# IMPLEMENTING PROBLEM-BASED LEARNING PROJECTS TO SYNTHESIZE FEEDBACK CONTROLLERS USING MATLAB/SIMULINK AND STUDENTS ASSESSMENT

**Dr. Rajnish Sharma, University of Maryland, Eastern Shore**

Dr. Rajnish Sharma, an Assistant Professor in the Department of Engineering and Aviation Sciences at the University of Maryland Eastern Shore, received his doctoral degree in Aerospace Engineering from Texas A&M University, College Station in Dec. 2008. He received his Bachelor of Technology in Mechanical Engineering from Indian Institute of Technology, Kanpur in 1999. He entered the Aerospace Department at Indian Institute of Technology, Kanpur in July 2001 and received his Master of Technology degree in May 2003. He was an Assistant Professor at the University of Alabama from Fall 2008 to Spring 2012. He also got industrial experience in several multinational companies from 1999 to 2001. He is a senior member of AIAA and AAS and member of IEEE, ASME, ASEE, Sigma Xi and Tau Beta Pi. Including many peer reviewed conference proceedings, his selected publications are in IEEE, ASME, AAS and AIAA journals. His primary research interests include optimal control theory and estimation, nonlinear feedback methods, dynamic differential games, spacecraft/aircraft control, flight mechanics, mechatronics and nonlinear dynamical systems.

**Dr. Abhijit Nagchaudhuri, University of Maryland, Eastern Shore**

Abhijit Nagchaudhuri is a Professor in the Department of Engineering and Aviation Sciences at University of Maryland Eastern Shore. Dr. Nagchaudhuri is a member of ASME and ASEE professional societies and is actively involved in teaching and research in the fields of engineering mechanics, robotics, and control systems; precision agriculture and remote sensing; and biofuels and renewable energy. Dr. Nagchaudhuri received his bachelors degree from Jadavpur University in Calcutta, India with a honors in Mechanical Engineering in 1983, thereafter, he worked in a multinational industry for four years before joining Tulane University as a graduate student in the fall of 1987. He received his M.S. degree from Tulane University in 1989 and Ph.D. degree from Duke University in 1992.

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## Abstract

**I**n the quest for automatic control [1] to the real-world dynamical systems, meeting the requirements with strict design standards including ascertaining optimality throughout the phases of engineering, modeling and applications still need much more emphasis on teaching methods due to be revised and implemented. In order to customize a part of it in the engineering education, this paper attempts to present a novel approach of implementing problem-based learning projects in the class. In particular, to learn classical and modern control techniques and simulation, these types of projects can be introduced in the class projects of control systems, robotics and mechatronics courses offered to junior and senior level undergraduate students in mechanical, electrical and aerospace engineering. As in the literature, these type of activities mostly have been practiced and relied upon establishing a separate one or two credits laboratory course devoted to experiments on classical control methods and design, which certainly should be, however, it may not be offered all times as a co-requisite and this significantly causes a subtle gap to realize the practical importance of the subject while learning the theory first time. The primary objective of the paper is to introduce simultaneous need of "project-based learning" that is implementable and viable in the class for teaching the theory of automatic control techniques using real-time simulation methods as SIMULINK, Ref. [13]. Technically, the projects' implementation indeed is intended to demonstrate the classical control methods first along with an idea of establishing a sound background on the programming methods using MATLAB and SIMULINK [13].

In view of modern engineering and technology, focusing on emerging needs for the subject's knowledge, the practical understanding of modern software tools is inevitably required to suitably fit it in for resolving the challenges in the research and studies. To start the project-based learning task on implementing the classical and new theoretical techniques embedded with high level applied mathematics, there are many well-known problems in engineering dynamics, control systems, aerospace structures, space services and observations that can subjectively be opened to undergraduate and graduate level classes existed in the engineering course curriculum. The main advantage of the problem-based learning project is to simultaneously enhance the students' creativity, interest and motivation to adapt active learning of the course material. This activity also helps the students realize the subject's practical advancements as, i) To many short-term goals as performing well in the class and preparing for a culminating experience through senior design projects, ii) To the long-term goals as joining industry, higher education and the research in many directed areas in guidance, navigation and control. To meet these learning objectives for the mentioned topics, especially in the field of aerospace engineering, some of the project problems are specifically considered for designing automatic control for flight systems. The proposed activity, especially to interested students for their culminating research/senior design projects in the area of controls, also acts as an excellent primer necessitated for understanding nonlinear feedback controller, e.g. a controller design such as working with state-dependent Riccati equations that require to solve a system of coupled governing nonlinear

differential equations using state-space modeling, LQ type design, and many other solution methods in nonlinear automatic control.

As one of the main course activities, the novel part of this paper is to introduce an undergraduate level in-class project exercise of solving 2-3 extensive problems that requires developing MATLAB subroutines and SIMULINK modeling to present the method of solution and grasp the theoretical ideas in practice to use it for multifaceted analysis of the control problem given in its nonlinear version as a real-world problem. Finally, author presents a study of students' assessment, grasping capabilities and challenges to make it thorough and rewarding for undergraduate research experiences in Systems Dynamics & Controls and Aerospace Engineering.

