# AC 2009-1013: SYSTEM DYNAMICS TAKE-HOME LABORATORY KITS

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# System Dynamics Take-Home Laboratory Kits

## *Abstract*

To make the teaching of dynamic systems concepts more engaging and interesting to students, we need to relate class theory to the dynamic performance of real engineering systems including ones that are available at home. This paper addresses the design of take-home software and hardware kits that can be used to perform laboratory experiments and measurements at home to improve the understanding of system dynamics concepts in an undergraduate student population. Rather than having students perform an experiment in the university laboratory, the students are given a compact, low cost kit with which they can perform an experiment at home using their own PC/laptop. The kits are designed so that the experiments can be conducted on a provided experimental setup or can be used to perform dynamic measurements on engineering systems that are available at home such as motor powered devices and heating/cooling systems. The take-home kit consists of three components. The first component is a hardware interface board that interfaces with the student's PC/laptop and with the experiment hardware. The second component is the User-Interface Program that is loaded on the student's PC/laptop and is used to run the experiment and collect data. The third component is the actual experimental setup or the sensor system to perform the measurement. This paper addresses the hardware and software design aspects of the kits as well as the development of two experimental setups. These setups are: a DC motor with tachometer, and a temperature measurement system. The kits are planned to be initially tested in two mechanical engineering courses in the Spring 2009 semester.

## Introduction

Most Mechanical Engineering curricula include courses in system dynamics, controls, mechatronics, and vibrations. At most schools, these courses do not have a laboratory component. Even at schools that have such a component, laboratory access is often limited. *We need to supplement the course lectures with experiential learning.* Providing engaging laboratory experience is one of several challenges to effective undergraduate education in STEM disciplines as reported by The National Research Council (NRC) [1].

To make the teaching of dynamic systems concepts more engaging and interesting to students, we need to relate class theory to the dynamic performance of real engineering systems including ones that are available at home. We are addressing this by developing take-home software and hardware kits that can be used to perform laboratory experiments and measurements at home to improve the understanding of system dynamics concepts in an undergraduate student population. Rather than having students perform an experiment in the university laboratory, the students are given a compact, low cost kit with which they can perform an experiment at home using their own PC/laptop. The kits are designed so that the experiments can be conducted on a provided experimental setup or can be used to perform dynamic measurements on engineering systems that are available at home such as motor powered devices and heating/cooling systems.

A survey of the literature showed that there is an increasing interest in performing measurements and experimentation in engineering programs outside of the traditional university laboratory. Jiji et al. [2] described an approach where students build simple home experiments to illustrate solid mechanics principles using household supplies and materials. Scott [3] reported on take-home experiments in fluid mechanics to illustrate basic concepts such as hydrostatics and the Bernoulli equation. Berg and Boughton [4] reported on the use of commercially available attaché cases or electronic trainers that cost in the $200 to $350 range for conducting experiments at home in lower division electronic laboratory courses. Durfee, Li and Waletzko [5] were funded by NSF to develop take home experimental setups. They developed two setups, a fourth order, linear mass spring-damper-system for frequency response and system identification, and an analog filtering system that uses music and synthetic sound as an input. Wang, Lacombe, and Rogers [6] discuss the use of the LEGO programmable brick as a portable data acquisition system to conduct personal engineering experiments at home that can be used to illustrate engineering concepts that are covered in sophomore or junior-level laboratory courses. Long, Florance, and Joordens [7] reported on the use of a home experimentation kit for digital and analog electronics in a first-year undergraduate electronics course. A challenge in performing experiments at home is developing low cost experimental setups that are rugged, easy to set up and use by the students, and also at the same time produce meaningful results and opportunities for testing of theory. Many people have also reported work on remote control of experiments; see for example [8-13], where students perform an experiment at a distance location using the Internet as the control interface. This approach allows the same experimental setup to be used by many students, while also giving the students the opportunity to conduct an experiment at their own convenient time and location. However, it does not give the same experience as performing the experiment in person, and there could be issues in equipment availability, especially in large classes.

## Take-Home Laboratory Kit

The take-home kit consists of three components. The first component is a hardware interface board that interfaces with the student's PC/laptop and with the experiment hardware. The second component is the User-Interface Program that is loaded on the student's PC/laptop and is used to run the experiment and collect data. The third component is the actual experimental setup or the sensor system to perform the measurement. In this project, we are planning to develop and test five experiments that will be tested in various courses in the mechanical engineering curriculum at the University of Rhode Island. In this paper, we will discuss two of these setups: a DC motor with tachometer, and a temperature measurement system. In the following sections, we will discuss the three components of the kits along with our plan for testing of the take-home laboratory kits.

