

# Micro-controller Based Update of Inexpensive Undergraduate Control Systems Laboratory Hardware

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**Abstract** — This paper describes an updated version of the hardware used for an undergraduate control systems laboratory, and describes a complete set of laboratory experiments for an introductory control systems course using the hardware. It applies to a system described in a previous paper [1]. We continue to update the hardware and the software for this system because it is has proven to be a very successful platform on which we base the laboratory experience for our students. The mechanical and electromechanical hardware for the lab has remained nearly the same for well over a decade, but is still a reflection of modern hardware used in industry. It utilizes a brushless servo motor, a transmission element with mechanical compliance, high resolution optical encoders, and a motor controller with a current control loop. The latest update is mainly comprised of changing the controller to a micro-controller based system and a graphical user interface (GUI) written in MATLAB. The microcontroller is a 32 bit ARM based system with a floating point coprocessor and all the peripherals needed to implement the controller, including a full speed USB interface. This latest generation of the system is the least expensive, the most efficiently connected to MATLAB, the easiest to use and the most reliable in terms of both hardware and of software.

## I. INTRODUCTION

The importance of laboratories in undergraduate engineering education is well established, and it is our observation that the faculty involved in control systems education recognize this importance. It is also our observation that it is generally accepted by most Mechanical Engineering instructors teaching control systems courses that "Mechanical Engineers have little experience relating Laplace-space or Frequency-space equations to physical systems [2]," making the laboratory experience even more important in Mechanical Engineering than some other disciplines such as Electrical Engineering. However, development of effective laboratory equipment is difficult, and development of equipment that can be used to demonstrate the majority of the concepts covered in a typical course is extremely difficult. The undergraduate control systems laboratory has made use of such equipment, the Motorlab system, for over a decade. In this paper we describe the latest update of this equipment.

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The equipment described here has several advantages. First it is easily and inexpensively reproduced. Second, it can be used to develop laboratory exercises that clearly and rigorously demonstrate the majority of the concepts covered in the associated course work. Third, it makes efficient use of the student's time in completing the laboratory assignments. Finally, with very little maintenance and repair, it is rugged enough to withstand the wear accrued by running five laboratory groups of up to 16 students through the lab each week of the semester.

In the following section, Section II, the current Motorlab system, resulting from the update, is described. Section III describes the importance of the system and the update. Section IV describes the laboratory exercises using this equipment, which are closely coupled with the lecture portion of a four credit hour course.

Tightly coupling the laboratory content and lecture content of a course is effective for student comprehension and retention. The authors propose that it has the additional benefit of keeping the instructor honest by encouraging instruction of material that can be verified in lab. While not all course material must be verifiable with the particular laboratory equipment used, it is not uncommon for text books to perpetuate material that is marginally useful in solving engineering problems [3].

In the "Conclusions" section a website is given where a parts list, wiring diagrams, CAD models, and the software for the Motorlab system can be obtained. The documentation on this website has been used to produce ten Motorlab systems for the undergraduate control systems laboratory in the Mechanical and Nuclear Engineering (MNE) Department at Kansas State University.

## II. UPDATED MOTORLAB SYSTEM

The updated configuration of the Motorlab system retains much of the hardware of the previous configuration. It is shown in Fig. 1 and Fig. 2, and shown schematically in Fig. 3. The major differences between it and the previous configuration are the computer control hardware and the Graphical User Interface (GUI) on the host PC. The major components of this system are:

- Brushless motor: LA052-040E from Shinano Kenshi
- Motor Amplifier/Controller: Model 503 DC brushless servo amplifier from Copley Controls
- Load encoder: RCML15 low profile encoder from Renco Encoders, Inc.
- 24 Volt DC power supply

- Control Computer: STM32F4Discovery board from STMicroelectronics

All of the major components are still currently available at relatively low prices. The specific model of the 24 Volt power supply is not of importance. There are numerous models with similar output currents that will work with the system.