## 1.0 INTRODUCTION

In the curriculum of the Department of Engineering and Aviation Sciences, there are two compulsory courses on Control Systems; one is purely on learning the linear (classical) control methods very first time and the other course is on familiarizing the concepts of classical control in the laboratory settings integrated with a fixed set of experiments on Instrumentations and Control using LABVOLT equipment, Ref. [14]. Author has been teaching the courses on flight mechanics, control, engineering mechanics and mechatronics since last 4-5 years and he with his learned colleagues thoroughly realize that merely presenting the theoretical knowledge of the subject is just not enough to convey the critical part of the subject, how to apply its most for the practical purposes of applied engineering and technology. Also, to provide a solid background on the course material, it is utmost important to provide some type of on-going in-class activity in which the students get engaged with a practical opportunity to apply the factual/theoretical study collectively for gaining a crispy hands-on experience. In order to fulfill this missing connectivity in the existed courses, one standard way as practiced traditionally, which is though helpful with a "realistic constraint of certain number of curriculum hours", is to instruct a separate laboratory course on the specific subject that certainly needs additional contact hours requiring much more in terms of resources as equipment, lab space, set-ups and instructor's time to manage the facility and some more extra burden on students to mandatorily take these lab credits along with the theoretical course **OR** a little simpler way what author has decided is to include some problem driven class projects in the course itself. Basically, as a main proposition, the goal is to establish a compulsory demonstrative activity in the course material. In order to exercise this thoughtful idea which is nothing but the problem-based project implementation in the course, the author introduces problem-based learning projects in the courses; Control Systems, ENGE 382 and Mechatronics, ENAE/ENME 440, for designing automatic control for aerospace and mechanical engineering problems using the known programming interfaces, MATLAB and SIMULINK. In the given project, each problem therein will require the learners to present a detailed method of solution, MATLAB subroutines, development of SIMULINK modeling, and numerical analysis including a final class presentation for the results obtained with respect to a variety of control input as open-loop and feedback mixed with different set of initial conditions.

As mentioned earlier in the abstract of the paper, the introduction of this type of project activity is also to motivate the students to envision the work for applying it in their senior design projects on aerospace/mechanical control problems and later for conducting the undergraduate/graduate research work in the similar areas. Therefore, for interested beings, the problems are chosen from the subject so that the project-based framework firstly can be utilized to gain a primer on learning the fundamentals and later the evolved approach can be extended smoothly to study and practice nonlinear numerical techniques in applied mathematics and engineering to design nonlinear feedback control for aerospace control problems such as , just to mention a few, air traffic control, space monitoring, missile guidance, bio-inspired design of unmanned vehicles & trajectory planning, space situational awareness, atmospheric reentry and optimal rendezvous.

As a gist, the advantages of implementing a project-based learning exercise are multifold. It is also intended to build a sound programming background for numerical analysis, ordinary differential equations and developing user-interactive simulation interfaces using MATLAB toolboxes, which is sort of a judicious investment to practice almost all the engineering fundamentals, not only limited for dynamic systems and controls. The problems in the project are also chosen to primarily address multiple ABET outcomes [8], especially c, d, h and k and enthuse a diversified interdisciplinary research orientation to undergraduate students' technical mindset. Moreover, unlike the usual laboratory set-ups on a fixed set of experiments that can cover only a limited number of physical systems and are available to the students only for a limited period of time, MATLAB/SIMULINK software tools [13] can be learnt for realizing controls and simulation of an unlimited variety of physical systems that can be thought of for novel design and implementation on a simulation platform without foreseeing any such risk of much damage or maintenance and are available as student version to use it for a longer period of time at their leisure.

To mention the structure of the paper, it is organized in the next five Sections. The next Section emphasizes the description of the course, "Control Systems" along with the aligned learning objectives with ABET [8] and Assessment Scheme. Section 3.0 presents the outline of problem-based project and one full example of such project including the problem descriptions as provided to the students. The 4th Section is on the discussion of the project implementation and the required efforts on the respective solutions of the assigned problems using MATLAB/SIMULINK. Section 5.0 is provided on project assessment including remarks on student assessment and future work to be implemented, followed by the final Section, Conclusions and the list of References at the end.

## 2.0 COURSE DESCRIPTION, OBJECTIVES and ASSESMENT SCHEME

For a ready reference, this Section provides the course description, objectives, and assessment scheme. 30-35% of the final grade was tentatively announced to the class project, HWs, class participation in which almost all the activities require the topic prerequisite mentioned as,

- Familiarity with computer programming.
- Knowledge of linear algebra, differential equations, basic dynamics and circuits.
- Ability to use software tools (in particular C, MATLAB and SIMULINK).

*Course Description (as included in the curriculum)*

Mathematical models for control system components. Laplace Transform and time domain methods for linear control systems. Introduction to stability theory. Root locus, Bode, and Nyquist plots. Design specifications in the time and frequency domains. Design via compensation.

*Course Objectives*

- To provide a clear understanding of how dynamic systems can be simplified and modeled by linear differential equations and their response to initial conditions and forcing functions be obtained.
- To introduce fundamental concepts associated with stability analysis and design of control systems using time and frequency response specification.
- To provide students with the ability to use modern software tools such as MATLAB for design and analysis of control systems.
- To provide an overview of concepts of design and control in the time domain and control of nonlinear systems.
- To provide students with the ability to use modern simulation tools such as SIMULINK and LabView for design and analysis of control systems.

