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MATLAB AND SIMULINK LABORATORY – A BASIS FOR LEARNING REAL CONTROL APPLICATIONS

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Abstract

A laboratory for teaching computer programming and engineering concepts related to control applications was recently established in the Department of Electrical Engineering and Electronics at the Ariel University Center of Samaria. The new laboratory provides hands-on experience in the design of control systems used in different fields of engineering. The lab offers an excellent introduction to programming concepts and research concepts that are often troublesome for the undergraduates. This paper describes the general approach and practical application of MATLAB and Simulink in the frame of a laboratory for teaching control. The main aim of the laboratory is to help students gain a deep understanding of typical problems in control applications. Students prepare codes in MATLAB and Simulink, based on knowledge acquired in a preliminary course on the theory of control. These codes are further used to investigate and design various control systems. In this way, control lab assignments with models of various physical processes are performed.
Key words: *control laboratory, control systems, MATLAB and Simulink, programming.*

Introduction

One of the most important features of engineering education is the combination of theoretical knowledge and practical experience (Schmid, 2000)0. It is well known that engineering education in recent decades has become more and more powerful as modern software tools assist in solving complicated complex problems, allowing the professor to focus lectures on both fundamental and advanced concepts. Applying the theoretical knowledge to solve real engineering problems creates deeper understanding of the subject and provides motivation for students to engage in further independent research.

The importance of laboratory experiments in engineering education can never be overemphasized. One of the aims in control engineering education is to teach the techniques and theory-based design methods applied in practice in different fields of engineering. The control system design process, involving practical experiments and observing the dynamics of a real plant, offers valuable insights. For this reason, control engineering students must be in a laboratory to gain hands-on experience.

Another important question is how to prepare undergraduate engineering students to work on real-world problems. This issue remains relevant and becomes even more and more so in the recent years, when deeper knowledge is required to solve complicated design problems. Although undergraduate research is one of the possible answers, most undergraduates are not yet able to perform research during their studies. Participation in the laboratory and solving problems with elements of scientific research creates an attractive platform and provides students with basic experience which they can apply when conducting independent research in their future professional activity.

Control is an interdisciplinary engineering subject applied in electrical, mechanical, aeronautical, structural engineering and other fields. After studying basic courses in linear dynamic systems and control theory, students are familiar with the basic concepts of control however they do not have enough experience in the design of real control systems used in different areas. Further learning of most important parameters of control systems and their influence on efficiency of control is therefore essential.

Control laboratories provide students with real-world data and allow deeper learning of control systems and limitations that affect their proper design. Computer modeling and simulation tools have been extensively used to support and enhance control courses and labs. MATLAB and Simulink is one of the most popular software packages used by educators to enhance the instruction of control systems (Schmid, 2000). Hunt, Lipman & Rosenberg (2002) have presented a short, focused introduction to MATLAB. It contains concise explanations of essential MATLAB commands, easily understood instructions for using MATLAB's programming features, graphical capabilities, simulation models, and desktop interface.

Analysis and design of continuous-time control systems and solving computational problems with MATLAB avoids highly mathematical arguments, and features an abundance of examples and worked problems (Ogata, 1994, Ogata, 2002). MATLAB helps students study the Laplace transform, mathematical modeling of mechanical, electrical, fluid and thermal systems; to conduct transient and steady-state-response analyses, perform root-locus analysis and control systems design by the root-locus method; find frequency-responses and use them to design control systems. MATLAB allows students to perform state space analysis of control systems and design control systems in state space (Ogata, 2002) 0.

A data acquisition and control laboratory was established at Texas A&M University-Corpus Christi (Bachnak & Steidley, 2002)**.** The laboratory provides interdisciplinary educational and research capabilities across several science and engineering areas, including sensor technology, data acquisition, control system design, system modeling, signal and image processing, neural networks, and data visualization. The laboratory supports several courses and also offers training opportunities for computer science and engineering technology students. The laboratory is equipped with state-of-the-art instruments offering opportunities for internet-based experimentation, process variable measurements and analysis, control system modeling and design, signal and image processing, and sensor technology applications.

Teaching automatic control at Karlstad University has benefited from the incorporation of MATLAB, Simulink and the Real-Time Toolbox (Wilson, 2001). These tools allowed teaching of more advanced topics such as optimal control in undergraduate courses to engineers. Traditionally these topics have suffered from requirements of higher mathematics, non-trivial topics of numerical analysis and implementation problems. A substantial learning period was required for the students before they were able to test the schemes on actual equipment.