## Hardware Interface Board

The hardware interface board houses all the components that perform measurement, actuation, control, and communication. The hardware interface board was custom-designed and was built around a PIC18F4550 microcontroller from Microchip Technology, Inc. A photo of the developed board is shown in Figure 1. The board is designed to be mounted inside a plastic enclosure with opening at both ends. The openings are designed to allow cables and connectors to be easily attached to the board. We decided to design a custom board because there is no commercially-available board that has all the components that we need to perform all the experiments. In addition to the microcontroller, the hardware interface board includes the following:

- 32k bytes of additional RAM since the PIC18F4550 has only 2k of RAM
- A 20 MHz crystal with associated capacitors to be used as the external clock
- Status LEDs
- A 5-amp H-bridge amplifier chip for motor and heater control experiments
- A MAX232 chip for serial communication with the PC
- Connector for a 12-volts power supply
- A programming connector to download software into the board
- USB and serial connectors for communication with the PC User-Interface Program
- A 3-pin connector for connection of the temperature or vibration sensor
- A 4-pin connector for connection of the motor-tachometer setup or the heated-plate setup
- A 2-pin connector for connection of fan used in the heated-plate setup
- A 5-pin extra connector
- Several resistors and capacitors

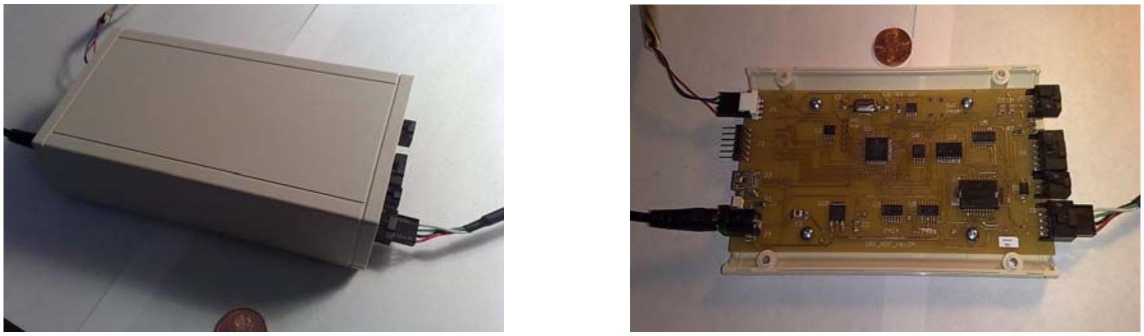


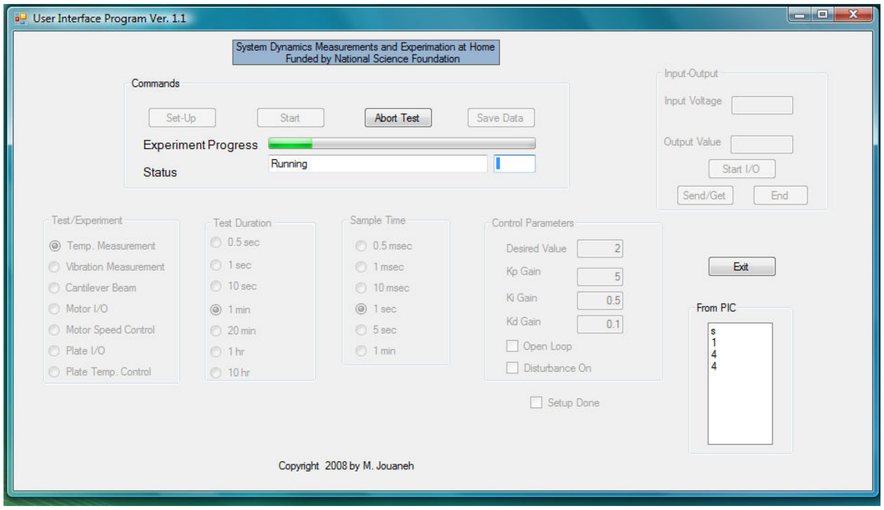
**Fig. 1** Hardware interface board

To use the hardware-interface board, the student simply connects the output of the provided 12-volt power supply adapter to the board. The student needs also to connect the serial/USB interface cable from the PC/Laptop to the board, and the cable for the specific experiment to be performed. With these connections, the experimental hardware is ready. Powering the board causes the loaded program inside the microcontroller to run. The program waits for user input from the User-Interface Program.