*Course and Project Assessments*

The course is assessed using formative and summative assessments in the form of homework, quizzes, tests/finals, term project, project report and presentation. Tests, homework and quizzes will assess ABET outcomes a, b, c, h, j and k. Project/Term Paper, report and oral presentations will assess ABET outcomes d, g, i, and k. The framework based on Criterion 3 of ABET [8] is outlined below:

Table 1: ABET CRITERION FOR ASSESSMENT

| **Course Objectives** | **Course Assessment Methods** | **Applicable ABET Outcomes [Competencies a through k]** | **Extent of Coverage of ABET Outcomes 1- Some, 2-Modest, 3-Significant** |
|---|---|---|---|
| 1 | Tests, HW, Quizzes and Final Examination | a, c, h, j, k | a-3, b -2 c -3, h-1,j-2, k -2 |
| | Laboratory Demonstration Class Discussions/ internet surfing/ Term Paper/Project | d, i, k g, j | d -1, i -1, k-2 g-2, i-1, j-2 |
| 2 | Tests, HW, Quizzes and Final Examination | a, k | a -3, b-2, c-2, k-3 |
| | Class discussions/Term paper/project | g | g -2 |
| 3 | Tests, HW, Quizzes and Final Examination | a, c, k | a-2, c -3, k-2 |
| | Class discussion/internet surfing/Project/Term paper | g, i | i-3, g-2 |
| 4,5 | Class discussion, Internet Surfing | a, c, k | a-3,b-1,c-1, k-2 |
| | Laboratory Demonstrations | i, k | i-2, k-1 |

*List of Learning Outcomes*

ENGE 382 Control Systems Project with a computational/simulation project work were planned to assess it based on the following criterion. The main objective of assigning this project was to develop the learning capabilities of applied software "SIMULINK" in conjunction with teaching the subject and developing the computational skills to solve CONTROLS problems. Other important objectives which are included for assessment were as follows,

- Development of understanding of the automatic control problem, influencing parameters and the significance of units and its applications in practice.
- Knowledge of applying the known methods of solutions for practical problems and learn these usages in a programming environment.
- Learning about the team work and presentation of the engineering and technical work
- Development of writing a technical report.
- Learning about the correctness and efficacy of computed solution and present the comparison with the solution which is obtained by using the hand calculation.
- Learn the challenges and limitations of using the in-build module of the given software for a new problem.

Through the assigned class project, an attempt was conducted to meet the above objectives in the class settings. In the project description, there were 3 problems chosen from the class text and the CONTROLS' text books and a variety of tasks were assigned to learn the simulation package and then to apply it with some modifications in accordance to solve the similar problems (a modified version of the solved problems in the class demos). Finally, the task was assigned to compare and verify the computer solution with the hand calculation and report the accuracy of the results. The next section clearly elaborates on the project problems.

## 3.0 PROJECT DESCRIPTION

The class project includes a set of 3 problems selected from the different text books Ref. [2-4]. As such, just to avoid the possibility of any plagiarism, the students were not informed directly about the References with respect to the selected problems. To complete the project, the instructions are to be followed as,

- Problem 1 is *compulsory*, choose any one from other 2 problems.
- Exchange of ideas can be allowed, however, each student must submit his/her own work. The solutions must be individual and explained with the analysis of the obtained results as asked in the problem statements.
- The project report must be neat, organized, comprehensive and self-contained.
- Each problem requires a computer solution (MATLAB/SIMULINK), you need to attach a copy of subroutine (.m files) and all the results/plots/analyses obtained by using the Simulink files.
- Prepare a list of challenges including the reasons to be explained if something was not achieved to finish the problem(s).

Just to elaborate the project work and make it as a comprehensive study, the problems chosen from Ref. [2-4] are also added with many subparts, the project problems are developed as follows:

Problem 1

[P7.10, REF. [1] MODERN CONTROL SYSTEMS 11th Edition, Dorf and Bishop]

(a)

New concepts in passenger airliner design will have the range to cross the Pacific in a single flight and the efficiency to make it economical . These new designs will require the use of temperature-resistant, lightweight materials and advanced control systems. Noise control is an important issue in modern aircraft designs since most airports have strict noise level requirements. One interesting concept is the Boeing Sonic Cruiser depicted in Figure 1 (a). It would seat 200 to 250 passengers and cruise at just below the speed of sound.

The flight control system must provide good handling characteristics and comfortable flying conditions. An automatic control system can be designed for the next generation passenger aircraft.

The desired characteristics of the dominant roots of the control system shown in Figure 1 (b) have a $\zeta = 0.707$. The characteristics of the aircraft are $\omega_n = 2.5$, $\zeta = 0.30$, and $\tau = 0.1$. The gain factor $K_1$, however, will vary over the range 0.02 at medium-weight cruise conditions to 0.20 at lightweight descent conditions. (a) Sketch the root locus as a function of the loop gain $K_1K_2$. (b) Determine the gain $K_2$ necessary to yield roots with $\zeta = 0.707$ when the aircraft is in the medium-cruise condition. (c) With the gain $K_2$ as found in part (b), determine the $\zeta$ of the roots when the gain $K_1$ results from the condition of light descent.

