2017

Integrative Experiences Through Modeling and Simulation of Mechatronic Systems

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Repository Citation

Tomovic, Mileta; Tomovic, Cynthia; Jovanovic, Vukica M.; Lin, Cheng Y.; Yao, Nan; and Katsioloudis, Petros J., "Integrative Experiences Through Modeling and Simulation of Mechatronic Systems" (2017). *Engineering Technology Faculty Publications*. 68.
https://digitalcommons.odu.edu/engtech_fac_pubs/68

Original Publication Citation

Tomovic, M., Tomovic, C., Jovanovic, V. M., Lin, C. Y., Yao, N., & Katsioloudis, P. J. (2017). *Integrative experiences through modeling and simulation of mechatronic systems.* Paper presented at the 2017 ASEE Annual Conference and Exposition, Columbus, Ohio.

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Integrative Experiences through Modeling and Simulation of Mechatronic Systems

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Integrative Experiences through Modeling and Simulation of Mechatronic Systems

Abstract

Learning is integrative lifelong process which requires continuous refreshing of old material and learning new material. This principle holds also for student experiences during their undergraduate studies. Students learn new material throughout their studies, and they may or may not have opportunity to use the material in different context and at different levels. As a result some of the acquired knowledge may be forgotten by the time student graduates or it may not be placed in the context of the overall program outcomes, thus material presented may not seem to have relevance to student's career. An effective method to address this issue is a required capstone course that combines a number of different disciplines into a single comprehensive experience. In addition to required capstone experience, authors have collaborated in development of an elective course on modeling and simulation of mechatronic systems. The course introduces modern computer tools and techniques which integrates number of different areas including statics, strength of materials, dynamics, electrical systems, fluid systems, hydraulic systems, pneumatic systems, thermal systems, and control systems. The course provides several benefits including review of material covered at different stages of the undergraduate program, connecting different fields by analyzing mechatronic systems, and introduction to the tools that enable students to solve real world problems that cannot be solved analytically. Although some courses introduce the basics of modern computer tools, most do not have sufficient time to devote to modern computer tools. Hence, the introduction of a modeling and simulation course of mechatronic systems in the engineering technology program provides an opportunity to further improve the quality of the program and satisfy a number of ABET related learning outcomes.

Introduction

Engineering programs have been striving to provide students with numerous opportunities for integrative experiences [1]. Universities and colleges have created introductory freshmen engineering courses [2] with the intent to provide students opportunity to learn about various engineering disciplines through hands-on, problem solving, engineering design experiences before they decide on a particular engineering field. The courses have been very effective in preparing students for the structured and rigorous engineering program, which is evidenced by increasing retention and graduation rates [2]. Another approach to enhancing engineering education experiences is Project Based Learning [3] which has proven to be very successful in engaging students in an active learning process while increasing teamwork and improving communication skills. In addition to integrating project based experiences throughout all four years, most engineering programs culminate in a major design experience [4]. In most cases, this experience takes the form of a sequence of two 3 credit hour courses at the senior level. The experience provides students an opportunity to apply most if not all of their engineering knowledge to the design and build of a physical system that, in most cases, has real-world application relevance [5]. The capstone experience is highly valuable, but due to limited time, for obvious reasons, it has some limitations including insufficient time for closing the loop, namely in terms of product refinement and commercialization [6]. Another limitation is related to the lack of ability to analyze real world problems at a significant depth, since most of the problems that students deal with during their academic careers are textbook examples, and the tools that they have learned are applied mostly to simple structures and systems. There are currently few courses in the undergraduate Engineering Technology curriculum that expose students to tools that would enable them to analyze complex structures and multidisciplinary physical systems. Hence, the problems they select and the work they conduct in the capstone design projects tend to have limited analysis component. This could be relatively easily resolved through application of modern modeling and simulation tools which are reasonably easy to use and could assist students in dealing with complex problems. An example of such a tool is the Matlab/Simulink/Simscape set of modeling and simulation tools that can model many complex physical systems [7].

