treated as homework assignments that are done entirely at home just like a problem set.

For this project, we focused on introductory system dynamics and control. This core engineering topic rests on a rigorous mathematical foundation that causes many students to miss gaining a physical intuition of basic concepts because they become enmeshed in the equations. Principles such as time and frequency response, resonance, poles and zeros, stability and controller performance lie at the core of system dynamics and control, but can be abstract and obtuse for first-time students. A laboratory experience is essential for students of system dynamics and control.

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## II. LAB KITS

### A. Design Requirements

The major requirements for the take home kits are:

1. Demonstrates fundamental principles (for high learning impact)
2. Rugged (to survive trips back and forth to school in a backpack)
3. Small (about the size of a large textbook for portability and storage)
4. Simple (operation is easily understood)
5. Inexpensive (under \$100 in parts cost per unit in lots of 100 units)
6. Easily manufactured by unskilled labor (for in-house assembly)

### B. Module Architecture

The lab kit modules have three parts (Fig. 1). First is the host PC running supervisory software written in Visual Basic and talking to the control board through its serial port. The PC is used for setting experiment parameters, viewing results through plots, and other supervisory tasks. The host software is easily maintained through updates, downloadable by the student. We make the assumption that students own or have ready access to a PC running Windows. From recent surveys, over 90% of students in Mechanical Engineering own a Windows PC, a number we expect will approach 100% in the next few years. School computers are available for those who do not own.

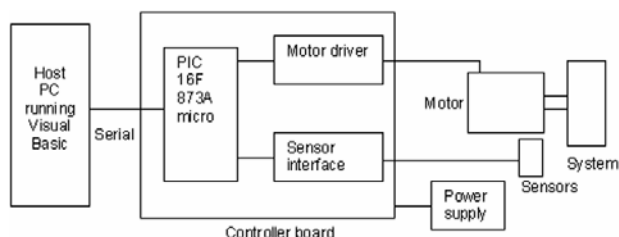


Fig. 1. Diagram of module architecture. The PC controls the experiment and collects data. The controller board reads sensors and drives actuators.

Second is the control board, a custom 2-sided printed circuit board containing a PIC16C873A microcontroller clocked at 4 MHz that performs all real-time control tasks. The microcontroller has an on-board, 10-bit analog-to-digital converter for reading analog sensors and PWM output for driving a small DC motor. The board is powered by a 12 VDC, 0.5 A wall plug power supply that also provides power to sensors and motor.

Third is the dynamic system that the student tests, controls and observes. Sensors measure system output and are used by the real-time controller and sent upstream to the PC for display, plotting and analysis. The dynamic system can be integrated onto the control board or be a separate unit the plugs into the control board.

Two lab kit modules were designed and constructed in lots of 25 for the pilot project. One module is a fourth-order mass spring damper (MSD) system that approximates a quarter-car suspension. The other is an analog filtering (AF) system where passive resistor and capacitor networks are constructed by students and applied to music and other sound sources from the PC to hear and analyze the effects of first order high and low pass filters.

### C. Mass-Spring-Damper System

The MSD system teaches principles of time and frequency response, resonant systems, and the effect of parameter changes on a system. It is implemented as a vertical stack of masses and springs configured in a classic quarter car model with a lower mass connected to the driving input through a spring and the sprung mass connected to the lower mass through a parallel spring and damper (Fig. 2). The lower spring is tied through a linkage to a small gear motor to provide a variable speed sinusoidal input. All components slide up and down on a post. Friction damping is implemented by a rubber band squeezing a foam ring against the shaft. Parameters are changed by replacing springs and masses from a collection included with the kit. Removing the top mass and spring reduces the system to a second order model. Ring magnets are fastened to the masses with matching Hall effect sensors on the control board to measure mass positions. An optical sensor on the drive link is used for motor speed control. The system was designed to minimize parts cost and assembly time. For example, all components, including the motor and sensors, attach directly to the circuit board to eliminate most wiring and connectors. The circuit board is also the main vertical structural support to position the sensors near the masses.

The host program on the PC displays a real-time graph of the mass positions (Fig. 3). Students can specify a particular drive frequency and record position output amplitude to develop measurement based Bode magnitude and phase plots. Releasing the system from an initial condition provides a step response. Effects of damping on resonance for second and fourth order systems are studied by using a tighter rubber band on the foam. Other simple experiments are used to measure or identify values of springs, masses and damper.

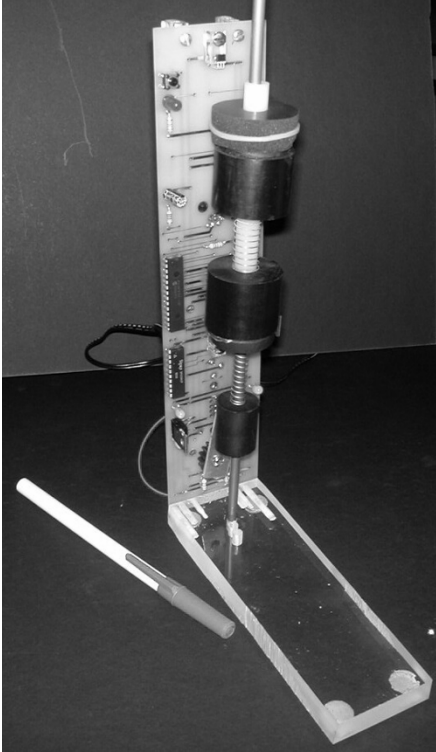


Fig. 2. Prototype fourth order mass-spring-damper system.