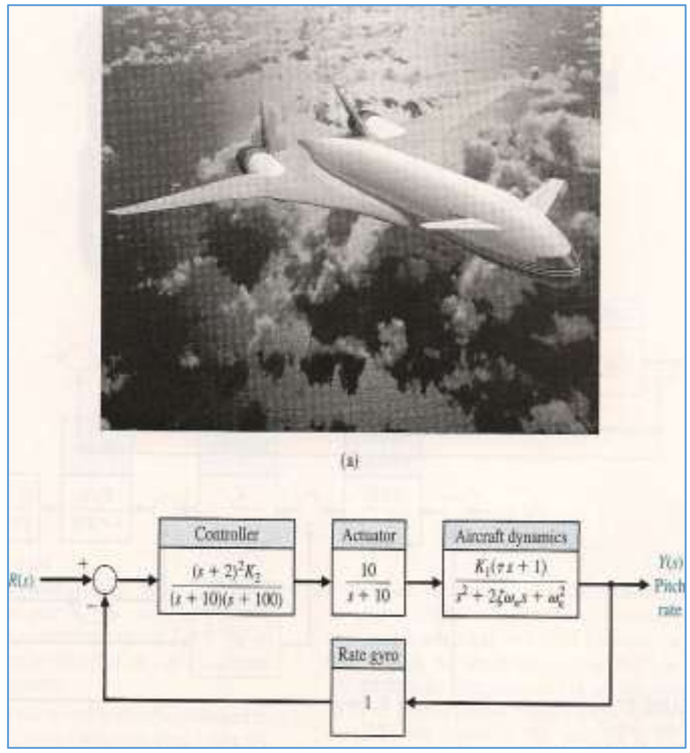


Figure 1 Sketch and Block Diagram of Feedback System

(b) For the given characteristics of the aircraft in the medium-weight cruise condition. Plot the unit step responses of the system if the dominant roots vary as $0.5 \le \zeta < 1.0$ (show it for at least for 5 values in the range including $\zeta = 0.707$).

Problem 2

[Solved Example 3-11 REF. [3] MATLAB FOR CONTROL ENGINEERS by K. OGATA]

Consider a third order system defined by $\frac{Y(s)}{\eta(s)} = \frac{6}{s^3 + 6s^2 + 11s + 6}$ .

a) Find a second order system of the form $\frac{Y(s)}{U(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$ that closely approximates the unit-step response of the given third-order system. Show the response plots for the obtained values of $\zeta$ and $\omega_n$ .

b) Find the state-space formulation of the third order system and evaluate the stability of the system. Justify the same for the second order system as obtained in part (i).

c) For the third order system mentioned above, determine the optimal control law that minimizes the performance index, $J$ as follows:

$J = \int_0^\infty (x^T Q x + \eta^T R \eta)dt$ with respect to some suitable choices of the matrices $Q$ and $R$.

Problem 3
[Problem 15.2 REF. [4] Engineering Computations and Modeling in Simulink by Yakimenko]

Consider the following two-body mass–spring–damper system (which may describe, for instance, an aircraft gear), excited by some external input $u = \varepsilon \sin(\omega t)$ (runway surface)

Assume parameters of the system to be $m_1 = 1$, $m_2 = 1000$, $k_1 = 10$, $k_2 = 2$, and $c = 5$. Do the following:

a. Develop a Simulink model for this mechanical system
b. Check the output of a homogeneous part of the system for the case when $x(0) = 0$, $y(0) = 0$, $\dot{x}(0) = 1$, and $\dot{y}(0) = 0$
c. Simulate the behavior of the system with zero ICs as a response to input $u$ (pick the values of $\varepsilon$ and $\omega$ that seem reasonable yourself).

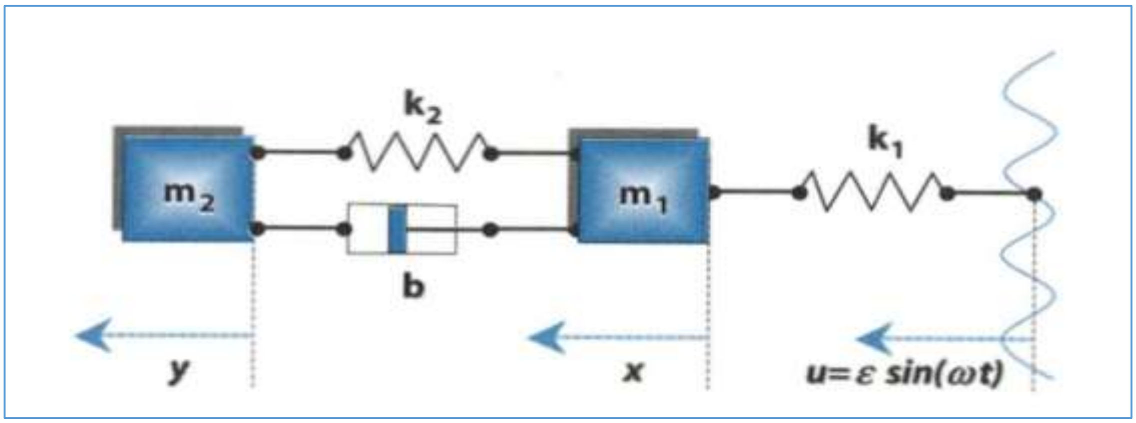


Fig. 2 SKETCH OF DYNAMICAL SYSTEM for PROBLEM 3

d. Verify the behavior of the system using State-space approach as obtained in part (c).
e. Develop a model and feedback control scheme if the spring between the masses is a nonlinear spring (The force model for nonlinear spring is $F_s = -k_{21}\Delta s - k_{22}\Delta s^3$).