The course that is discussed in this paper integrates fundamental ideas from integrative experiences and project based learning. The course builds on the material covered across a number of different engineering and science courses, and extends student ability from dealing with simple textbook problems to solving complex real world engineering problems. The course is going through development stages and reflects a number of lessons learned that already have been integrated or will be implemented in the future as further feedback from students is compiled. Since the course is currently offered as elective course, and because of its usefulness it will be proposed that the course be considered as required pre- or co-requisite for the capstone course, which will allow students to increase depth of analysis of selected real world problem.

The course was initiated as a need to develop mechatronics area of specialization within the Mechanical Engineering Technology program, and was part of the Office of Naval Research grant to Tidewater Community College and Old Dominion University to establish pathways for students from community colleges to pursue four year baccalaureate degree in the mechatronics area, Fig. 1 [8, 9]. The grant is intended to support a three year development process which would identify courses at both institutions that could be part of a larger and possibly a full-fledged mechatronics program [9]. Since both Old Dominion University and Tidewater Community College are in the area with significant military and veteran population, specifically Navy, the course tried to implement components that are have relevance to that particular group [10] while at the same time it is trying to be general enough so that that students can apply acquired knowledge across different application areas. The grant was received in 2015, various modules were created in 2016, and the course was offered in the Spring 2017.

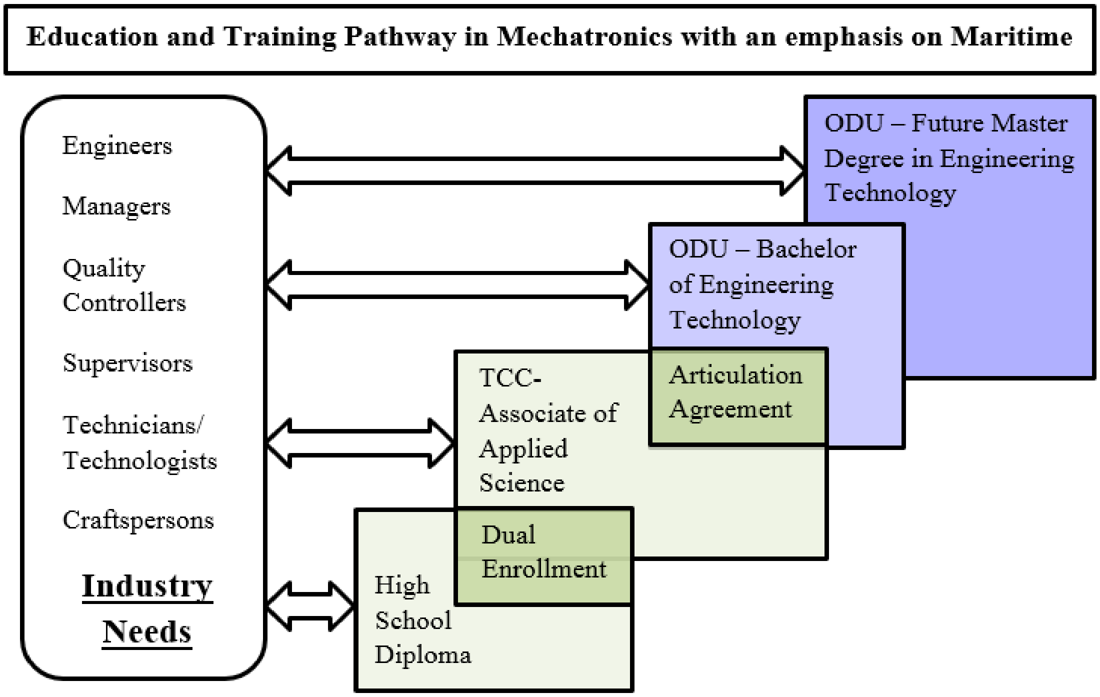

Figure 1: Education and Training Pathway in Mechatronics with an Emphasis on Maritime Mechatronics [8, 9]

Prior to designing the mechatronics program, including the course on modeling and simulation of mechatronics systems, the authors conducted survey of industry needs and compared them with the existing programs and identified areas that need to be expanded and further developed. The survey results were analyzed, conclusions drawn and gradually implemented. Some of them are topical and are addressed through various modules and appropriate examples. In addition, a semester long project of student choice is introduced and is conducted under instructor's supervision through regular meetings and discussion.