## User-Interface Program

A screen shot of the developed Windows-based User-Interface Program is shown in Fig. 2. The User-Interface Program was designed to serve as the user-interface for all the experiments that are planned to be performed in this project. The User-Interface Program was developed in Visual Basic Express 2008, and it communicates with the embedded program on the PIC18F4550 microcontroller through either a serial or USB connection. The embedded program was developed in C using PICC compiler from CCS, Inc. The User-Interface Program transfers the experiment settings to the PIC microcontroller, provides monitoring and control of the experiment progress, retrieves the data collected after the experiment is completed, and performs saving of the collected data to a file. The User-Interface Program does not perform any measurement or feedback control activities. All measurement, timing, actuation, control and data storage activities are performed by the PIC microcontroller while an experiment is running.

To use the User-Interface Program, the student first selects the *Set-Up* command to set the parameters for the particular experiment. These include the selection of the type of experiment such as temperature measurement or motor speed control, the test duration time, the sampling time to record the data, and, if applicable for the particular experiment, the feedback control parameters. Once the experimental parameters are selected, the user checks the *Setup Done* check box. This disables all the *Set-Up* menus and enables the *Start* command, which upon pressing it, the experiment starts. The experiment progress is indicated by a progress bar, but the user can abort an experiment by pressing the *Abort Test* command. When the experiment is completed, the *Save Data* command is enabled, which upon pressing it allows the user to store the collected data into a file. The collected data can then be imported into plotting software such as Excel.



Status: Running

Test/Experiment
● Temp. Measurement
○ Vibration Measurement
○ Cantilever Beam
○ Motor I/O
○ Motor Speed Control
○ Plate I/O
○ Plate Temp. Control

Test Duration
○ 0.5 sec
○ 1 sec
○ 10 sec
● 1 min
○ 20 min
○ 1 hr
○ 10 hr

Sample Time
○ 0.5 msec
○ 1 msec
○ 10 msec
● 1 sec
○ 5 sec
○ 1 min

Control Parameters
Desired Value 2
Kp Gain 5
Ki Gain 0.5
Kd Gain 0.1
☐ Open Loop
☐ Disturbance On

☐ Setup Done

From PIC
s
1
4
4

**Fig. 2** A screen-shot of the User-Interface Program

## Experimental Setups

We have developed two experimental setups to be used in the spring 2009 semester. Below is information about these two setups. Additional experimental setups are currently being developed to be used in later semesters.

### *DC Motor with Tachometer*

This experimental setup is useful in illustrating concepts such as time constant, system order, linearity, and the effect of different control actions on the behavior of the system. The experimental hardware consists of a small DC motor (Transicoil 1121-110 DC Servo Motor Tachometer from Servo Systems, Inc.) with a built in tachometer (see Figure 3). The control input to the motor is supplied from the PWM output of the micro controller through the H-Bridge amplifier. The speed of the motor is measured from the tachometer using the 10-bit A/D converter on the micro controller. Using the User-Interface Program, the student will be able to perform the following **Speed Control Experiment**:

- Perform a calibration test to relate the steady state speed of the motor to the input voltage. This is done be selecting the *Motor I/O* experiment from the experiment list. This test will reveal any nonlinearities in the response such as those caused by friction.
- Perform an open-loop step response of the motor-tachometer system using different voltage inputs.
- Control the speed of the motor in closed loop fashion by setting the PID control gains and the sampling interval. The last two activities are performed when the student selects the *Motor Speed Control* experiment from the experiment list.