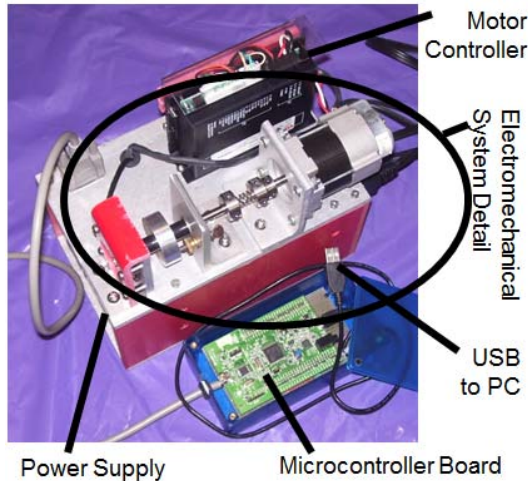


Figure 1. The Motorlab system

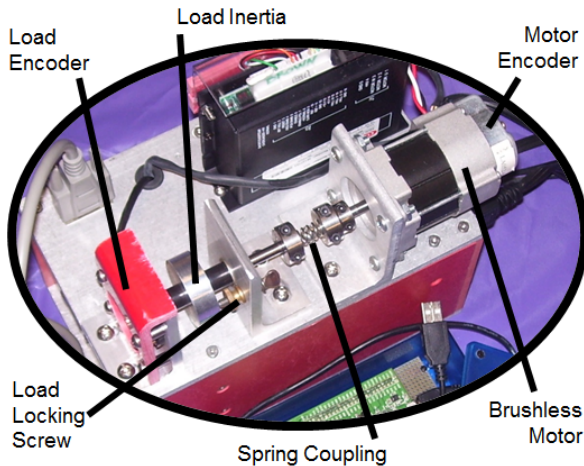


Figure 2. Electromechanical system's detail

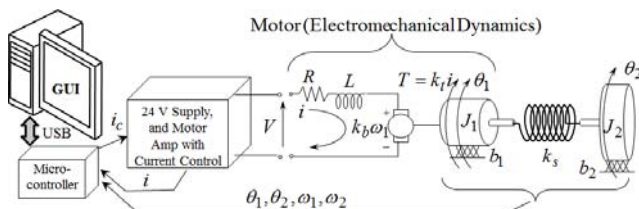


Figure 3. Schematic depiction of the Motorlab system

The Motorlab system includes two position sensors. The position of the motor shaft is measured using the encoder supplied with the motor and the position of the load inertia

is measured using a separate, modular encoder. The timer/counter peripherals on the STM32F4 microcontroller can be configured to directly interface with quadrature encoder signals, handling the encoder interfaces in hardware rather than software. Digital filters running in software on the microcontroller provide estimates for the angular speeds of the two inertias using the encoder measurements. These filters implement a discrete time version of the continuous time filter shown in Fig. 4, which includes both a derivative and a second order low pass filter. With the high resolution encoders (1600 counts/rev and 2000 counts/rev for the motor and load, respectively), these speed estimates are more than sufficient for any of the experiments conducted in the laboratory.

Position Measurement (deg)	Speed Filter	Speed Measurement (rpm)
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$$\theta(s) \rightarrow \frac{k_{rd} \cdot 300^2 s}{s^2 + 212 s + 300^2} \omega(s)$$

$$k_{rd} = 1(\text{rpm}) / 6(\text{deg} / \text{s})$$

Figure 4. Speed filters used in the Motorlab system

The motor amplifier/controller includes an analog control loop that measures and controls the electric current in the motor windings, resulting in what is commonly known as a “torque controlled” motor. The bandwidth of this control loop is approximately 400 Hz. While it is possible to tune the amplifier to obtain a higher bandwidth, it is left low intentionally to enable observation of the loop dynamics with a 10 kHz sample frequency. The desired current is provided through an analog voltage using pulse width modulation (PWM) outputs from timer/counter peripherals on the microcontroller. Although the microcontroller has two digital to analog converters (DACs), they are unipolar outputs. The motor amplifier takes a bipolar analog input, which is filtered with a differential amplifier and low pass filter. To eliminate the need for circuitry external to the microcontroller, this differential voltage is generated with two 3.3 Volt PWM outputs, providing a voltage range of +/- 3.3 Volt when filtered by the differential amplifier inside the motor controller. For observation purposes the current sensing inside the motor controller is also provided as an analog output. It is sensed using an analog to digital converter (ADC) peripheral on the microcontroller and a passive resistor network to convert the bipolar signal to a unipolar signal.

Several different configurations of the system are utilized in experiments. These configurations are chosen with selections in the GUI (shown in Fig. 5) or through configurations of the mechanical hardware. With a selection in the user interface, either the motor or load encoder is used for control loop feedback. The motor encoder is a collocated sensor while the load encoder is a non-collocated sensor. Additionally, the mechanical system is changed with the lock down screw and spring coupling. And, with radio

buttons in the user interface a choice is made between speed control, position control, or an open loop system. The mechanical models shown in Fig. 6 can be realized with this system, providing a large number of variations when used in different combinations with the control mode and feedback sensor selections. This results in many different variations for laboratory exercises.