## 4.0 DISCUSSION ON THE PROJECT PROBLEMS and SOLUTIONS

Prior to the project assignment, the students were assigned many homework problems to get a good familiarity with the MATLAB basics for using its tool boxes. In-class demos were also provided to learn the programming language and how to use mathematical tools for writing a subroutine for many topics as transfer function, linear algebra problems, matrices, Laplace transformation, root locus, residues and dealing with complex numbers. To fulfill the task the class text by Ogata, Ref. [5] worked as an anecdote to learn from the ready and solved control problem with MATLAB solution scripts. Next step towards developing the building blocks was on SIMULINK. Approximately 3 weeks before the project, the students were demonstrated with the demo files of Simulink Library Browser, how to create new model, then modeling continuous dynamic systems, tuning a model, PID controller, working with state-space modeling, Matlab integration using "odes" library. The in-class primer on MATLAB commands (control tool box) to write a subroutine was also provided for programming/ writing .m files.

The list of MATLAB commands discussed in the class lectures is very long, however, the typical MATLAB commands which needs to be utilized to solve the project problems are “tf, feedback, rlocus, step, and sgrid, margin, eig, lqr, place”. These commands were mentioned several times through class homework. In the beginning, the main focus was given to learn the classical control techniques using MATLAB and SIMULINK.

As mentioned in Section 3.0 three problems were chosen on different topics of feedback control systems. As it can be seen from the statement of Problem 1 which requires to draw the root locus diagram with constant damping ratio lines for finding the control solution, the underlying idea behind Problem 1 was to give an opportunity to see the usages of the MATLAB commands through the development of automatic control for an aircraft using the classical control technique. The next part in Problem 1 asks to repeat the same solution procedure for a range of damping ratios. In the solution from the students, it was expected that they justify the choice of the final solution when the intersection of constant damping ratio line with the root locus diagram occurs at two points and what the occurrence at each intersection signifies.

Problem 2 of the project was mainly to give some emphasis on MATLAB programming methods on numerical techniques for approximating the response by choosing the appropriate parameters. The last two parts of the problem were focused to show state-space modeling and present the LQ technique to solve for the optimal gains with respect to the judicious choices of $Q$ and $R$ matrices. The last part of Problem 2 also enables to look at the practical feature of learning about optimality and why $R$ cannot be zero or $Q$ cannot be negative definite.

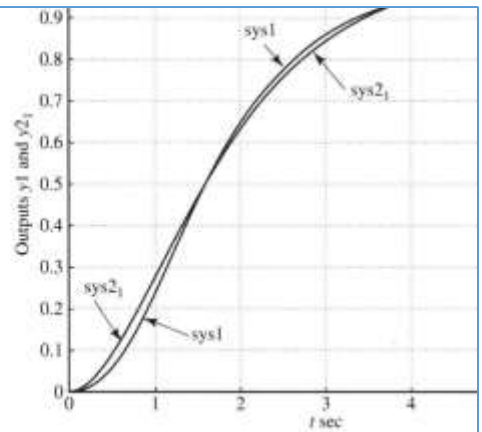


**Figure 3**
Unit-step response curves of System 1 and System $2_1$.

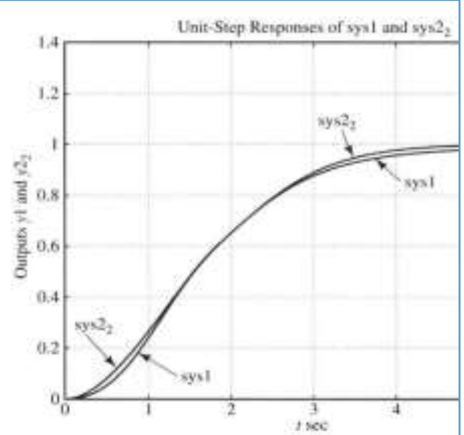


**Figure 4**
Unit-step response curves of System 1 and System $2_2$.

As shown in Figures 3 and 4, Problem 2 has 2 qualified numerical solutions. The main objective was to let the students learn how to select the appropriate one that produces the lowest error while comparing the unit step responses from the given second and third order transfer functions. Additionally, Problem 2 of the project assignment was to provide an active learning framework to the students to get a deeper appreciation of MATLAB programming on numerical analysis capabilities.

Problem 3 chosen from REF. [4] was mainly on working for the frequency-response and modeling the plant dynamics using SIMULINK. The last part of the problem was to let the students exercise on how to extend/develop the control scheme for its nonlinear version.