Course Structure

The course is a senior elective and requires students to complete a number of junior level courses such as dynamics, fluid mechanics, fundamentals of electrical systems, and automation as a pre-requisite to enrolling in the course. In addition, students are expected to have a basic knowledge of MATLAB which is taught in the Advanced Technical Analysis course. The course is intended to provide students with the working knowledge of tools to model and analyze complex disciplinary dynamic systems (e.g. suspension system, hydraulic circuit systems, etc.) as well as complex mechatronic systems (e.g. robotic arm, ship propulsion system, etc.). In addition, the course is intended to provide students with an opportunity to integrate the knowledge acquired in different courses in an integrative capstone-like experience. The students are expected to apply their knowledge of dynamics, fluid mechanics, thermodynamics, electrical systems, and controls to solve practical problems that require the application of numerical methods and simulation software. The course covers ten different topic areas, each of which has a number of quizzes and homework problems with numerous questions that require students to model, simulate, and analyze the systems. As the course is in the initial stages of its offering, modifications will be made to emphasize system integration, system analysis and modification to achieve desired performance, and component selection to achieve desired systems specifications. Ultimately, the focus will be on the "what-if" analysis and understanding of how tools can be utilized to create better, if not "optimal", solutions to achieve desired design objectives.

Course objectives

After completing this course students should be able to: (a) develop models of physical systems (mechanical, fluid, hydraulic, pneumatic, electric) using Matlab and its Simulink and Simscape toolboxes, (b) analyze system behavior with respect to parameter modifications, (c) integrate systems across different physical domains (e.g. electro-mechanical), and (d) understand the control aspects to achieve desired system behavior.

After completing this course the students should be able to apply MATLAB software, including Simulink and Simscape, to:

1. Perform basic operations and create scripts.
2. Model and simulate multibody systems. Interpret simulation results and perform appropriate modifications to the system to achieve desired function.
3. Model and simulate mechanical systems. Interpret simulation results and perform appropriate modifications to the system to achieve desired function.
4. Model and simulate basic electrical systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
5. Model and simulate electro-mechanical systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
6. Model and simulate fluid systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
7. Model and simulate hydraulic systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
8. Model and simulate thermal systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.

Since practical problems require tools and techniques that transcend the material covered in the basic courses, the objective of this course is to introduce students to necessary tools to solve real world problems. Since time is limited to go into great depth of each of the areas covered in the course, like for any other course, students are introduced to the basics of numerical methods and tools required to model and simulate complex systems. The students are also expected to learn some of the material on their own which will expose them to the breadth and depth of the methods and tools so that once they need it in the practice they will be able to learn additional material on their own and solve increasingly complex problems in their specific area.

ETAC ABET Student Outcomes

The course is structured in such a way as to address the following ETAC ABET student outcomes:

a. Ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly-defined engineering technology activities;
b. Ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies;
d. Ability to design systems, components, or processes for broadly defined engineering technology problems appropriate to program educational objectives;
f. Ability to identify, analyze, and solve broadly-defined engineering technology problems;
g. Ability to apply written, oral, and graphical communication in both technical and non-technical environments; and an ability to identify and use appropriate technical literature;
h. Understand the need for and an ability to engage in self-directed continuing professional development.

The course will be modified in the future to include the following student outcomes:

c. Ability to conduct standard tests and measurements; to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes;
e. Ability to function effectively as a member or leader on a technical team;
k. Encourage commitment to quality, timeliness, and continuous improvement.

Examples of Physical System Models

The course provides numerous examples of different physical systems, starting with electrical circuits, common mechanical systems, basic hydraulic circuits to complex electromechanical systems that integrate mechanical, hydraulic, and electric components. The course also provides number of simple examples so that students can compare the results from simulations with analytical solutions which they can derive using their basic knowledge and thus gain confidence in the numerical methods and simulation results. The course then provides more complex problems that are not necessarily at the level of real world cases but that could be very difficult to solve analytically. The course continues to build the complexity of the analyzed systems to the point of real world problems. For example, one of the cases looks into a robot arm [11] that consists of a mechanical end effector and an electric motor that is driving the arm. The system also includes a PID controller that assures desired system behavior.