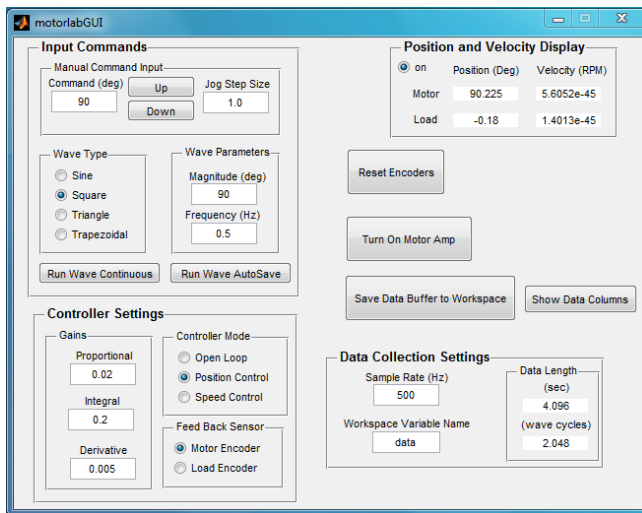


Figure 5. Host GUI for the Motorlab system.

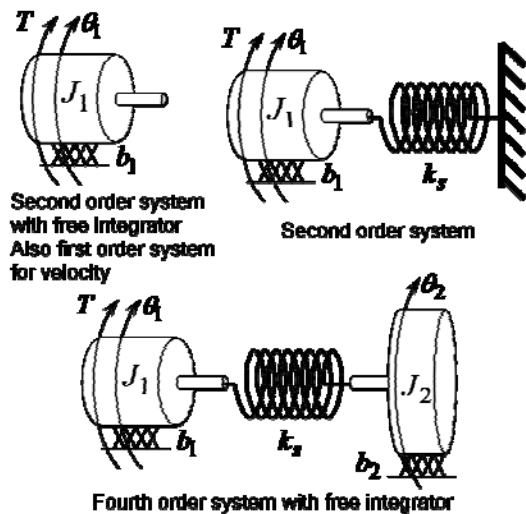


Figure 6. Variations on the mechanical model with position output

The most significant difference between the current generation of the Motorlab system and previous ones is the control computer and the software. The current generation uses the STM32F4Discovery board for the control computer. The Discovery board includes the STM32F407VGT6, an ARM based microcontroller, which has ample resources for the implementation requirements. It is a 32-bit microcontroller with a multitude of peripherals and a floating point coprocessor. In addition the Discovery board includes an ST-Link debugger chip which simplifies

software development and debugging on the board. There are several software development environments that can be used for this board that are either free or inexpensive.

The software on the board is comprised of two tasks implemented in a simple task scheduler which uses the hardware interrupt handler for context switching. This task scheduler was written as part of this project. The control and data acquisition task runs with a 10 kHz update rate while consuming only about 10 percent of the processing power available. The other task is a communications task which is responsible for communications with the host computer. This is a lower priority task that consumes very little processing power. There are a few other hardware interrupts needed for things such as the implementation of the USB protocol. ADC results are transferred through direct memory access. Much of the required functionality, such as ADC conversions and quadrature decoding, is implemented in hardware through the peripherals available on the microcontroller. There is very significant processing power still available for software growth if needed, and therefore very little attention to code efficiency is required.

The GUI on the lab station PC is implemented in MATLAB, which is also used in the laboratory for modelling and data analysis. It communicates with the microcontroller software using a virtual com port over a full speed USB port through a Windows driver provided by STMicroelectronics. The companion software on the microcontroller was modified to fit this application.

This hardware and software environment provides a robust, reliable, and versatile system that is an easily maintained system. In addition it optimizes the student and instructor use of time in the laboratory by minimizing complexity and providing direct access to the data from the system in the MATLAB command window.

