AC 2009-1887: TEACHING EMERGING TECHNOLOGIES USING A SOCIOTECHNOLOGICAL DEVELOPMENT MODEL

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Weapons and Systems Engineering
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Introduction

The Systems Engineering department at the United States Naval Academy (USNA) offers an ABET-accredited degree program that focuses on feedback control and mechatronics, including aspects of mechanical and electrical systems design. Several years ago, an effort was begun toward developing an engineering management elective track to supplement the existing specialization courses in robotics, control theory, information systems and embedded computing. As part of that initial effort, the author developed a course involving study and analysis of emerging technologies. The course evolved in such a way as to take on a life separate from the engineering management track, and has become one of the most popular electives offered in the department. The core content of the course was considered so important to the development of our students that it became a required course for the new Honors major offered by the department starting in 2008.

In this paper, we discuss the pedagogical foundations of, and our practical experiences with, teaching students to analyze new and emerging technologies from a global perspective. In the emerging technologies course offered as a senior-level engineering elective at USNA, students are introduced to the fundamental methods and tools for ongoing evaluation of new, potentially disruptive technologies. Students use the tools of socio-technological analysis to carry out projection (determining what is *possible*, based on currently understood science), prediction (analyzing what is likely to be *achievable* under the limitations of current understanding, existing capabilities, and the economic, political and social realities of the day) and valuation (determining what is *valuable*, based on risk and reward, ethics, etc.).

The described course has as its main outcome a skill set that supports life-long learning and fosters an understanding of the factors that affect and effect technological change. Students who take the course are, ideally, inspired to take part in some aspect of technological development outside of the normal R&D focus of an engineering education. Students are asked to think as if they were advisors to the President, directors of research programs, or analysts for various institutions. This requires a new set of tools and a new mindset for most of these students, and offers a challenging but rewarding experience that is equaled by that of the professor who teaches the course.

The Fundamental Questions

Knowing what questions to ask is the first step in being able to analyze an emerging technology. Based on the forward-looking work of Eric Drexler in *Engines of Creation*[1], students in the emerging technologies course at USNA are taught to ask the aforementioned three fundamental questions:

Question 1: What is *possible*, based on our current understanding of the laws of the universe?

This is *projection*, and is important in that it prevents the students from discussing their favorite Faster-Than-Light travel methods and techniques for perpetual motion as part of the class, and also makes them question closely the science behind current projects aimed at extremely esoteric objectives. Projection is rarely a negative, in that it is very difficult to say with certainty that something is *not* possible. Rather, projection typically results in either a positive (a thing is possible) or a neutral (it may be possible, but there is no reason to suggest such). Students are cautioned to be careful with unproven theories and new scientific hypotheses, as these can be problematic for projection.

Question 2: What is *achievable*, based on an analysis of current economic, political and social environment?

This question is *prediction*, and is extremely challenging, especially unless carried forward using rational models of human behavior and a 'what-if' style of exploration. Here, students consider the details of the technology, including the 'who, what, when, where and why' questions that define it completely, but are asked to shy away from what *will* happen and focus on what is *likely* and poses the most *opportunity*, as well as how to take advantage of the same or even drive the development of the possibilities.

Question 3: What is *valuable*, from a particular perspective?

Here, students must carry out a cost-benefit and risk analysis, consider unintended consequences, and look at the big picture… the technology in a global context. They must also identify an appropriate set of metrics on which to evaluate the merits of a technology. From a personal transportation perspective, the low-cost Tata car recently introduced in India is a great boon, an affordable, quite capable small car that will open the roads to millions of people who could not previously afford such transportation. From a financial perspective, it is easy to see that added mobility can strongly affect an economy, but the glow begins to fade when one begins to count into the equation the potential impact of millions of additional cars on the roads of India and how that might affect the environment as well as the smooth operation of the transportation infrastructure.

None of these three questions is a static or solitary investigation. Each answer should lead to additional questions and directions for research and analysis. Projection methods applied to the concept of teleportation, for instance, might lead the student to look at quantum mechanics or perhaps the duality of matter, which may generate new ideas about communications theory. When predicting that the Segway personal transporter will not fundamentally shift the nature of urban transportation, students must consider how that problem might be solved, or how the device might be marketed, modified or adapted to allow it to reach its goal.