Control tutorials for MATLAB were designed at the University of Michigan in USA to help the students learn how to use MATLAB for analysis and design of automatic control systems ("Control Tutorials for MATLAB," 1996). The tutorials cover the basics of MATLAB, the most common classical control design techniques as well as state-space control design. There are also examples, followed through the tutorials.

Today's students often face great frustration when they work with the unfamiliar language and operating system. To address these shortcomings, the Mechanical and Manufacturing Engineering Department at Miami University introduced MATLAB as an alternative Window-based interface language to better reflect the current educational experience of students (Hamilton, 2007) With MATLAB, instructors can develop projects that enhance students' experience and give them greater insight into robotic applications.

The fundamental focus in the development of an undergraduate control systems laboratory at Ohio State University was to provide an appropriate atmosphere for instruction as

well as for independent learning ("Undergraduate Control Laboratory," 2011)0. Students spend approximately four hours in each lab and are required to prepare written reports, some for single labs, or for groups of labs (five or six reports throughout the term). Students are able to prepare prior to the meeting with short "pre-Lab" exercises.

The Lab Objectives and Requirements

The main objective of this Lab is to help the undergraduates to become more familiar with the theory of control that was taught in an introductory-level course. Students should learn to write routines allowing simulation, investigation and design of control systems from different fields of engineering, like electrical, mechanical, civil, structural, etc. The laboratory is expected to create a deeper understanding of basic general concepts of control like time response of various systems, system's root locus, Nyquist criteria, etc.

One of the important goals of the laboratory is to develop students' understanding of computational errors, which may be caused in the process of design and calculations. To this end, students in the laboratory acquire skills required for verification of results and selection of suitable calculation parameters as well as simulation algorithms.

To maintain students' focus on control design problems, the software used for computer-aided simulations of control systems should be convenient for design and analysis. MATLAB and Simulink are well-known powerful tools that can solve complex problems in engineering design (Ayasun and Nwankpa, 2006, Davidovitch and Ribakov, 2010)00. This package was chosen for the laboratory course for the aforementioned reasons. The accompanying manual is invaluable in describing the package's operation and functionality. The package provides effective computer-based design of control systems used in various fields of engineering. Interactive graphics provide excellent visualization of theoretical analysis and design, required for implementation on computer-based control systems in the laboratory.

Course Outline

The course comprises six exercises. Before each exercise a short introductory lecture (between 30 to 60 minutes) is given to introduce students to the control problem, MATLAB-based techniques of solution, and calculation properties. For each exercise, students individually prepare a code in MATLAB or Simulink and use this code to investigate a control system. At the conclusion of the laboratory session, students submit a report. In the initial labs, students receive ready-made examples of programs or their fragments for calculations. This allows the students to gain initial experience of good programming and, on the other hand, allows them to concentration on the research part of the work.

Exercise 1. Modeling Linear Time Invariant Systems using MATLAB

The main aim of the first exercise is to teach students fundamental skills in modeling classic control systems using routines that they write by themselves in MATLAB. In the first task, students are asked to check the roots of polynomial multiplication and construct polynomials from given roots by using the 'conv', 'poly' and 'roots' MATLAB functions. One of the major research aspects in this task is the analysis of root calculation errors.

In the next task, students construct two models of a control system. The first one is described by a transfer function and it is created with the 'tf' MATLAB function. The second is a state-space model and it is created by the 'ss' function. Stability of a system is the basis for any control design process. After the models are ready, several functions such as 'zpk',

'minreal' and 'poles' are applied to investigate different quantities of the systems such as the difference between inner and input-output stability, which is very important for understanding of linear system stability definitions and their properties.

The third task, studied in the frame of this exercise using the MATLAB routines, is the study of the influence of matrix determinants and eigenvalue analysis. As the eigenvalues of the state matrix are the poles of the system, they hold important information on its behavior. Hence, using the routines that students write by themselves in MATLAB to perform numerical simulations of control systems with various parameters, allows them to learn the influence of these parameters on the system's properties and performance. In this task, a special emphasis is given to the limitation of numerical analysis due to floating-point inaccuracy. In some cases this limitation has significant affect on the system's stability.

The MATLAB functions used by students in this experiment are fundamental tools that are used in subsequent lessons. Hence, it is important to become familiar with them at the beginning of the course, in the first exercise.