First, students learn how to model the electrical side of motor, Fig. 2, and simulate its performance for various inputs. Second they add rotor and associate mass properties to the electrical motor, Fig. 3, and analyze motor behavior to various inputs. They look at the effects of dynamics of various components and decide how a detailed model needs to be in order to determine the required outputs.

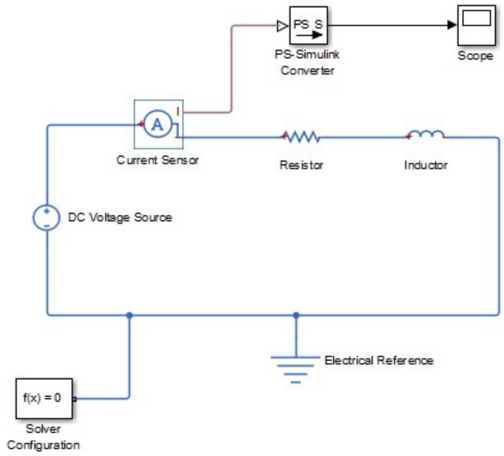

Fig. 2. Model of electrical circuit

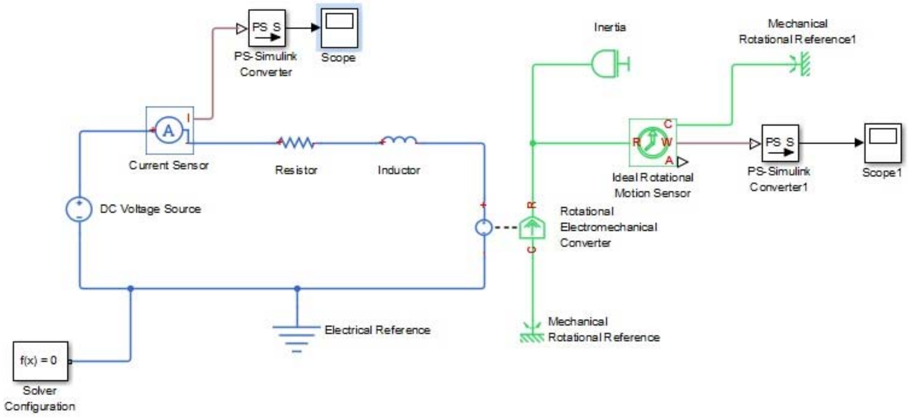

Fig. 3. Model of electric motor

Once students have developed a model of the electrical motor, they add the gear box and end effector to the overall model, Fig. 4, and simulate its behavior, Fig. 4. In this case the end effector is moving in the horizontal plane and gravitational effects are not included in the model. The next problem is to change the plane in which the end effector is moving to the vertical plane, in which case the gravitational effect needs to be added to the model, Fig. 6. Students can see that the system has significantly different behavior once gravity is included, Fig. 7. The resulting system behavior is not a desirable one, as it has uneven angular velocity as it moves from one position to another. At this moment students discover the need for the controller which will smooth the motion of the end-effector. They are asked to design a PID controller, Fig. 8, which will give them the desired result, Fig. 9.

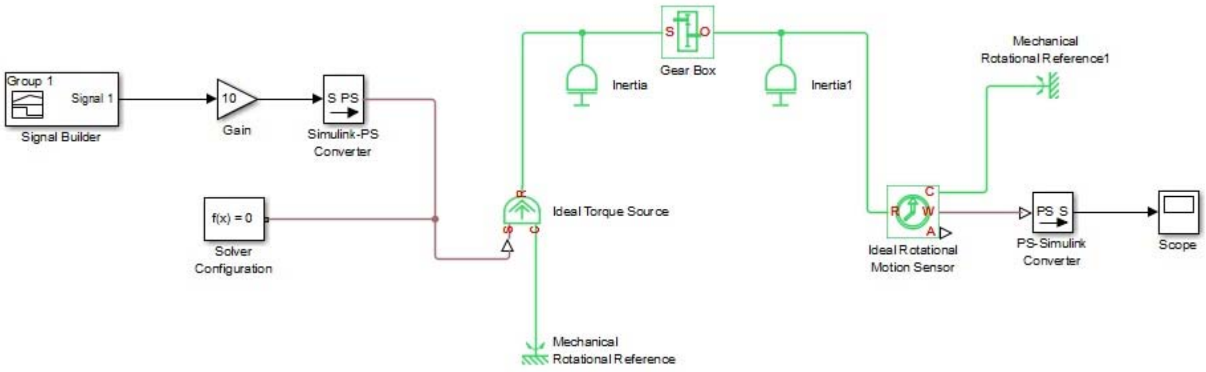

Fig. 4. Model of electric motor, gear box, and robot arm.

