Systems Engineering at the Naval Academy

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ABSTRACT

This paper describes the current curriculum of the Systems Engineering Department at the U. S. Naval Academy in detail. We show how our program not only serves the needs of each military graduate and meets the objectives and requirements of an ABET accredited program, but also why this curriculum has become one of the most popular and successful undergraduate programs at the U. S. Naval Academy.

OVERVIEW

The Weapons and Systems Engineering Department at the U. S. Naval Academy has a long history. It has existed, in various forms and with various names, since the founding of the Naval Academy in 1845. In the early years the Department provided instruction about specific weapons and their underlying principles. As weapons grew in complexity they evolved into weapon systems. While early weapon systems were primarily electro-mechanical in nature, more recent weapon systems frequently also include aspects of computers, control, communication, and robotics.

Several years ago retired Air Force Brigadier General Charles E. "Chuck" Yeager addressed the Naval Academy midshipmen. Among other things, he told them to "Know your systems." It was his clear message that as the American armed services become increasingly technological, officers must have a thorough knowledge of how their weapons function as a system in order to take full advantage of them. It is for this reason that the primary emphasis of the Systems Engineering major at the Naval Academy has remained oriented more towards the engineering of control systems, like those commonly in modern weaponry.

The present curriculum of the Systems Engineering major contains six required courses, covering fundamentals in mathematical modeling, simulation, and control. Each major takes five additional elective courses. These are organized as two two-course elective sequences in an area of specialization and a fifth major elective that may be taken in any engineering-related course. Two-course elective tracks currently produced within the Weapons and Systems Engineering Department includes automatic control, computers, communication, robotics, and environmental systems. These areas are in contrast to the more traditional Systems Engineering topics such as optimization, economics, behavioral science, and decision-making. USNA Systems Engineering majors must also complete a significant capstone design project during their senior year. Our senior students choose their own topic for this project and produce a complete design document during the fall semester. They then build, test, and present their project during the spring semester. With this mix of technical topics and flexibility to student interest, the Systems Engineering major has become the largest engineering major at the Naval Academy.

The Systems Engineering Department continues to evolve. Recognizing that as naval officers' careers advance they take on more management responsibility, two management systems courses are under development that will incorporate some of the more traditional Systems Engineering topics. When fully developed it is anticipated that these courses will form an additional elective track.

INTRO TO SYSTEMS ENGINEERING

At the Naval Academy the midshipmen have a common curriculum during their plebe (freshman) year that does not include an introductory engineering course. Their choice of major, made midway through their second semester, is made based upon information obtained from briefs provided by the individual departments. While some engineering majors have an introductory course during the fall semester of the sophomore year, Systems Engineering requires a C programming course during that semester so the Introduction to Systems Engineering course takes place the following semester.

The purpose of the Introduction to Systems Engineering course is to get the midshipmen excited about their major and to provide them with some basic skills that they will use in the courses within their major. The course consists of two class hours and two lab hours per week. The initial class time consists of an introduction to their major in the form of a discussion of the senior elective tracks: controls, computers, communication, robotics, and environmental engineering. The remaining class time is devoted to an introduction to matrix operations in preparation for modern control, an introduction to Laplace transforms and block diagrams in preparation for classical control, and an introduction to operational amplifiers for use in various signal conditioning applications.

The labs are an interesting and engaging part of the course. The initial lab, done with no theoretical preparation, is an exercise in designing and building a Lego puck firing mechanism. The purpose of the lab is to provide an experience in teamwork including rapid design, construction, testing, and communication. For the following lab a motor driven Lego cart, with an available shaft encoded rate signal, is provided to each team. By simple modification of provided C code running in the embedded computer, the teams build a cruise controller that demonstrates open loop control, proportional rate control, and proportional plus integral rate control. For the following lab they write all of the embedded computer code required to control a multi-floor Lego elevator.

Having experienced the difficulties of hand calculations involved in matrix manipulation and Laplace transforms, Matlab is introduced not only as a tool to help with these problems, but as a tool that they will use in every one of their Systems Engineering courses. Likewise, Simulink is introduced as a simulation tool to be used for nonlinear simulations or simulations of linear systems beyond a trivial level of complexity.

The culmination of their introductory course is the simulation and construction of a system meant to resemble home heating. Under the control of an embedded computer, a hair dryer is switched on and off in order to keep the temperature within a cardboard box within a prescribed range. While design of this nonlinear system is beyond the scope of the course, reasonable control parameters can be obtained by Simulink simulation. The hardware aspect of the project includes the design and construction of an op amp scale and shift circuit needed to make the thermistor voltage range compatible with the embedded computer A/D converter. The software aspect is the development of the C code within the embedded control computer that makes the computer act as a thermostat. A relay to switch the hair dryer is provided.