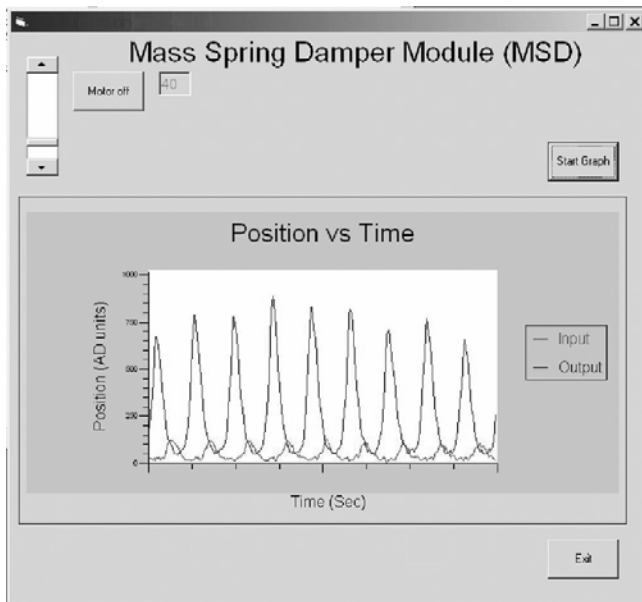


Fig. 3. Screen shot of MSD system control program on PC.

#### D. Analog Filter System

The AF filter teaches principles of first order high and low pass networks. Using an audio circuit allows students to hear the effect of the filters they build on their favorite music or on combinations of sine waves. The module is constructed on a single circuit board that connects to the PC sound card line in and line out ports (Fig. 4). Sound

files or real-time sine waves are sent to the board via the sound card. A small breadboard on the module provides a platform for constructing first or higher order passive filter networks from a kit of discrete resistors and capacitors. The student plugs headphones or powered speakers into the audio output jack and select a switch to hear either the filtered or unfiltered sound wave. The board has an onboard headphone amplifier with volume control. The filtered and unfiltered signals are sent back to the PC via left and right channels of the line in port on the sound card.

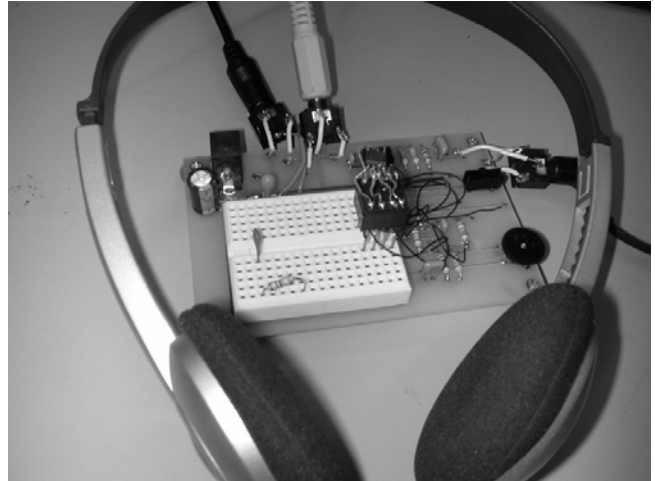


Fig. 4. Prototype analog filter system.

The host program displays real-time wave forms of the filtered and unfiltered signals, or a real-time spectrogram of the signals (Fig. 5). The student can pick any .wav or .mp3 music file to send to the module, or a single sine wave or sum of two sine waves at any set of frequencies. Single sine wave input can be used to construct experimental Bode plots.

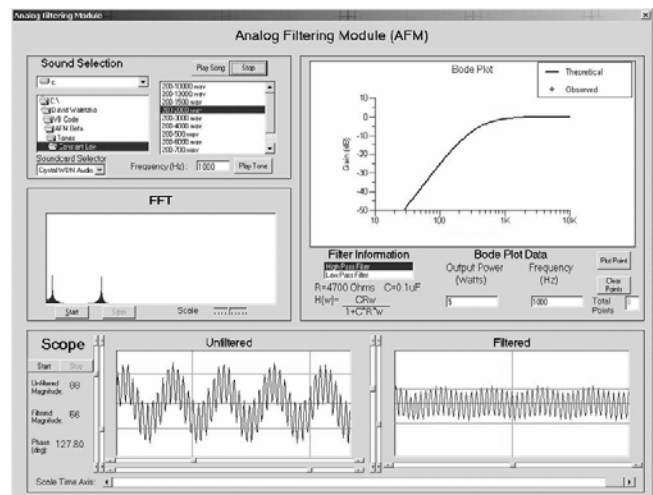


Fig. 5. Screen shot of analog filter system control program on PC.

### III. EVALUATION

Lab kits will be given to 25 of the 67 undergraduate mechanical engineering students in the beginning system dynamics course as part of their regular curriculum. The students selected to receive kits will be randomly drawn from all those in the class who own a Windows PC. The remainder of the class will serve as a control group for the experiment. Students with kits will receive alternate assignments that substitute experiments with the kits in place of some of the traditional problems that the control group will receive.

Summative evaluation will measure the effectiveness of the distributed laboratory and its impact on student learning. Summative methods will include questionnaires, observations, depth-interviews and test questions as listed in the table below.

<b>Outcome</b>	<b>Measurement</b>
Students become comfortable with applying system dynamics and control theory to physical systems.	1. In-class questionnaire. 2. Single quiz or final exam question Both measurements applied to students each semester, before, during and after study.
Students are able to set up and conduct the labs by themselves with no assistance from teaching staff.	Silent observations
Laboratory does not have a negative impact on student's final grade	Grade distributions for entire class for each semester, before, during and after study.
Students are able to identify dynamic properties of one or more real physical systems	Lab report