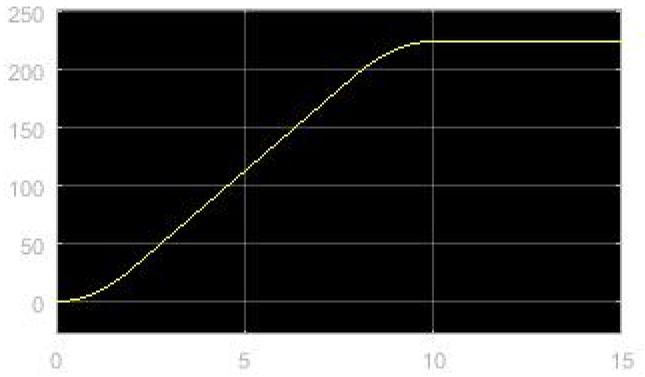

Fig. 5. Time response of electric motor, gear box, and robot arm.

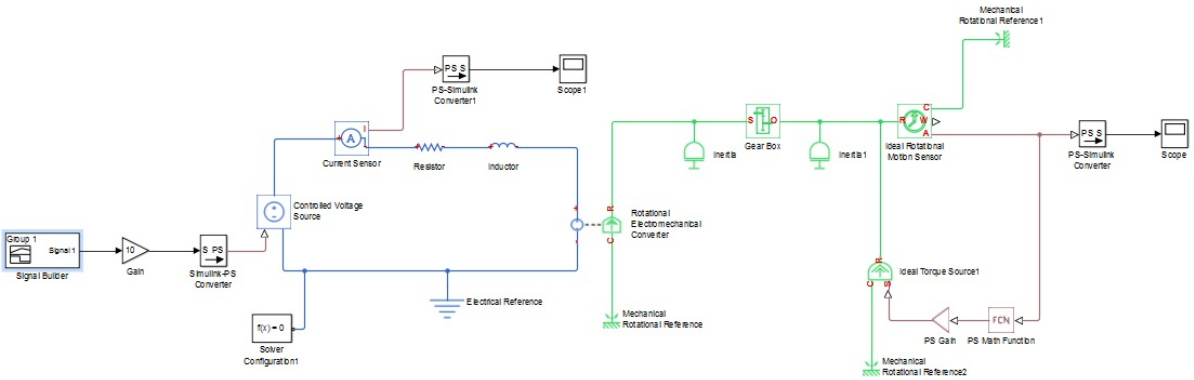

Fig. 6. Model of electric motor, gear box, and robot arm – gravitational effect included.

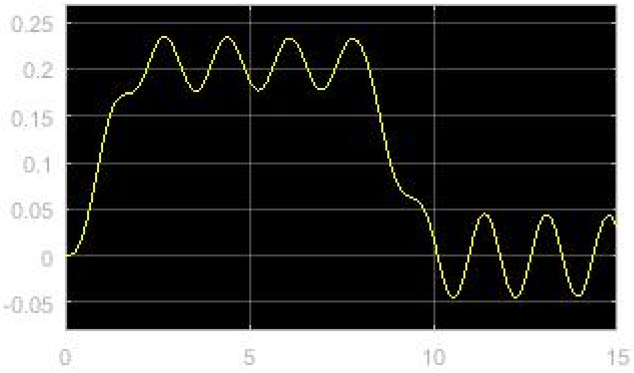

Fig. 7. Time response of electric motor, gear box, and robot arm – gravitational effect included.