In summary, the Introduction to Systems Engineering course provides the students with theoretical, computational, and simulation tools that will be of use throughout their major. The laboratory exercises are designed as a preview of simulation and control, and are done in such a way to provide a positive and useful experience at a stage in their major when the theoretical basis for what is being done is not fully developed.

SYSTEMS ENGINEERING CORE COURSES

Automatic control systems are the core of the Systems Engineering Major at USNA. Systems majors take five courses in their junior and senior year that provide them with breadth and depth in automatic control systems.

In the fall term junior year, systems engineering majors are required to take a course in modeling and simulation of dynamic systems and a course in classical control theory. In the modeling and simulation course the principles of computer simulation of linear and nonlinear multivariable systems are applied to the study of the behavior of realistic engineering control systems. The course includes a hands-on hardware design and construction problem and a computer simulation design project. In the classical control course the students learn how to analyze the transient and steady-state behavior and the stability of linear dynamic physical systems, under the influence of basic cascade and feedback controllers. They also learn how to apply the root locus and frequency response methods for analyzing the behavior of closed loop control systems and for designing cascade controllers.

In the spring term junior year, systems engineering majors take a control systems lab and a course on control system sensing and actuation. The control systems lab serves to bridge the gap between the theory and the practical realities that the students will see in the real world. In this class students learn how to complete the entire control system design process for a given physical plant. Steps of the design process that the students are responsible for include the following: modeling and system identification, analysis, simulation, compensator design, rapid prototyping, implementation, and testing. Students learn how to implement control systems using an analog circuit or a digital computer. The control system sensing and actuation course is designed to complement previous classes in system components and modeling by concentrating on specific examples of sensors and servo system actuators and control. Additional experience is provided in analysis and hardware usage. Statistical methods are used.

Finally, in the fall term of their senior year, systems engineering majors take a course in modern control theory. The students learn to apply modern state variable techniques to the modeling, analysis, simulation, and design of linear feedback control systems. The students also are required to apply the knowledge and skills gained at the USNA to a senior design project, through the project definition, analysis, and simulation phases, culminating in a formal design paper.

TECHNICAL ELECTIVES

Each systems engineering major is required to take five technical elective courses. These courses are organized as two sequences of two courses (i.e. tracks) in an area of specialization and a fifth major elective that may be taken in any engineering-related course. The tracks currently offered within the Systems Engineering Department include automatic control, computers, communication, robotics, and environmental systems. While students are required to take at least one track offered by the Systems Engineering Department, students may choose for their second track an approved course sequence available from other engineering departments. Typical tracks offered by other engineering departments include electrical engineering, mechanical dynamics, nuclear engineering, aerospace engineering, and astronautics engineering.

Excellent students can also take Research Project Courses for their technical elective. Research Project Courses offer students the opportunity to undertake a research project of limited scope under the supervision of a faculty member. Such courses are restricted to senior and junior level students whose grade point average is above at specified level. In a research project course, a student often seeks to investigate that which is new or unexplored in a discipline, or to examine previously reported research results within a new context or via a new approach. Tracks and research courses provide avenues for individual interests.

CAPSTONE DESIGN PROJECT

During their final year, all systems engineering majors must complete a comprehensive “capstone” project that includes system design, project construction, and formal demonstration. Although a capstone design experience is a standard requirement for ABET accreditation of any engineering curriculum, we have found that a well-managed program is not only a wonderful way for students to develop a deeper understanding of their theoretical courses through a practical application of systems engineering, but is also a point of great pride. Indeed, most of our visiting graduate students (and faculty) remember their project long after other specifics of the systems engineering curriculum have faded.

We believe that individual student ownership in this experience is paramount to achieving maximum and lasting benefits. For this reason we allow our students great latitude in picking the subject area for their project and in forming "teaming" relationships with other students, in some cases even from other departments. Over the years the department has provided some competition-based projects as alternatives for students who may not have particular area that they want to explore in a project. Because of absolute constraints on available time and realistic constraints on project cost, it then becomes a management task for the faculty to ensure that each project takes on a form and scope that can be both meaningful and achievable.

In its current form our capstone design experience is split into two phases: "design" and "build-demonstrate", which coincide with the two semesters of each student's final year. During the fall semester in the design phase our students must determine the subject area for their project, form teams where it will be beneficial from an educational perspective, and produce a detailed design document. These requirements are presently being managed academically as a part of a required senior course in advanced control systems - though we are exploring alternatives for a separate design course within our highly constrained curriculum.

Early in the first semester, after our students have announced the subject area of their design and have proposed teaming arrangements, they are assigned two advisors from our faculty. A military advisor is assigned to monitor (and in some cases direct) the progress of the project, much as a military "project manager" might do in the fleet. A civilian faculty is assigned to provide direct technical assistance to the project. This arrangement provides some direct ties between students and faculty to make sure that they have a known place to go to get answers, and to make sure that they make consistent progress throughout the year. During the first semester some limited laboratory and material resources are also made available so students may experiment with unfamiliar devices or systems to better understand their applicability to their project. At the end of the first semester, each student team produces a design document that includes a complete conceptual description of their project, a proposed timetable for completion, a list of resources and sections that addresses any potential safety, ethics or ecological issues.