In the process of prediction, students must begin to grapple with the inertia of the modern technology environment and think about ways in which change can be generated. Similar ideas must arise from the valuation exercises, especially in relation to unintended consequences and so-called 'cage' technologies. This sort of discussion leads inexorably toward policy and funding mandates as well, both entire disciplines in their own right. The scope of the analysis and discussion is by necessity limited, but the implications are not.

Technological Development Analysis Tools

The main tools used in the emerging technologies analysis in the course involve modeling how society and technology interact. We rely, as a frame of reference, on Brian Sager's technological integration coordinate system[2]. Here, technologies are mapped in Cartesian space based on their levels of societal acceptance and technological integration. The coordinates are broken down into four generic quadrants, from the nascent *Emerging* technologies to the Big-Brother-esque *Police State*, the hopeful, consumer-driven *Grass Roots* and the golden *Techno-Utopia*, in which a technology is ubiquitous and well accepted by society in general.

Sager's coordinates help us understand how a technology develops as it moves from a new, untested idea into an integrated component of the modern technological scene, or alternatively, crashes and disappears, becoming an interesting historical footnote. Driving a technology from the *Emerging* quadrant into the *Techno-Utopia* is the goal of directed technological development. In the course, we consider methods for driving change as much as possible to avoid the *Police State,* in which technologies are ubiquitous but engender resentment or mistrust in the public. Even so, students must grapple with many technological innovations and ideas that propose to go against public acceptance initially in order to make a sufficient foothold on integration to become ubiquitous and accepted. This instrument must be understood as a *general* tool, and it is often instructive to show independent locations for relevant social groups (young people vs. elderly, Americans vs. Europeans, techno-geeks vs. Luddites, etc.). All technologies proposed and investigated by students during the course are mapped on these coordinates for relevant social groups, and plans for, or analysis of, their trajectory in these coordinates are discussed.

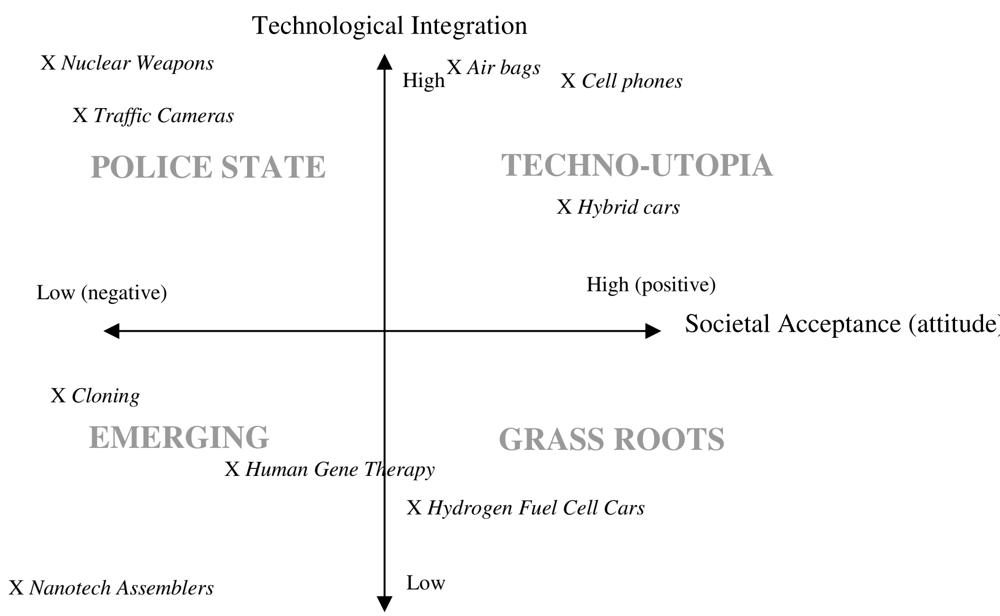

Figure 1: Sager's Technological Integration Coordinates[2] with sample technologies as mapped by students in the course.

To really understand the fundamentals of transitions in social acceptance and integration, students are provided with a variety of technological innovation models. These models help to categorize a variety of factors relating to technological change and help to understand how and why technologies move through Sager's coordinates.