Exercise 2. System Time Response

Understanding the response of second-order transfer functions to step signals is an important introduction to the behavior of more complex systems. When designing a controlled system, simulation and visualization of its dynamic response to various input signals is a very important tool that gives the students a clue about the response of the designed system, which is the main goal of the design. By training students to design effective control system using MATLAB, it is necessary to teach simulation and visualization capabilities.

With this aim in mind, students are asked to simulate responses of different second order systems to step signals using analytical solutions and basic commands in order to perform graphic analysis of system characteristics such as stabilization time and overshoot. The results of the analysis are compared to predicted values, based on known data from the previous course formulas. Furthermore, the system's parameters and their influence on its response are analyzed. Finally, students repeat the exercise using a 'step' function to compute and plot the response of the control system to this kind of input.

This experiment teaches the students to simulate a system's step response. It demonstrates the influence of the system's properties on its response, emphasizing the advantages and shortcomings of graphical analysis.

Exercise 3. System Time Response

When designing a control system for a missile, the designer should take into account that the system will operate under extreme and rapidly varying accelerations. Therefore, the system's response to acceleration signals should be simulated. In such cases, the 'lsim' function of MATLAB can be used. The experiment conducted by the students in this exercise starts with a parametric study on the influence of the transfer function time constants on the behavior of a control system. Response to step, velocity, and frequency inputs is simulated.

For each response, characteristics such as change in rise time, overshoot, lag time, amplitude and phase and angle are examined. These parameters are extremely important for control systems, for example, in a structure that suffers a sudden support sink. Such structures can be modeled as dynamic systems subjected to a step input load. If the overshoot exceeds a certain allowed threshold value, the structure will be damaged.

Proportional-Differential-Integral (PID) is the most popular type of industrial controller. Understanding the design rules of PID controllers is essential for every practical control engineer. Therefore the final task in the exercise is to design a PID controller for a submarine

circular motion system. The design is based on trial and error in order to reach a desired settling time, steady state error, and overshoot values. The goal of this experiment is to provide students with the basic intuition in understanding the role of PID controller components and tuning of their parameters.

Exercise 4. Simulink

The main objectives of this lab are mastering visual programming in a Simulink environment and its application to study the properties of filters and control systems. In the first two tasks students learn to program first-order real-time filters and realizable differentiator. Programming is based on transfer functions and differential equations. Students must consider the accuracy and quality of filtering for specified types of signals and noise, and select appropriate values of filter parameters. The final two labs are devoted to the simulation and design of a PID controller for models of nonlinear systems. The first lab deals with a system for control of an antenna's angular position and the second lab is focused on a robotic arm control system.

Exercise 5. Control System Design by the Root Locus Method

One effective methods used in the design of controlled system in the field of control engineering, is the Root Locus Method. In some classical control design problems, the main design task is to find a gain of a proportional controller such that certain requirements are met by the system. Using to this method, the gain can be determined from the root locus graph to satisfy the requirements. Furthermore, design of Proportional-Differential (PD) and PID should be performed based on this method.

Students must determine the gain values for several transfer functions by plotting the root locus for each system using the 'rlocus' MATLAB function. In the course of the design work, the relationship between the locus and the transfer function parameters is emphasized. Next, PD and PID controllers are designed for two additional systems with a desired steady-state error as well as stability time and overshoot values. Closed loop systems responses to step and velocity input signals are simulated to visualize the behavior of the designed system. In the final task, a PD controller for a radar angle control system is designed. In this experiment students investigate the behavior of a closed-loop system, designed using the root locus method, and gain experience in selecting its parameters.

Exercise 6. Nyquist Criteria and Control System Design using Bode Diagram

Another controller design method is based on Nyquist stability criteria and Bode diagrams. The advantage of this method is its ability to shape frequency responses of the control system and assign system's gain and phase margins.

The purpose of this exercise is to acquaint students with MATLAB tools for plotting Bode and Nyquist diagrams. The exercise contains stability check and controller design for several systems using Nyquist criteria and Bode diagram. For each system, students check the influence of different gains values on the system's phase and gain margin. They then conduct a simulation of the closed-loop system in order to examine the design results. Finally a controller is designed for a direct-current motor with a given state-space model. Students gain experience in the design of controllers using Nyquist criteria for stability and Bode diagrams.