Just to understand the solution procedure, the SIMULINK model is shown below in Figure 5 as,

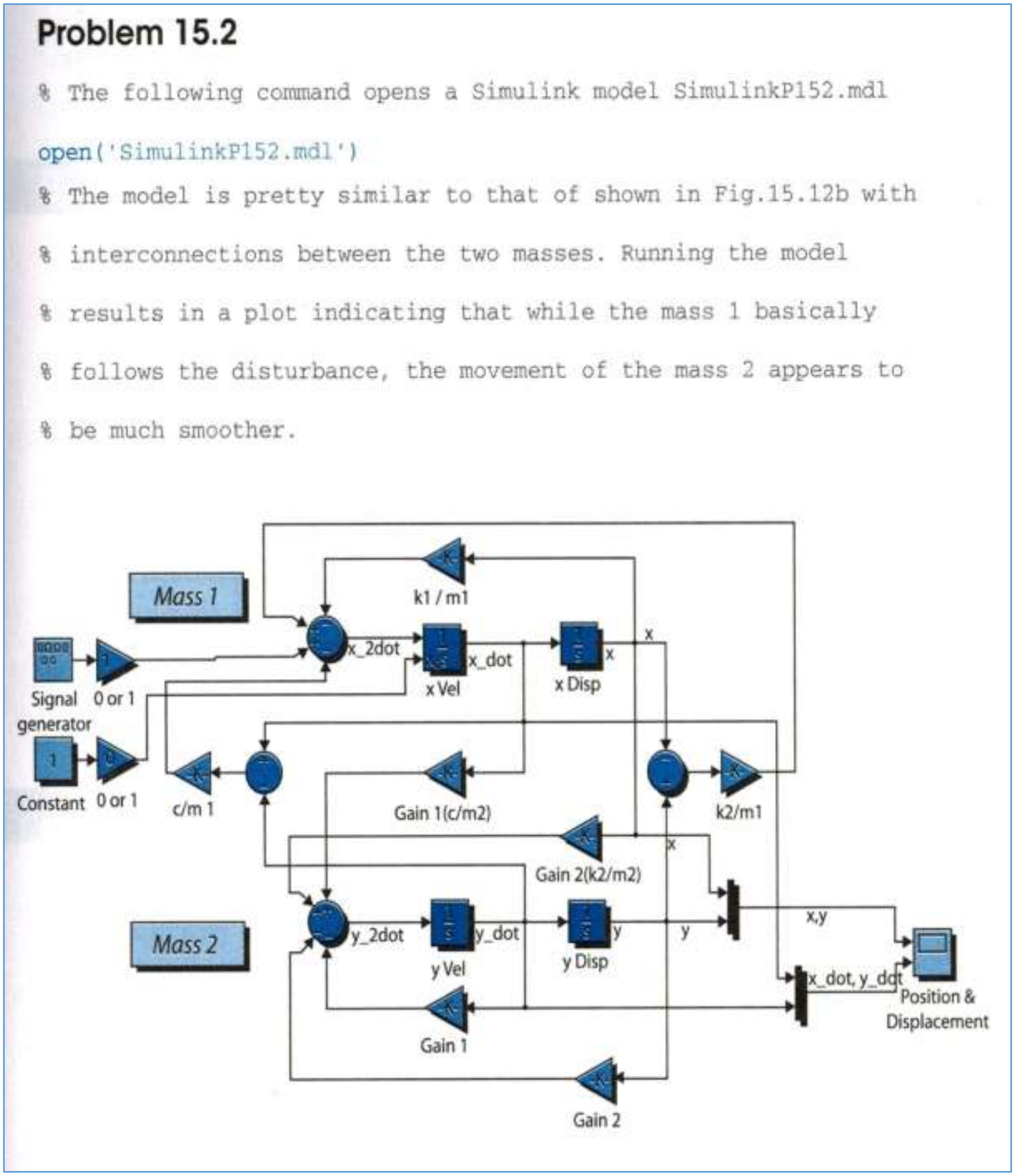

Figure 5. SIMULINK MODEL for PROJECT PROBLEM 3

Interested readers may also consider the solution manual that provides the full solution of Problem 3 (a)-(c) whereas part (d) requires the solution using state-space modeling that was covered through in-class lectures based on Chapters 9-10 of the class text [6] and homework. As asked in the part (e) of Problem 3, the modeling can be extended further as to modify it for its nonlinear version to consider a nonlinear spring (modeled as, $F_s = -k_{21}x - k_{22}x^3$ ) between the masses, $m_1$ and $m_2$. That type of problem was also assigned to ENAE/ENME 440 Mechatronics course project. Adding this part in Problem 3 fulfills another underlying objective that was to motivate students for learning integration of nonlinear dynamical system using SIMULINK and achieve a good grasp of automatic nonlinear control in the simulative environment with respect to many adaptive parameters in the problem like masses, spring constants, initial conditions and the nonlinearity of the spring with respect to $k_{21}, k_{22}$ . It was also assigned to analyze and verify the results with the available integration schemes, adaptive step sizes and time steps.