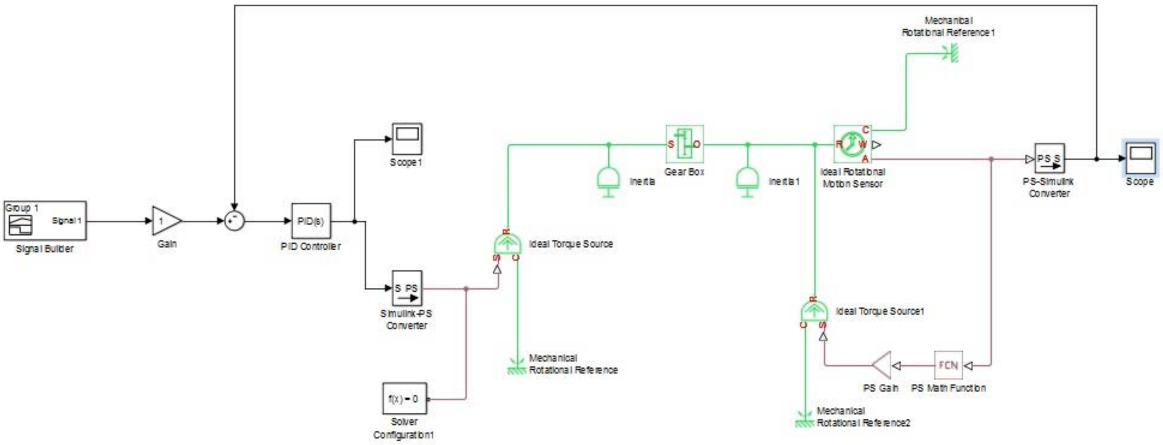

Fig. 8. Model of electric motor, gear box, and robot arm with PID controller – gravitational effect included.

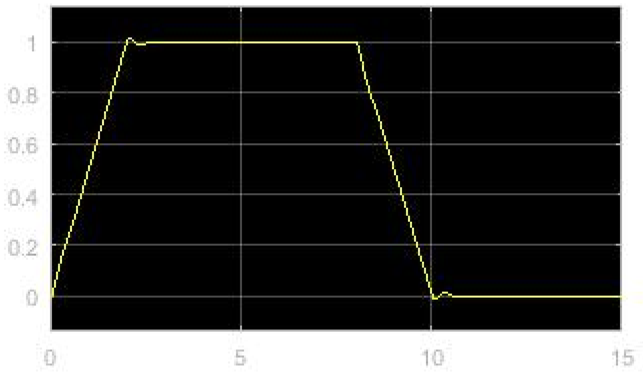

Fig. 9. Time response of electric motor, gear box, and robot arm with PID controller – gravitational effect included.

The students are also asked to select a physical system of their choice and work in teams to come up with appropriate model for the system. They are tasked with applying their engineering knowledge in analyzing the system. For example, students worked on the problem of modeling and simulation of a 4-cylinder 4-cycle internal combustion engine, Fig. 10. Specifically they modeled and analyzed the crank shaft – connecting rod – piston mechanism, including the effects of time varying forces acting on the cylinder over four different cycles, Fig. 11. The students were asked to analyze the effects of masses and moments of inertia of various components in the system on the engine RPM. They were also asked to look into the reaction forces in the joints so that they can propose appropriate types and sizes of bearings for the system. They were also asked to review output RPM and see if and how they can minimize variations by including different mechanical components to the overall design.

Fig. 10. Example of four cylinder engine analyzed by the students.
https://en.wikipedia.org/wiki/Inline-four_engine