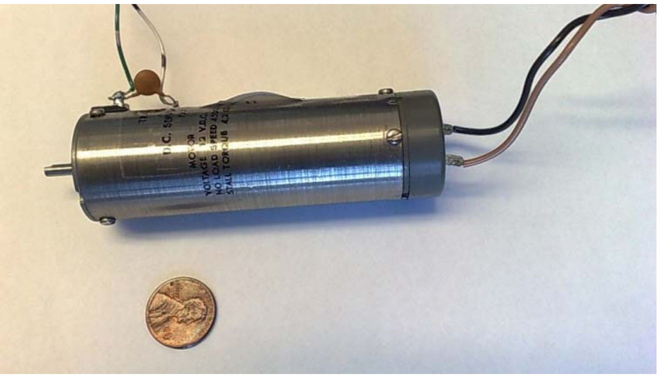


**Fig. 3** Motor-Tachometer Setup

A motor is a second-order system, but it can be approximated with a first-order model if the time constant of the armature circuit is small compared to the time constant associated with the inertia. The step response data can be used to verify that a first-order model is adequate. Furthermore, by determining the time constant from the step response data, this test can reveal whether the time constant is dependent on the input magnitude (true if system is nonlinear), and how its value changes as the inertia driven by the motor is changed. A plot of the open-loop speed response of the motor subjected to a 7 volt input obtained by the Kit is shown in Figure 4. The plotted speed of the motor is shown in voltage units. Also shown is the fitted model that includes the *RC* filter whose time constant is 0.01 s.

*Temperature Measurement Setup*

This setup uses a thermo-transistor temperature sensor (LM35C metal package from National Semiconductor) with three wires. The sensor can operate over a temperature range of -10 to 110 °C, and we have enclosed it in a protective sealed casing (see Figure 5) so that it can be used to measure the temperature in different environments such as air and in liquids. Using this setup, the student will be able to perform timed measurements on the response of many engineering systems that are available in the home such as heated/cooled fluids, and heating/cooling systems. Below is one of the activities that are planned for this setup:

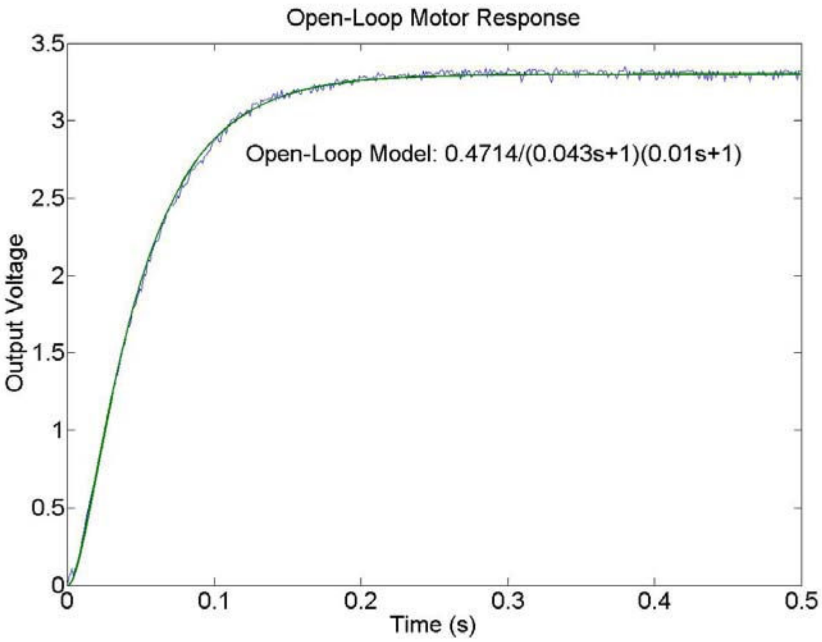


**Fig. 4** Open loop speed response of motor-tachometer system

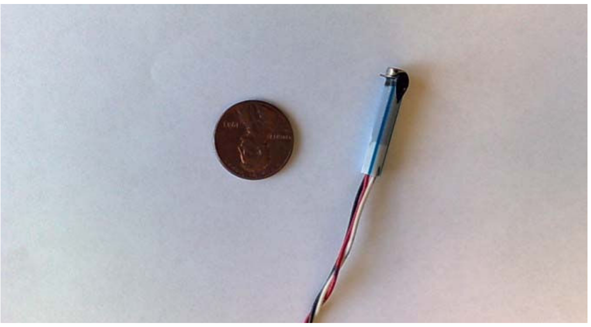


**Fig. 5** Photo of the developed temperature sensor

**Liquid Temperature Measurement Experiment:** Measure the temperature of a set amount of hot liquid (e.g. 8 oz and 16 oz) that is set to cool in a cup. This experiment can be used to investigate the concepts of thermal capacitance (by using different liquid volumes), thermal resistance (by using glass and Styrofoam cups), and the three modes of heat transfer: conductive, convective, and radiative.