In the second semester students or teams build and demonstrate the project that they have designed during the first semester. They are provided bench space, tools, test equipment, parts, and other support (e.g., local shop fabrication) as required during this phase. Academically, the projects are managed during this phase through a two classroom-hour, four laboratory-hour course. The same military and civilian instructors that were assigned to the project during the first semester provide additional management and technical oversight. Each of these supervisors must help to make sure that scope, costs, and timeframes all remain within reasonable limits. Of these considerations, schedule is probably the most critical, since our students must complete all their requirements for graduation in this single semester. In addition to providing assigned laboratory periods for the project, the design course also explores project management practices, construction practices, shop fabrication practices, and engineering ethical studies.

The spring semester can be described easily by the word “hectic”. For many students this is the first time that they have constructed something of their own design – and many find that things do not go quite as smoothly as planned. Faculty interaction requirements can be intense as students experience the difference between theoretical and applied engineering, but by design it is spread throughout the staff, rather than relegated to a few. The faculty and support services must help the students understand and manage “lead-time” when they request parts and manufacturing assistance. In part this is accomplished by insisting that parts not in our inventory and major manufacturing are ordered early in the semester, and that each time have one or two fallback plans.

The design experience culminates in a series of formal presentations that take place during the last weeks of the semester. All faculty are invited to attend these presentations and junior level students are typically required to attend several. In addition, several lower division classes tour the project labs at the close of the semester. This is done both to motivate the students and to provide them with a clearer picture of what will be expected from them the following year. About a dozen of the best projects are chosen to be shown to the Superintendent of the Naval Academy and to the public during graduation week festivities. Projects that are constructed for department competitions go head-to-head in a separate spirited event that is publicized and televised on the campus closed-circuit network.

FUTURE DIRECTIONS

The curriculum for Systems Engineering majors will remain an intense blend of theory and practicum. We expect the backbone of the major will continue to be control systems. However, our tracks should continually evolve to keep pace with changes in emphasis and technology. As an example of how these evolutionary changes may take place we shall examine the Robotics Track.

The Robotics Track is the most popular track in the major, attracting around 100 students per semester. It is comprised of a basic robotics course and an advanced course in robotic vision. Four years ago a course in mobile robots was developed and it has been very popular as well. A fourth course has most recently emerged. A description of the course is:

> ***Introduction to Computer Vision*:** An introductory course covering both theory and application of image processing techniques used for automation, medical imaging, and remote sensing. The assignments will be programming intensive.

So now our student as undergraduates may take four courses in Robotics, quite a specialization. Recently, we have started a two course sequence Engineering Management. Many midshipmen will find themselves in management positions a few years after graduation and would greatly benefit from the formal training these new courses will provide. These courses are:

Engineering Management ***I:*** An introduction to operations research and its application to engineering. Topics include optimization of engineering systems, game theory, sensitivity analysis, project management with PERT/CPM, and decision analysis. Prereq: permission of chair.

Engineering Management ***II:*** Focuses on evaluation of the implications of advanced technologies from a global, societal and financial perspective. Topics include funding, analysis of past technological revolutions, and investigations into the science behind new technologies such as nanotech and human genetic engineering.

These two courses will shortly become the basis for an Engineering Management track in Systems Engineering. Indeed, a new engineering degree in Engineering Management may be offered in the future. The above developments are typical of the kinds of evolution that occur in all of our tracks.

CONCLUSION

The Systems Engineering major has a long history of very successful ABET visits. We are currently in our fourth year of a six year ABET approval. The changes in the ABET review have our department working hard on the assessment issues which will be raised during our next inspection in two years.

The midshipmen are attracted to a program with lots of diversity and choices in the courses selected. We are also blessed with many fine instructors who are natural magnets for these motivated students. Many of our majors are selected for graduate school at some of the finest institutions in the country. The masters level programs to which they are selected points to the major's diversity- nuclear engineering, electrical engineering, mechanical engineering, the MBA, environmental engineering and engineering management to name a few.

The midshipmen are also very well prepared for training in their Navy service careers, whether it be aviation, nuclear submarines, surface ships, Marines or special forces. The track record of our majors in these service selection areas is outstanding.

The Systems Engineering major remains the most popular technical major at USNA. All indicators point to the continued success and popularity of this major. Upon graduation, systems engineering majors are well prepared for the fleet and flourish in their military and civilian careers. In fact, many of our newly commissioned officers go on to pursue graduate degrees in mechanical, electrical, and computer engineering at some of the top graduate schools in the country.