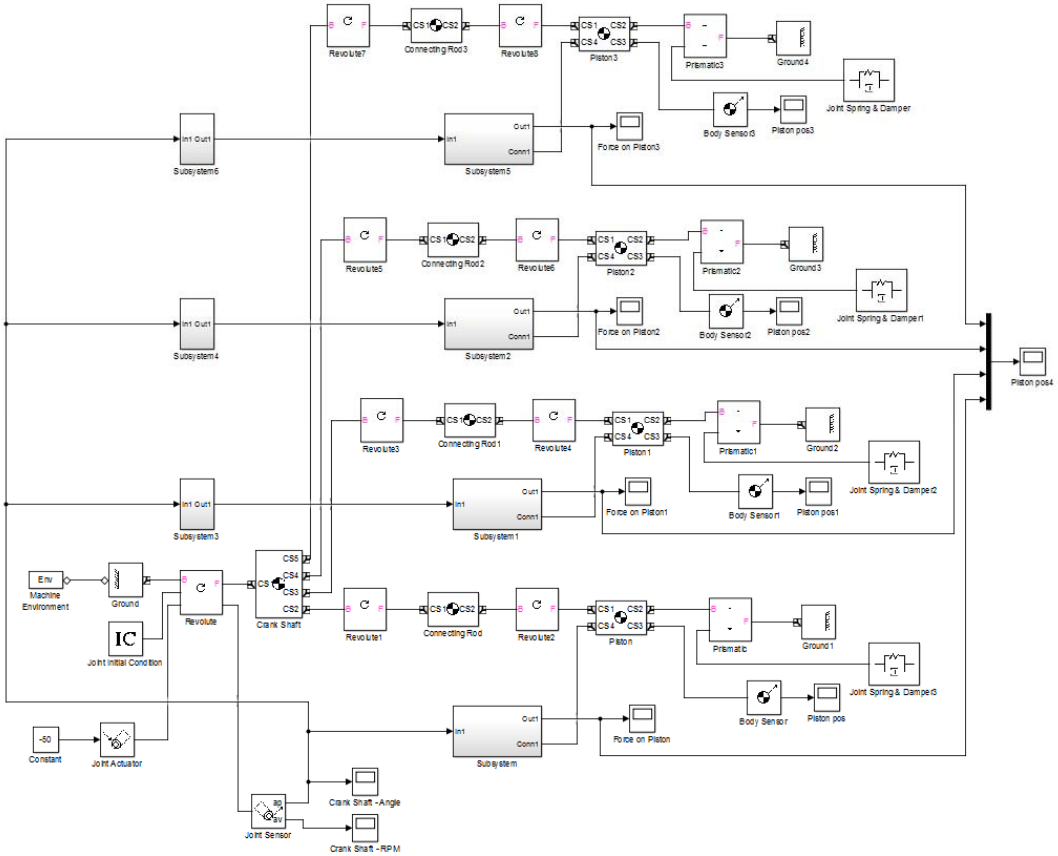

Fig. 11. Model of the engine shown in Fig. 10.

The model of the internal combustion engine could have applications both in the ship propulsion system as well as in automotive applications. It provides good example of how the course provides opportunity to students to analyze similar systems across different disciplines. As number of students are in Navy, another project involved design of the ship rudder, Fig. 12, and its control system. The students were asked to analyze system dynamics for different rudder sizes, shape, as well as for different controller types (P, PI, PID) and see how the system behaves when the system receives change in the input. Students were also asked to make the system more realistic by introducing external disturbances related to waves. They have developed model shown in Fig. 13, and some of the results are shown in Fig. 14 indicating ruder response to step input and to influence of the wave forces.

Fig. 12. Ship rudder [12].

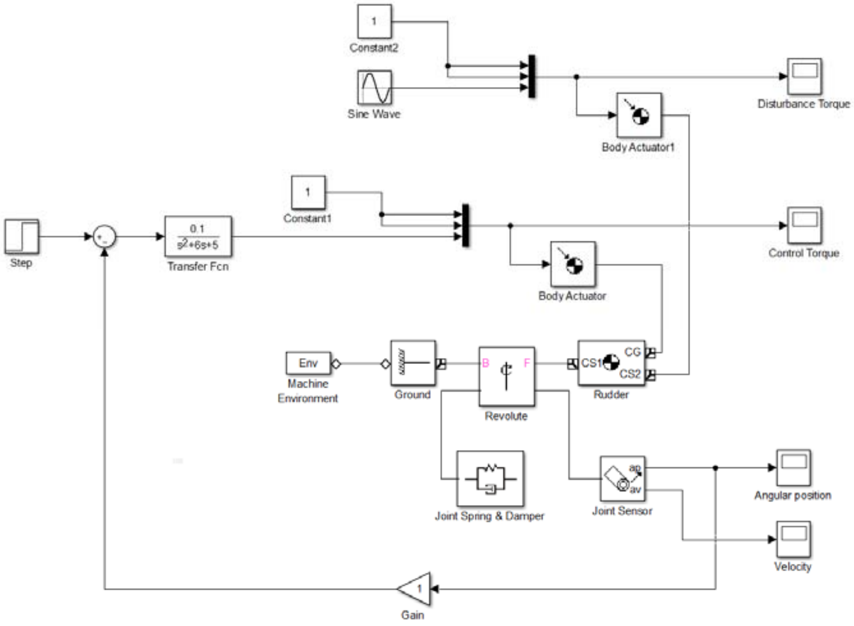

Fig. 13. Matlab model of the ship rudder.