If the temperature vs. time data deviates from a straight line at high temperatures when plotted on logarithmic coordinates, then heat loss due to radiation is significant. The effects of radiative heat loss can be studied by using liquids of different colors (water, black coffee, and coffee with creamer).The effects of convective heat loss can be studied by using a fan (or hair dryer) to blow on the cup at different speeds while it cools. A plot of the temperature of water measured by the take-home kit is shown in Figure 6, along with the fitted model. Note that the linear model is less accurate at higher temperatures, where radiative loss is more significant.

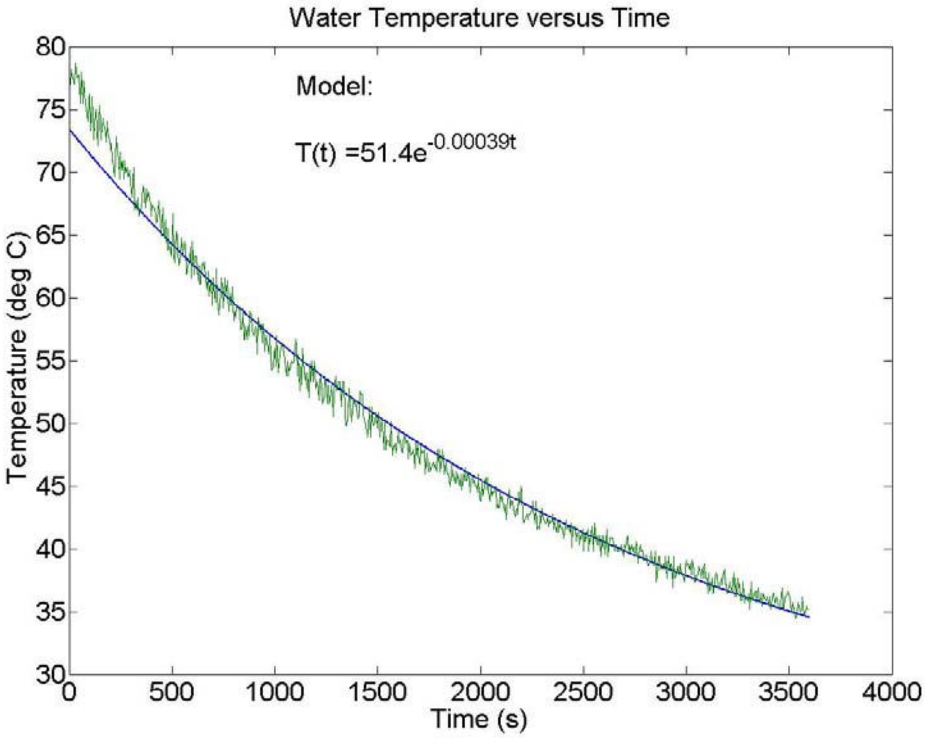


**Fig. 6** Temperature of water in Styrofoam cup obtained by the take-home kit

## Plan for Conducting Experiments

The goal of this project was to design a low cost take-home kit and associated educational material to be used in improving student understanding of system dynamics concepts. The project started in June of 2008, and at time of writing this paper, we have completed the design and coding of the User-Interface Program and the embedded program in the microcontroller, and completed the fabrication and assembly of 55 hardware interface kits, 25 motor-tachometer setups, and 50 temperature sensors.

The two experiments discussed above are planned to be first tested in the spring 2009 semester. The Speed Control Experiment will be tested in the senior level Computer Control of Mechanical Systems course (MCE431), a technical elective course that has an enrollment of about 10 students. The Liquid Temperature Measurement System will be tested in the junior level System Dynamics Course (MCE366), a required course than has an enrollment of about 50 students. We plan to give each student one complete kit that consists of the hardware interface board, and the experimental system. The students will be asked to download and install the User-Interface Program on their PC/laptop. The students will be given about a week to do the take-home experiment, after which they are required to submit a report on the experiment conduct.

To evaluate the effectiveness of these kits in increasing student understanding of system dynamics concepts, the students in each course will be given a survey at the beginning of the course and after they complete the experiment. In addition to the report that the students need to write on the take-home experiment, the students will be also tested on the topics related to the take-home experiment in one of the exams given in each course. The evaluation and assessment of the effectiveness of this project is conducted with the help of an external evaluator, Dr. John Boulmetis, a Professor in the School of Education at URI.

While we have not administered the kits yet, we believe that the take-home experimentation offered by the developed kits will increase student understanding of system dynamic concepts.

## Acknowledgments

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