### III. IMPORTANCE OF THE LATEST MOTORLAB SYSTEM

The introductory undergraduate controls class in the MNE Department at KSU has included a laboratory component with a version of the Motorlab system since 2002. This is the third generation of the Motorlab system, which is still a very good example of components in modern motion control systems that Mechanical Engineers might encounter in industry. The torque-controlled brushless motor is the mainstay of this industry and will probably be so for quite some time. Also, multiple configurations of the system allow us to demonstrate many different concepts. Continuing to develop laboratory hardware based on the same basic electromechanical hardware has allowed us to develop, maintain, and improve laboratory exercises that are effective in providing students an opportunity to relate difficult mathematical concepts to actual hardware. Furthermore, the latest generation of the Motorlab system is:

- the least expensive,
- the most efficiently connected to MATLAB, the main

- software used in the laboratory,
- the easiest to maintain in terms of both hardware and of software upgrades for the laboratory computers,
- and the most reliable in terms of software.

Using the STM32F4Discovery board as the control computer in the hardware has resulted in the least expensive version of the Motorlab system, without a loss in versatility or performance. This board is very inexpensive (less than \$20) and all software for it has been developed in the free Kickstart version of EWARM from IAR Systems. EWARM is a professional integrated development environment for ARM processors. Previous versions of the Motorlab system have used either a motion control card inside the laboratory station's PC or a separate PC running LabVIEW Real-Time, both of which cost thousands of dollars per station.

Using a virtual com port over USB, which is hosted on the microcontroller, has resulted in an efficient and fairly simple to implement interface to MATLAB. This has allowed us to write the GUI in MATLAB itself so the control and data collection are directly connected to the MATLAB command window without the need for bridging software or import utilities. This has resulted in less time spent by the students collecting data, and more time to focus on the lessons in the laboratory exercises.

The latest generation the Motorlab is also proving to be the easiest to maintain. In terms of hardware a slight modification of the spring coupling hardware has made it much easier to change the springs which are frequently broken during frequency response laboratories where the students purposely excite the resonance. Also covering the connections to the motor amplifier with clear plastic has resulted in no broken wires to date, while still allowing the students to investigate to the connections in the system. In terms of software the new Motorlab is dependent on virtual com port support in MATLAB, an inexpensive (or free) version of a development environment for ARM microcontrollers, and a Windows driver for the virtual com port software on the microcontroller. The first two dependencies do not seem to be a concern. The Motorlab has proven compatible for MATLAB versions R2011b through to the version currently being used in the lab, R2014b. In regard to the third dependency, we believe there will be an easy fix for the Windows driver if versions beyond Windows 8 do not support the current driver. The solution would be to use a serial com port from the microcontroller with a common virtual com port chip such as those from Future Technology Devices International (FTDI) Limited.

The latest generation of the Motorlab is also proving to be the most reliable in terms of software. The previous version utilized a separate PC running LabVIEW Real-Time and a dedicated Ethernet connection between the Windows PC and the realtime box. This required that each time the students started the laboratory exercise they launch two

separate applications in LabVIEW and that the Ethernet connection in a laboratory environment with student profiles was working properly. Laboratory instructors frequently spent significant and valuable laboratory time debugging this system. Furthermore, each time LabVIEW was updated on the laboratory computers there were issues with the LabVIEW software for the Motorlab that needed to be resolved. The latest generation has run smoothly with very few issues through two semesters and two MATLAB version changes from the original version in which the GUI was developed. In general, the reduced complexity has resulted in a more reliable system

#### IV. BRIEF DESCRIPTIONS OF LABORATORY EXPERIMENTS

Students complete fifteen assignments in laboratory associated with the introductory level control systems course in the MNE Department. These laboratories progress from the fundamentals of modeling dynamic systems with differential equations and transfer functions to detailed analysis and design of closed loop control systems using methods from the time-domain and frequency domain. This progression is coincident with the topics in the lecture portion of the course. All of the labs make use of large amounts of high sample rate data from physical systems, solidifying difficult theoretical concepts for the students by giving them the ability to perform rigorous analyses.

*Intro Laboratory:* This is an introduction to the Motorlab apparatus and software and to MATLAB. The students are introduced to both as well as to how they will be used throughout the semester.

*Laboratory 1:* To whet the appetite of the students for the need to understand the theory behind control system design, they study the performance of two different position controllers. One is a proportional controller with a gain very near the ultimate gain that drives the system unstable, and the second is a proportional-derivative (PD) controller with a much higher proportional gain and significantly improved performance.

*Laboratory 2:* Using constant motor current inputs to create constant speeds, the students experimentally determine an approximation for the viscous friction coefficient of the brushless motor system shown in the upper left hand corner of Fig. 6. Then the students use this coefficient together with other motor parameters to predict the system response to an initial condition (initial speed) in MATLAB and compare it to a measured response.