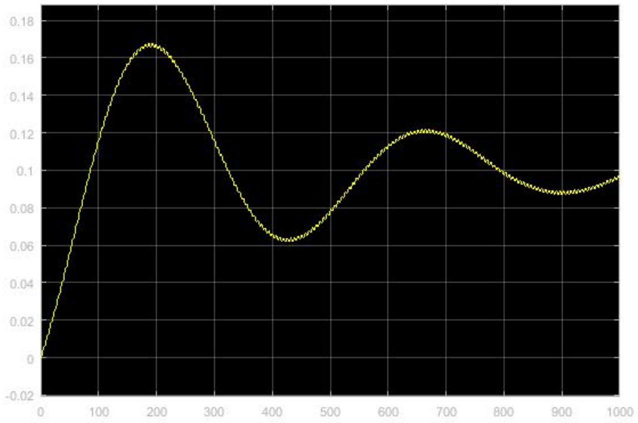

Fig. 14. Time response of the rudder to step input and wave disturbances.

Discussion

The course is designed with the intent to provide students opportunity to integrate their knowledge from various mechanical engineering technology courses to design, model, simulate, and analyze complex mechatronic systems. The course addresses a number of ETAC ABET student outcome criteria from the application of modern tools and techniques to the design of complex systems. Some of those outcomes are directly measured and some of them will be measured and evaluated in the future as appropriate assessment techniques are integrated in the course structure. The course was designed to address ETAC ABET student outcome (a), specifically element of outcome (a) related to application of modern tools and techniques. The primary and only modern tool that students were exposed to was one of the CAD software packages to create a solid model of a mechanical component or assembly. In some instances finite element components of the CAD software were presented to students. However, overall there is a limited number of software packages that students used in the classroom, and this course was designed to address that aspect of the ETAC ABET student outcomes and better prepare students for industry. Exit survey, conducted on the population of senior students in department, indicated that students would like to have additional exposure to and opportunity to work with modern engineering tools in their area. It is expected that this course will address some of those issues and that students will become more satisfied with their experience in terms of that particular objective. Since the course is in the initial stages of its offering, there is insufficient statistical data to analyze impact of this course on the student opinion in terms of that particular outcome. However, the initial feedback from students is positive indicating that students find presented material very useful and that it extends their ability to deal with complex systems and real world problems. The long term effectiveness of the material presented in the course will be measured in the future after students/alumni have had the opportunity to use their knowledge in industry.

In addition to offering opportunity for expanding technical competency, the course also offers opportunity to students to work on teams, write technical reports, and make presentation of the findings. The students are also asked to expand their knowledge of the particular area of mechatronics on their own as there is limited time to cover all topics in great depth. By choosing practical problem, ship propulsion problem, students are expected to explore SimMechanics portion of the Matlab software and integrate CAD design with Matlab simulation of rigid bodies. As they work on various semester-long projects they are in regular contact with instructor to make sure that their applied research and design stays within the scope and that they are guided in the correct direction.

Since the course is also supporting marine mechatronics systems, as a part of the ONR grant, feedback from professionals in the field will be solicited on a continuous and periodic basis to insure its relevance and yet allow students to gain knowledge and skills that can be applied in many different application areas. As the course gains more feedback from students and industry it will be modified accordingly and the results will be reported in the future.

Conclusion

The course is another small step in the evolution of the engineering curriculum towards the integration of theory and practice, from simple to complex systems, and from a single discipline to a multidisciplinary view of the world. The course takes advantage of developments in numerical methods, modeling and simulation, and computer software to provide students with tools to deal with increasingly complex technical systems. The course addresses the request from the Industrial Advisory Committee to provide students with tools to effectively perform multiple "what-if" analysis and come up with optimal performance and cost effective solutions. Future work will integrate feedback from students and industry, and will look into the overall impact on student opinion of the integrative experiences at the undergraduate level.

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