*Extension to Senior Design Project as an Implementation for Nonlinear Systems*

As it is mentioned before, through this activity, author attempted to generate much interest among the good students to choose some controls problems for their senior design projects. Author with other colleagues in the Department is currently working with some junior/senior students who really enjoyed working with the class project and accepted it to extend the similar work as presented in [9] for creating a computational senior design project in which student implements state-dependent Riccati equation method (SDRE) [11] using MATLAB/SIMULINK modeling to generate the suboptimal nonlinear control for dynamical systems. As shown in Refs. [9-11] thoroughly, for the sake of completing the discussion on what is being performed for the senior design project, the theoretical part of the technique is again stated below with schematics* as,

A continuous-time dynamical system can be represented in a state space form as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t)$$

where $\mathbf{x} \in \mathbb{R}^n$ is a vector of the system's states, $\mathbf{u} \in \mathbb{R}^m$ is a vector of the inputs, and $t$ is time. This can be described in matrix form to be

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

where $\mathbf{A} \in \mathbb{R}^{n\times n}$ and $\mathbf{B} \in \mathbb{R}^{n\times m}$ are coefficient matrices. The diagram in Fig. 6 is a graphical representation of a linear dynamical system.

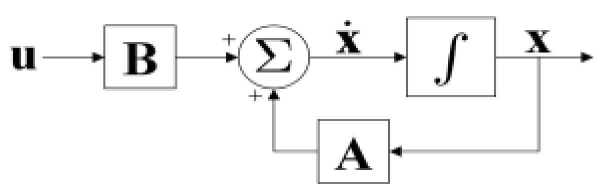


Fig. 6. Diagram of a the system

A closed-loop control system uses a control law that is based on time and state **x**. This type of system, shown in Fig. 7, can compensate for unpredicted disturbances and other uncertainties.

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* (*Some parts and Figures are directly taken from* Ref. [10], *a master's thesis work under the principal author*.)

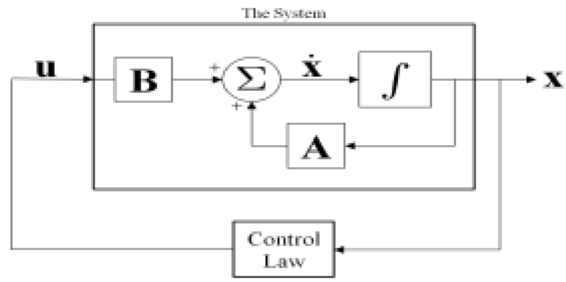


Fig.7. Diagram of a closed-loop control system

To extend it for nonlinear systems, the heart of the SDRE strategy is to factor the nonlinear model using state dependent coefficient (SDC) into a linear-like form as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t) = \mathbf{A}(\mathbf{x})\mathbf{x}(t) + \mathbf{B}(\mathbf{x})\mathbf{u}(t)$$

In this form, **A** and **B** are functions of x, and their numerical values change throughout the trajectory of **x**. There are many possibilities for the form of **A(x)** and **B(x).** The forms for **A(x)** and **B(x)** have to be decided to achieve the desired results**.** After the final choices decided for these matrices, they can be used for the SDRE technique to calculate required control input $\mathbf{u}(t)$ in the real time.

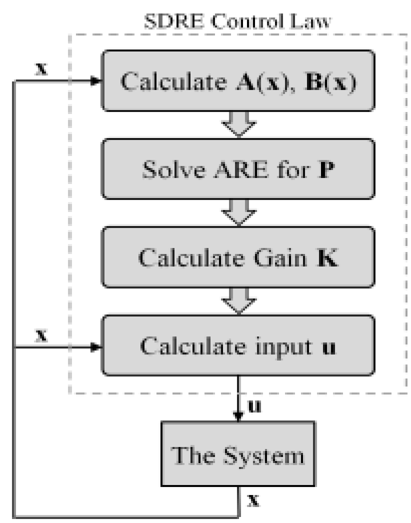


Fig. 9. Process of the SDRE technique

Fig. 9 shows a schematic of the SDRE technique. To implement it numerically, at each sample time, the following procedure is accomplished using MATLAB and SIMULINK. First, the current state vector **x** is used to calculate numerical values for system matrices, **A**(**x**) and **B**(**x**). Then, using the linear quadratic regulator [12] equations, feedback gains, P and **K** are calculated. Control Input **u** that is function of these gains, state and current time, is then calculated and applied to the system. This procedure is then repeated at the next sample time.

To implement the SDRE technique, the algebraic Riccati equation (ARE) [12] is solved at every time for each new value of **A**(**x**) and **B**(**x**). It must be noted that the solution of ARE can be easily obtained by using a MATLAB command “are” for the linear systems. This can be linked with the implementation for the nonlinear system to be approximated as a series of linear systems. Also, the shorter time increments increase the accuracy of the control law, because this decreases the amount of time that each approximation is applied. Because of its approximating nature, the SDRE technique considered here is a suboptimal solution. However, with the proper choices for the **A**(**x**) and **B**(**x**) matrices, and with the proper amount of sample times, the SDRE technique can provide a very adequate solution for nonlinear systems and the gains can be stored without much requirement of an exhaustive computational burden of nonlinear integration at each time step.

## 5.0 PROJECT ASSESSMENT ON DELIVERABLES

All the students were assessed based on the parameters and weights summarized as in the following table.