1) **McKenzie's certainty trough**[3]. This model helps the students visualize the factors that affect perceptions of new technologies based on the social distance between the subject and knowledge production. Specifically, the McKenzie model suggests that managers (among other groups) act with much less uncertainty than engineers or scientists in many circumstances not because they want to, nor because they lack the intellectual capability to analyze the situation more closely, but because they *must* make decisions.

   Key to understanding the certainty trough is the idea that groups socially close to knowledge production (engineers, scientists, technical writers, etc.) show more uncertainty than non-technical peers, with those very far (socially) from knowledge production showing the greatest uncertainty and distrust. The uncertainty for knowledge producers takes two forms: *personal* uncertainty (knowing enough to know what is unknown) and *group* uncertainty (when multiple engineers disagree on some aspect of a technological application). Managers are often non-technical people who must make decisions on very technical problems based on a wide variety of inputs. When the engineers cannot agree, other factors drive the decisions, many times with disastrous results. In class, we use the uncertainty trough to help understand how various groups are likely to react when decisions are required, no matter how big or small, and how legislators, investors and consumers respond to opportunities relating to technological change.

2) **Power of Technology** model. Identified by Pip Coburn in *The Change Function*[4], this model relies on application of Moore's Law regarding the exponential increase in computing power over time (with a comparable drop in price for older generations) as well as the concept of 10X disruptive capability (suggesting that change occurs when a new technology improves capability by an order of magnitude). This is the 'build it and they will come' model of market development. In essence, this model purports that technology drives the market for, and acceptance of, the technology. Essentially, if the application is exciting enough and powerful enough, it will catch on.

   The *Power of Technology* model is useful for many case studies, such as the Segway personal transporter, a perfect example of a failed attempt at using this method. In the course, we reference the power of technology model when we see technologies that are being developed for non-existent markets or as major improvements to established (and often "good enough") technologies. It is important to stress that new innovations that follow this model may be incredibly important even though they fail in a specific market niche.

3) **Disruptive Innovation** model. Based on *The Innovator's Dilemma*[5] and *The Innovator's Solution*[6], the disruptive innovation model focuses on technologies that enter a market with lower performance than the current leaders, but appeal to a wide variety of consumers. The model states that, using Moore's Law extrapolated to technology in

general, a new technology will experience an initial exponential increase in capability and thereby will eventually catch and overtake existing technologies, especially with users who do not need or want the high-end performance of top systems.

The *Disruptive Innovation* model is perfectly reflected in the current success of the netbook. Netbooks have limited capability compared to a full-blown laptop, but are typically also much cheaper (~$300) and tend to be much more straightforward to operate and maintain. These devices have broken the mold currently used in laptop and portable computing and are changing the technological landscape, being sold at places such as Toys R Us and other vendors that typically will not handle computing equipment outside of gaming consoles. The disruptive innovation model is useful for thinking about how technology development may not follow the standard 'increasing capability' mode.

4) **The Change Function** model. This is the main premise of Pip Coburn's book[4], and plays an important role in our analysis of new technologies that enter any market (from national defense to the consumer market). The premise of the change function is simple: if the total perceived pain of adoption of a new technology is less than the crisis being experienced by the target consumer, change will occur. Of course, quantifying these abstract concepts is not possible, but a qualitative weighting is useful in understanding the way that change occurs.

   The *Change Function* model is used continuously throughout the course, as students attempt to carry out the prediction steps for technological analysis. The tool is especially important when it comes to analysis of suggestions for solutions to technological problems, as in our discussion of the urban transportation problem and in many of the assigned homework projects.

The combination of models for sociotechnological development with innovation models allows us to place some framework around a very complex and ephemeral conceptual core. These tools are not always applicable, not always appropriate, and not always complete, but they help the students frame ideas in relation to new technologies.

With these models in hand, students address specific technologies of interest in the modern environment. Key to this entire process is understanding the fundamental nature of the technology in question and its relationship to the existing infrastructure and technological landscape, so that the technical discussion remains sound. Equally important is for the students to be able to identify the key players (agencies, governmental or corporate bodies, consumers, and social groups) relevant to a specified technology and to consider each of the instruments from the perspective of each important group. When students begin to think this way, they dissolve away their own inherently calcified opinions on technology and begin to view the bigger picture, appreciating the 'why' as well as the 'how' of current technologies.