*Laboratory 3:* The students experimentally determine the coefficients for the plant model of the motor-and-spring system shown in the upper right hand corner of Fig. 6. They are able to determine the inertia from the motor specification sheet. They estimate the spring constant using experimental data from the steady state deflection obtained from a constant motor current/torque. And, they estimate the damping ratio from step response. The students also compare the computed step response of their model to

experimental data from the actual system. Because the course is still early in the semester, the students are grappling with the relationships between transfer functions involving physical parameters such as inertia and standard presentations of first and second order systems using time constants, damping ratios, and natural frequencies. This lab reinforces the process of drawing connections between the mathematic language and the physical system.

*Laboratory 4:* In Lab 2, the students found a linear estimate of viscous friction in the motor. It is obvious from their data that the friction also has nonlinear effects. In this lab the students explore these nonlinear effects through simulation in SIMULINK. They use a model which includes a high coefficient of friction at low velocity and a lower coefficient at high velocity to simulate the nonlinear friction. Using this simulation, the students are able to generate a nonlinear initial condition response for the speed of the motor that closely matches the experimental data in Lab 2. They then add motor current saturation and simulate a closed-loop position control system with two nonlinearities that accurately captures the behavior of the actual system.

*Laboratory 5:* In this lab the students experiment with a proportional position controller, where the current command to the motor amplifier is proportional to the error between the actual position and the command. Also, they use a model of the closed-loop position control system to predict the system response. They compare the theoretical step response with the actual response obtained experimentally from the Motorlab for three different proportional controller gains. Then they make connections between pole locations and characteristics of the response such as the frequency and decay rate of oscillations in the closed loop response. They also make observations about small differences between the experimental and theoretical responses and connect these back to saturations on motor voltage. Further, they note that as they turn up the gain the system eventually becomes unstable despite the fact that this is not predicted by the low-order model used in the lab.

*Laboratory 6:* Motivated by the observation in the previous lab that low-order models do not usually predict the performance limitations posed by stability limits, the students use a speed controller and its models to validate a rule of thumb given in class that attempts to introduce the concept of "higher frequency" dynamics. This rule of thumb is, "*We can ignore open loop poles and zeros when they are more than 10 times larger (in terms of magnitude, which is the distance from the origin of the  $s$  plane) than the closed loop poles that result from ignoring them.*"

This lab illustrates that there are always un-modeled, higher frequency dynamics that will affect the response if they "turn up the gains" too much. The students begin to learn when it is appropriate to ignore these dynamics and also how to account for them in control design without an exact model.

For a low range of the proportional gain,  $K_p$ , the students

observe that the predicted and measured performances are similar. However, the students see that as the poles of the simple model move farther from the origin of the  $s$ -plane it is necessary to include dynamic effects from the speed filter shown in Fig.4 to explain the response. They verify the following rule of thumb using the response of the actual system and the poles and zeros obtained from the two different models.

*Laboratory 7:* Again, motivated by the previous lab focusing on "higher frequency dynamics," this lab requires the students to model the closed-loop current control system implemented in the motor amplifier and to compare the response of their model to experimental data acquired from the system.

In a previous homework in the lecture portion of the course the students are required to develop a closed-loop block diagram model from the schematic of the motor amplifier/controller provided by the manufacturer. It captures the closed loop current control model of the motor using operational amplifier circuits that the students analyze in the homework assignment. The students develop a model of the closed loop current control system using the schematic and rudimentary explanations of the power electronics. The step response of the model gives nearly an exact match to the step response obtained experimentally from the system.

*Laboratory 8:* Lab 8 provides the students an opportunity to explore the benefits of including integral control using the speed control configuration of the Motorlab apparatus. It is modeled simply, ignoring all higher frequency effects beyond the first order model of the inertia and friction. The students compare proportional controllers to proportional-integral controllers in terms of command tracking and disturbance rejection. The disturbance is manually injected by the students grabbing the motor shaft. At this stage in the semester the students are capable of performing many detailed calculations relating the closed loop system to the open loop system. This simple model provides an opportunity to reinforce many of these calculations with real data and without confusion.