Table 2: Evaluation of the CONTROLS' Project

| **Main Performance Measures** | **Weights for Evaluation** |
|---|---|
| Understanding of the problem and units, and same for the demo files on SIMULATION. | 10 |
| Understanding of computational environment and applications ON presenting the solution methods | 35 |
| Understanding of the applied software and easiness to replicate the given solution process | 25 |
| Team work and presentation of the obtained results/Individual Efforts in discussion and participation | 15 |
| Accuracy of the obtained results and conclusions | 15 |
| Total | 100 |
| Extra Credit (Discussion and Answering Good Questions for Nonlinear Control) | 10 |

The main emphasis was given on the implemented code using the MATLAB, also the learning efforts were also evaluated through checking the accuracy of developed and executed Simulink models that shows interfaces with integration schemes and a variety of analysis with respect to the variable parameters in the assigned problem.

For solving Problem 2, some students used the brute-force method of guessing the parameters to obtain the desired results, however the evaluation points were devoted to the extent of accurate results. One of the important observations was that the students who had good hold on the prerequisite background as in differential equations and calculus excelled in the MATLAB programming and obtaining most of the results along with grasping the material as intended from this problem-based implementation through a class project. In comparison to the class, the same group of students did better in the final exam as well and they came in contact with the instructor for discussing their interest toward senior design project.

## 6.0 CONCLUSIONS

In this paper, the main proposition that is ‘to augment a compulsory project activity’ is emphasized on implementing practical design-type control problems side by side using the gained theoretical knowledge through the course material. As intended, the project assignment somewhat helped to promote the hypothesis of creating an environment of simultaneous learning and the implementation effectively. Since the project assignments were closely resembled with the text problems, the students were motivated enough to spend more time in reading and understanding the course material. As discussed, the practical mechanical/aerospace problems were assigned in the class projects to implement the project-based learning of the subject of control systems. The main emphasis was to focus on learning capabilities of the programming in MATLAB/SIMULINK [13] used for presenting the solution method for Control Systems. Often, it is seen if the student does not opt a lab course with the course dedicated to teach the theory, the arising situation somehow creates an ample chance of losing the students’ connectivity between the subjects’ understanding and its practical importance. Also, due to a fixed nature of adequate set of equipment in the laboratory, the lab course on Control Systems can only provide a good insight on a limited number of prescribed problems/experiments. Even if there is a separate lab course taken as a co-requisite, it is still very difficult to facilitate subjective experiences on a variety of computational problems of diversified nature. After assessing the problem-based in-class project activity against the projected learning outcomes, author seems confident to conclude that the project activity is comparatively more helpful to teach the theoretical ideas in the class rather than leaving this task alone for doing it in the lab course separately, though the lab course is also important and must be kept in the curriculum. It is also realized that this activity clearly broadens the domain of discussion of the class topics among the students and the instructor, especially on how to use the knowledge for practical purposes.

The future work is to make some more progress on the similar activities for enhancing the undergraduate research experience and providing culminating experiences through senior design projects. Keeping updated with a routine quality discussion with the colleagues and with the interested students, the concluding remark is that this project integration acts as a vital part in the mission of ‘learning by doing’ due to its selective nature of many implementable control problems in a small ‘3-4 weeks’ timeframe. As highlighted in Section 4.0, it also opens a clear avenue for interested beings to proceed this ground work for envisioning the future research on real-time nonlinear control implementation in the class-room settings and senior design projects in the fields of control systems and mechatronics.

## REFERENCES


1. Astrom, K. J. and Kumar, P.R., “Control: A Perspective”, *Automatica,* Vol. 50, 2014, pp. 3-43.
2. Dorf, R.C, and Bishop, R.H., “*Modern Control Systems*”, 11th Ed., Prentice Hall, 2008.
3. Katsuhiko, Ogata, “*MATLAB for Control Engineers*”, 1st Edition, Prentice Hall, 2008.

4. Yakimenko, O. A., "*Engineering Computations and Modeling in MATLAB/Simulink*", 1st Edition, AIAA Series, 2011.
5. Katsuhiko, Ogata, "*Modern Control Engineering*", 5th Edition, Prentice Hall, 2010.
6. Nise, N.S., "*Control Systems Engineering*", 4th Edition, John Wiley & Sons, 2004.
7. Phillips, C. L. and Parr, J. M., "*Feedback Control Systems*", 5th Edition, Pearson, 2011.
8. ABET Criteria 3 (Student Outcomes), Online http://www.abet.org/DisplayTemplates/DocsHandbook.aspx?id=3149
9. Parsley, J. and **Sharma, R.**, "Near Optimal Guidance for an Accurate Lunar Landing", Proceedings of 21st AAS/AIAA Space Flight Mechanics Meeting, New Orleans, Louisiana Feb. 13-17 2011, Paper AAS 11-166, Vol. 140, *Advances in the Astronautical Sciences*, pp. 929-943.
10. Parsley, J, "Near-Optimal Feedback Guidance for An Accurate Lunar Landing", MS Thesis, University of Alabama, 2012.
11. Cloutier, J. R., "State-Dependent Riccati Equation Techniques: An Overview", *American Control Conference*, 1997, Anonymous pp. 932-936.
12. Lewis, F.L., "Optimal Control", Wiley, New York, 1986, pp. 362
13. MATLAB/SIMULINK, http://www.mathworks.com/products/simulink/
14. LABVOLT literature and equipment, https://www.labvolt.com/