The Case Studies

It would be easy to take a single case study, say National Missile Defense and carry it through in-depth for the entire semester. This model was considered and discarded. The risk of specialization of the skills was deemed too great. It was feared that the students would not be able to generalize the skills to the rapidly changing world of technology. As such, the goals of the course were laid out as follows:

i) To develop an appreciation for the necessity of forward thinking in technology matters.

ii) To build up a methodology for sound projection, prediction and valuation of emerging technologies.

iii) To investigate a variety of important emerging technologies.

iv) To develop an understanding of the modern environment for emerging technologies.

v) To understand the roles of money, society and politics in technological development.

Of these, (i) and (ii) are considered the most important. Carrying a single case study through the semester will not help the students generalize these skills. As such, a syllabus and teaching methodology were developed to lead the students through increasingly sophisticated case studies, starting with historical technologies, advancing to new applications of modern, robust technologies, and then moving on to analysis of technologies in their infancy.

The course is currently taught using the following activities and case studies:

<u>Case Study #1:</u> The history of the cell phone in the US. This allows for an analysis of regulation and its influence on technological development, and also forces the students to consider the technological development cycle and the importance of projection and prediction. This discussion is typically handled in one lecture.

<u>Case Study #2:</u> Billy Mitchell and the history of modern air power, based on the accounts in *Flyboys* by James Bradley[7]. Here, students see the difficulties with entrenched beliefs and have a concrete example of the challenges of changing the basic nature of the technological landscape. This discussion takes at least a full lecture, and often spills over into a second period.

<u>Case Study #3:</u> Leonardo DaVinci's mechanisms. In this study, we see that DaVinci was far ahead of his contemporaries in development of mechanisms, but that his lack of mathematics for understanding flight caused him to waste significant effort on designing flying machines that would never support a human. He correctly *projected* that heavier-than-air flight was possible, based on his studies of birds, but he *predicted* the nature of human flight incorrectly due to his lack of understanding of aerodynamics.

<u>Case Study #4:</u> The sociotechnological development of the bicycle, based on *Of Bicycles, Bakelites and Bulbs: Toward a Theory of Sociotechnical Change*, W. E. Bijker[8]. Here, we look at a seemingly ludicrous device, the *high-wheel ordinary* bicycle, and see that its development actually follows a very rational path, based on social groups and uses of the device. This discussion, which also introduces the ideas of interpretational flexibility and relevant social groups, typically takes two full lectures.

Case Study #5: The *Challenger* and *Columbia* shuttle accidents. Here, we introduce the concept of McKenzie's uncertainty trough and how social distance from knowledge production has a strong influence on perceptions of a technology's capabilities. In these tragic accidents, engineers were split, based on their deep understanding of the technologies, while managers were forced to make decisions from a much-less informed position. This discussion typically runs an entire lecture.

Case Study #6: Personal Transportation:

Case Study #6a: The Segway personal transporter.

Here we see a technology that had a specific purpose (the iBot wheelchair) and was modified for a commercial application. We look at the techniques used to try to hype and sell the device, and study both the technology and its application as well as the wide gamut of inspired technologies. We also consider why this technology failed in its intended purpose. This leads to an introduction to the technological development models outlined previously.

Case Study #6b: Urban transportation.

Inspired by the Segway, we look more closely at the urban transportation problem. We consider the history of the interstate highway system[9] and compare it to the vision from GM at the 1940 World's Fair[10]. We look at the statistics related to urban transportation[11,12] to see the cost of congestion, and we consider the difficulties associated with the Big Dig in Boston. We then consider current ideas for modern urban transportation, from Dual-Mode vehicles to Personal Rapid Transit, applying to this problem the technology development tools we have explored. Students then propose and discuss alternatives.

Case Study #6c: Forward looking transportation ideas.

Here we look at some seemingly fanciful ideas that permeate modern thinking about the future of transportation, including the flying car and personal flying devices (rocket belts and jetpacks). We think about the maturity of the technologies, the promise of new capabilities, and the fundamental shift associated with flight-based urban transportation. We consider operational concepts, safety and infrastructure, and analyze the barriers to adoption of these technologies.

Case Study #7: Human genetic engineering and gene therapy. This is our first large case study on a truly emerging technology. We study the fundamental science of genetics at a high level, and analyze the methods used to perform genetic engineering on microbes, plants and animals. We look at current gene therapy trials and consider the implications for human gene therapy. We do projection and prediction as well as valuation, and consider the impact of genetic techniques on sport[13] and in the military.