*Laboratory 9:* At this point in the semester the students are learning the root-locus technique and are now capable of analyzing the effects of adding zeros to the controller. In labs 5 and 6 they have observed the limitations of using simple proportional control on two different systems, but have anecdotally observed that a PD controller might be used to improve this. In the position control system they have observed that as they raise the gain of the proportional controller that better control of the system can be obtained, but this improvement is limited. The gain can only be raised so much before the response becomes very oscillatory. Furthermore, the settling time cannot be improved. In this lab the students compare the proportional controller to a proportional-derivative (PD) controller. The PD controller adds a zero to the open-loop TF, changing the shape of the



root locus by pulling the poles to the left. This is the students' first hands on experience of adding dynamics to the controller to shape the dynamics of the closed loop system in the design process.

*Laboratory 10:* Because the introductory controls course in the MNE Department at KSU focuses on frequency response as its main design technique the students have quickly moved through root locus and are now focused on frequency response. This is a very foreign concept to most Mechanical Engineering students at this stage. In this lab the students experimentally relate frequency response calculations to an intuitive system with resonance. They determine five data points for the frequency response of the motor-and-spring system of the Motorlab (upper right hand corner of Fig. 6). Then the students compare their experimental response data to the theoretical frequency response from a transfer function they develop, tweaking the parameters of the model to obtain a close match. Sine waves generated by the microcontroller are used as input to the motor current, and the students begin the lab by experimenting to find the resonant frequency of the system. While the students are searching for resonance, they begin to understand the basics of frequency response including amplitude ratios and phase shifts.

*Laboratory 11:* The students examine the closed loop response of a fairly complex, higher order mechanical system, where there are many significant poles and zeros, and where there are substantially dominant poles and zeros with less dominant poles and zeros causing superimposed effects in the response. This mechanical system includes the inertia coupled by a spring, as shown in the bottom of Fig. 6. The students use full PID control with a position controller for this system. For most of the lab the students use the motor encoder for feedback, but they also use the load encoder for feedback, demonstrating the destabilizing effects of a non-collocated sensor. Independent of which sensor is used for feedback, data from both sensors is available from the experiments. Common to nearly all the labs, the students are required to develop models for the system, validate the model with experimental data, and make connections in the theory from the lecture part of the course.

*Laboratory 12:* In the lecture portion of the course the students have now had the opportunity make mathematical connections between the open-loop and closed-loop frequency responses. In lab 12 they experiment with frequency response design for the velocity control system using a PI controller. They simply adjust "the gain," not moving the zero of the PI controller. Then using their data and models they make connections between closed loop bandwidth and open loop crossover, between bandwidth and the dominant closed loop poles and the speed of the step response, and between the root locus and frequency response design techniques.

*Laboratory 13:* This is an investigation of the importance of low-frequency gain on the tracking capability of a control

system. The students use two PID controllers in the position control system of the Motorlab apparatus, both with the same crossover frequency and bandwidth, but with different open-loop, low-frequency gain. The students compare the tracking capabilities of the two closed-loop systems using motions generated from trapezoidal velocity profiles. This is not only an opportunity to reinforce an important frequency response design goal, but also to introduce command shaping, which is important in industry.

*Laboratory 14:* As a culminating experience the students tune a PI controller for the velocity control system of the Motorlab apparatus. The nominal dynamics of the plant,  $G_m$ , are known to be first order and therefore a PI controller works well. To tune the controller the students pretend to 1) know the structure of the nominal dynamics, 2) not know specific numbers for the model (just the structure), and 3) not know the higher frequency (limiting) dynamics, as is often the case when tuning a controller. The students use numerical estimates of the system parameters obtained from previous labs, not to tune the controller, but to generate Bode plots from the models at selected points in the tuning process to understand what they are seeing in the data and what they are doing during tuning process.

## V. CONCLUSIONS

A parts list, wiring diagrams, CAD models, and the software for the Motorlab system can be obtained: <http://www.mne.ksu.edu/research/laboratories/dynamic-systems-controls-laboratory-1/motorlab>. This system has proven to be a very robust system that allows us to effectively provide hands on experience to our students.

With the exception of Laboratory 11, the laboratory experiments are closely coupled with the lecture portion of the class, with the labs reinforcing important topics shortly after their coverage in the course. The versatility of the Motorlab system has allowed us to design individual exercises to achieve this coordination. It is our observation, from experiences teaching control systems courses without labs and with disjointed labs and lectures, that this coordination aids the students in a progression from a fear of differential equations in many cases, to capabilities in relating complex mathematical concepts to real engineering systems.

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