Using MATLAB for Structural Control Applications

Problem definition and guidelines for a set of benchmark control problems for seismically excited nonlinear buildings have been recently proposed (Ohtori, Christenson, Spencer, & Dyke, 2004). A nonlinear evaluation model that portrays the salient features of the structural system has been developed. Evaluation criteria and control constraints have been presented. The task was to define, evaluate, and report on proposed control strategies (including sensors and control algorithms). To illustrate some of the design challenges, a sample control strategy employing active control with a linear quadratic Gaussian control algorithm was applied to a 20-story building (Ohtori, Christenson, Spencer, & Dyke, 2004).

To perform research in the field of structural control graduate students should perform numerical analysis of different dynamic models subjected to various earthquakes. It is important to monitor structural data, especially in large systems. To this end, a dynamic model of a plane structure was developed. The model is described in three fundamental tables prepared in EXCEL spreadsheets. The tables include definitions of nodes, elements, and degrees of freedom.

MATLAB functions and codes were prepared by students to extract the data from an EXCEL file and create MATLAB variables containing the structural properties. Based on the imported data, the functions follow the next stages:

1. Creation of the structure's stiffness matrix by applying the stiffness method.
2. Creation of the structure's mass matrix.
3. Using Guyan and Ritz transformation (Craig, 1981), applying constraints, degrees of freedom (DOF) dependencies and condensation, to the mass and stiffness matrices.
4. Calculation of the damping matrix by assuming proportional (Rayleigh) damping (Chopra, 1995).
5. If supplemental dampers are used, a matrix that relates the forces in the dampers to the forces in direction of the DOF is calculated.
   Finally the structural properties are obtained in an array containing its static and dynamic characteristics.

A MATLAB function named 'modeldraw' was created. It draws a scheme of a structural model, describes the elements' numbers as well as nodes and degrees of freedom of the structure. If supplemental dampers are used, they are also drawn.

6. After a dynamic model in the DOF space is created, it is transformed into a state-space model by an originally developed MATLAB function named 'str2ss.' Structural dynamic responses to different earthquakes can be simulated using the linear simulation function 'lsim' from the MATLAB Control System Toolbox (Control System Toolbox User's Guide, 1999).

The first advantage of simulation using the ODE solver is its flexibility (Arnold and Polking, 1999). When observing optimal solutions of problems generated by a large number of simulations, a wise use of this method might save a lot of time. This benefit is obtained because the developed routines allow the user to terminate simulations of non-optimal control solutions. The second advantage is that ODE simulations can also be used for the analysis and design of controls of non-linear systems, which are more complicated and are not straightforwardly supported by MATLAB Control Toolbox.

Course Effectiveness, Evaluation, and Discussion

Konstantin Stanislavski, a prominent theoretician of Theatre Arts, developed a well-known concept of super-objective that would carry this "through line of action". Without solving super-goals, theater loses its ability not only to entertain the public, but also to develop it. Stanislavski called this super-objective the "final goal of every performance." The same

approach can be seen in the area of higher education. In the view of the current paper subject the super-objectives are:

- developing the students' research skills,
- offering students' well-known powerful computer-based tools that can solve complex problems in engineering design,
- developing students' understanding of computational errors, which may be caused in the process of design and calculations.

A special questionnaire was prepared to evaluate the effectiveness of the new laboratory in control engineering. The questionnaire was completed by students who attended the laboratory course in the last two years. Table 1 lists the 14 items of the questionnaire. For each item, students were required to choose the most appropriate response of five possible answers.

Table 1. Evaluation Questionnaire.

Item No.	Item	Not at all	Slightly	Moderately	To a large extent	To a very large extent
1	Extent of early computer programs use					
2	Extent of aid provided by lab to understanding theory learned on the topic					
3	Extent to which laboratory course is recommended for students studying other specialties					
4	Proportion of research element in laboratory					
5	Extent to which the research element in the laboratory contributes to learning theory					
6	Extent to which the research element in the laboratory contributes to a desire to specialize more extensively in control					
7	Extent to which laboratory provides assistance in other disciplines					
8	Degree of satisfaction with your studies in the laboratory					
9	Degree of congruence between the course and occupational requirements					
10	Extent to which theoretical knowledge is used in the laboratory					
11	Relationship between theoretical knowledge and its application in the laboratory					
12	Extent to which the laboratory involves skills not covered by theoretical studies					
13	Extent to which the laboratory is exposed to the applied work of engineers					
14	Extent to which laboratory is significant for courses on control topics					