Case Study #8: Nanotech assembler technology. This is the technology that everyone thinks of when discussing emerging tech, and it is the one that inspired Drexler to write *Engines* and therefore spawn this course. In this discussion, we focus on atomic-scale sensing and manipulation and think very long term about the possibility of molecular manufacturing and the implications of molecular assemblers. We study the analyses of Bill Joy[14] and Ray Kurzweil[15] a well as the very public war of words between Drexler and Prof. Robert Smalley[16]. Students end this segment of the course by discussing appropriate legislation for assembler technology (if such is even needed) and the implications of these techniques for other facets of engineering. Again, projection and prediction are carried out and the societal response is considered.

<u>Case Study #9:</u> Evolutionary computing and evolutionary design. This short discussion is intended to model the students' semester projects. In two lectures, we discuss the basics of evolutionary computing, the current applications and successes, and the implications of these techniques for engineering design, using all of the tools from the semester.

<u>Case Study #10:</u> Augmented Reality. Another short discussion used as needed in the course to balance presentation days between sections. Here, the focus is on the infrastructure required for high-quality augmented reality as well as the applications that will most likely see traction in the technological development cycle.

<u>Case Study #11:</u> Cybernetics and the future of prostheses. This discussion is typically the final one of the semester, as we discuss techniques for interfacing humans and machines for therapeutic reasons as well as augmentation. Questions relating to the implications of the brain-machine interface and the definition of what it means to be human round out our discussions.

The key concept here is to build an understanding of the issues associated with technological development using simple historical examples, and to slowly expand from concrete, easy to grasp technologies with major infrastructure and societal obstacles (such as transportation) to more complex technologies in their infancy, whose major obstacles must be discerned through careful analysis.

Assignments

The keys to successful implementation of this course are student engagement and an open, wide-ranging discussion format. To engender these, we rely on standard instructor-led discussions, but also on having students work in small groups and present material to the other students in the section.

As a regular part of the discussions on technologies in the course, students work in small groups addressing fundamental, concrete issues related to the current classroom topic. Using class time for these *thought labs* allows the instructor to interact with and guide the analysis as each group brainstorms new ideas. During the course, we carry out three thought labs: urban transportation, human genetic engineering in the military, and regulation of nanotech assembler technologies. Students present the results of their small group discussion and lead a Q&A session while their classmates perform a peer evaluation. These thought labs result in many novel ideas and bring forward points of view from students who tend to remain silent in a larger group, which leads to a very robust and wide-ranging discussion.

The capstone activity for students in the course is to research and prepare a complete case study. The product is not, however, a written paper. The results of each 4-student team's work are presented across two full lecture days (100 minutes, total). Students are expected to bring the class up to speed on the basics of the technology, to discuss its history and current state of the art, and to project and predict future improvements and applications using all of the tools developed during the semester.

Students carrying out their semester presentations prepare and hand out notes and reference materials just as an instructor would do. In a 20-24 students section (typical of this class), these presentations take up approximately three weeks of the sixteen week semester. It is vital that the instructor maintain appropriate focus during these discussions and keep the students on task by leading the Q&A session at the end of each group's work and by correcting any misstatements or errors in the presentation, as he/she has reviewed all of the materials in advance. Quizzes over the material are also a part of the standard engagement methodology for the students.

Students are also asked to write position papers on a wide variety of technological areas such as national missile defense, germline genetic engineering and flight-based personal transportation. Weekly quizzes round out the grading instruments and force the students to stay up-to-date with the discussion. The weekly quiz has proven invaluable in maintaining a core knowledge set so that discussions can be carried out with minimal repetition and a significant reduction in erroneous assumptions by the students.

Assessment

Grading is not necessarily assessment unless it is carefully designed. The assessments for this course rely on grades for the semester project, using a published rubric, but also on course critique sheets filled out anonymously by the students and on an Exit Survey of all Systems Engineering majors for each graduating class. In this section, we discuss some of the implications of the results generated.