Figure 1 presents the survey results. For convenience, "Not at all" and "Slightly" responses were collapsed into a single response category; Similarly, "To a large extent" and "To a very large extent" responses were collapsed into a single response category. As follows from Figure 1, although approximately 70% of the students who attended the laboratory had no or moderate previous computer program experience, most indicated that the laboratory is important for courses on control topics.
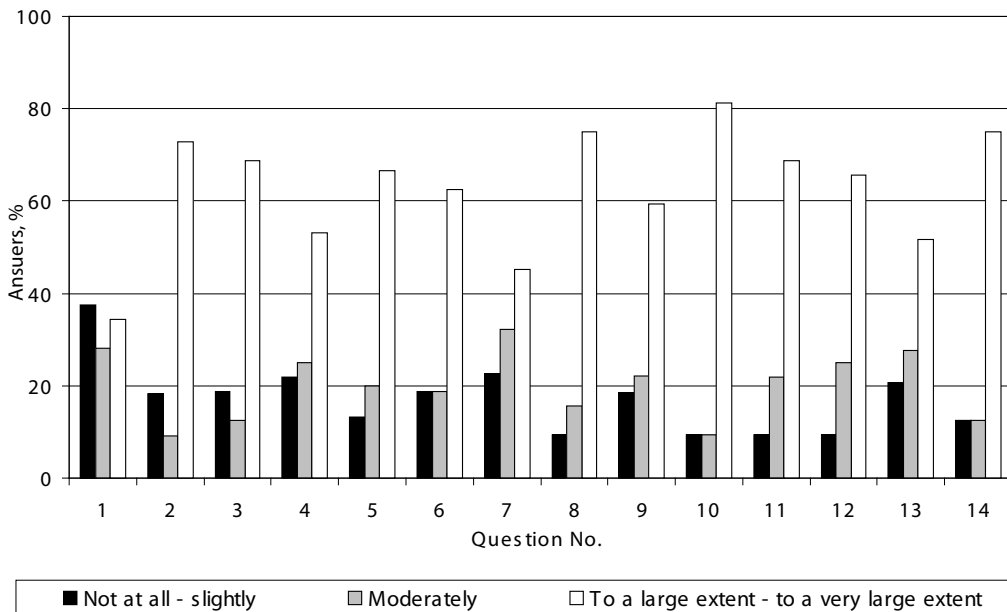

Figure 1: Results of students' survey.

According to the students, the laboratory is based on theoretical knowledge and makes a significant contribution to undergraduates' understanding of the theory learned on the topic. More than 80% of the students noted that the theoretical knowledge is used in the laboratory More than 75% of the students indicated high extent of aid provided by MATLAB and Simulink laboratory to understanding theory learned on the topic The laboratory was found significant for learning control topics as it helps the students to master their skills obtained in the frame of an introductory-level course on control theory.

Just about 45% of students feel that the laboratory can provide assistance in other disciplines, therefore more than 70% proposed to add laboratory courses for students studying other specialties. This finding suggests that it might be possible to rethink the structure of this and similar engineering courses, and integrate MATLAB more strongly in the course rather than use a more traditional combination of class lectures and laboratories. It is therefore worthwhile to explore additional engineering courses that combine theoretical and practical materials, and evaluate the relative proportions of theoretical and practical learning and the effect that changes in these proportions may have on students' learning and understanding.

Conclusions

A laboratory for teaching computer programming and engineering concepts related to control applications was established at the department of electrical engineering and electronics in Ariel University Center of Samaria. The main objective of the laboratory was

to help undergraduates to master the topic and gain practice in applying the theory of control to real engineering problems. The laboratory provides hands-on experience in the design of control systems used in different fields of engineering and offers an excellent introduction to independent student research.

MATLAB and Simulink are used in the frame of the lab. Students write routines for simulating, investigating, and designing control systems. Preparing codes and their application in subsequent laboratory tasks allows students to model various physical processes. The laboratory yields deeper understanding of general control concepts.

The results of the evaluation survey strongly indicated that students feel that the incorporation of MATLAB creates a significant contribution to their understanding of the theoretical material of the course. This finding suggests that it might be possible to rethink the structure of this and similar engineering courses, and integrate MATLAB more strongly in the course rather than use a more traditional combination of class lectures and laboratories. It is therefore worthwhile to explore additional engineering courses that combine theoretical and practical materials, and evaluate the relative proportions of theoretical and practical learning and the effect that changes in these proportions may have on students' learning and understanding.

The current study, based on a single case study in a single academic institution, should be replicated in additional institutions to explore whether the incorporation of technology in engineering laboratories generates a genuine contribution to students' understanding and knowledge, or whether it is merely part of a general fad that prioritizes technology over pedagogy.

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