Project Scores

Each student is required to present one quarter of the total content for a team's project, and each student is evaluated separately on content (technical background, state-of-the-art, societal analysis, projection and prediction, as appropriate), presentation (quality of A/V, oral presentation, organization, clarity), and overall integration with the remainder of the group (no repeated information, appropriate reliance on other students' work, etc.). The group is required to generate a sample homework assignment that is also evaluated for pedagogical merit in the framework of the course (based on criteria established by the homework actually assigned in the class).

We rely on a combination of instructor and peer evaluations for the final score, typically weighting the instructor score evenly with the students' aggregate score, but with the understanding that outliers will be disregarded and that the instructor has the right to overrule the students' score in case of a disagreement (which has never occurred). This method helps keep the instructor in tune with the expectations of the class, but also helps capture those situations in which the material was not properly tuned for the audience.

Since 2005, 63% of students have received an A on the project, 31% a B and 6% a C. No student achieved less than a 'C' on this assignment, which comprises 20-25% of the final grade in the course. The mean score was a 91% with a standard deviation of 5.3%. These numbers, which remain more or less consistent across all of the class years and all of the sections, reflect high quality work and a clear understanding of the methods and techniques from the course. Modeling the exercise is considered a vital component of the students' success on this project. Many students comment, at the completion of the course, that they did not anticipate how much work went into a lecture, which is another positive outcome from the effort.

Course Critiques

The course-related questions on the standard department course critique sheet used from 2005 – 2007 included two items in addition to questions relating to the instructor's teaching style and management of the course. The following table shows the students' responses to these two items over the 2005-2007 timeframe.

Metric	Year	1 (best)	2	3	4	5 (worst)
Overall Effectiveness Nurtured intellectual growth and maturity of the student in the course material and in skills such as communications, computer use and problem solving technique	2005 2006 2007	17 19 28	0 2 2	0 0 0	0 0 0	0 0 0
Course Evaluation Relative to your other courses, how do you rate the depth of the course material, homework, laboratory exercises and textbook?	2005 2006 2007	16 20 27	1 1 3	0 0 0	0 0 0	0 0 0

In 2008, the department changed its evaluation procedure. The only score for a course was 'overall effectiveness' rated on a scale of "Excellent," "Good," "Fair," and "Poor." The emerging technologies class received 22 "Excellent" ratings and 2 "Good" from the 24 students who took the course in 2008. The honors equivalent, taken by 16 Honors Systems Engineers, received 15 "Excellent" scores and one non-answer. Clearly, the students see the value of the methods applied and appreciate the nature of the course material.

Exit Survey

Each student in Systems Engineering is required to take five major electives from a list of thirteen offered by the department and several others offered by other departments. Of the 102 students in Systems Engineering graduating class of 2008, 40 of them took the emerging technologies course or the honors equivalent. Our exist survey asked students to pick their favorite elective course, and emerging technologies ranked second overall, with a total of 17.3% of the votes (first place was Mobile Robot Design at 30%). Thus, slightly less than half of the students who took emerging technologies considered it the best of the five elective courses that they took. For a non-traditional course such as this to outshine all of the other electives in the major is a strong testament to the impact of this different way of looking at technology and the students' perception of the same. Not one student selected this course as the worst elective they had taken.

While anecdotes are rarely of deep and meaningful value, the following are comments from students on the exit survey directly relating to the emerging technologies course:

> This course took us beyond the scope of a normal undergraduate and let us view the world as a shifting, changing body of technological advances. The prediction/projection skill is one that is rarely found in people our age, and is immensely useful in a number of applications.
>
> I get bored very easily and this class was constantly changing and exploring new ideas. It kept me interested. I actually took this as an extra class because I did not have room for it in my matrix.
>
> It was the best course I have ever taken, hands down. It was interesting and very informative. I learned a lot about new technologies, which was really cool.
>
> It was interesting, informative, and showed the 'why' of engineering, where the other classes focused on the 'how'.
>
> Hands down the best (and most different) class that I've taken. ... I didn't want to take bathroom breaks during class because I didn't want to miss anything.

Conclusion

It is difficult to anticipate the impact of this course on the students' careers, but it is clear that the topic is interesting, motivating and valued. The most challenging aspect of the course is maintaining currency in the various case studies, which often require major updates every year. Nonetheless, the course is very rewarding to teach, and offers students a very different view of the technological world in which their engineering discipline operates. From a departmental perspective, as well as for ABET and the mission of the United States Naval Academy, this course is a powerful tool in the education of modern engineers.

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