AC 2011-1211: SE CAPSTONE: INTEGRATING SYSTEMS ENGINEERING FUNDAMENTALS TO ENGINEERING CAPSTONE PROJECTS: EXPERIENTIAL AND ACTIVE

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SE Capstone: Experimental Learning in Distributed Classroom Environment for Systems Engineering Capstone Projects

Abstract

This paper highlights the use of active learning in a capstone engineering design track to create a distributed learning environment where students apply their knowledge of Systems Engineering fundamentals to complete a design project for a real-world customer. An organizational structure consisting of students at Missouri University of Science and Technology and distance education students across the country was developed for the use in two courses, mirroring current industry practices. Six student design teams were formed at the beginning of the first course; with each team assigned a graduate student facilitator, a faculty mentor, and a professional practitioner acting as an industry mentor to provide additional guidance, structure, and support. The capstone project was to implement systems engineering fundamentals and principles to design, specify, and construct a wireless vest for the use in immersive training, satisfying a documented need statement provided by United States of America's Department of Defense representatives. This paper highlights the implementation of this pedagogy within a distance education environment. Further, this paper highlights the development and use of this new pedagogy and elaborates on the details of the implementation. The paper provides a thorough synopsis of the courses' structure, an elaboration on shortcomings, a discussion of survey results provided as student feedback, and a description of the students' perception of learning.

Introduction

The instruction of systems engineering is a difficult task, as this new yet prevalent area of engineering requires knowledge within a practitioner that encompasses breadth and depth across various fields of engineering[1]. It is a requirement that any systems engineer have both breadth and depth in various niches of engineering poses an interesting problem in the development of any pedagogy relative to the instruction of key systems engineering fundamentals. These fundamentals include design alternative identification, cost assessments, interface integration, risk identification, and many others[2]. It is through the instruction of systems engineering that key skill sets necessary for completing the complex engineering tasks of today can be attained. Thus, in order to begin to develop engineering students that possess these key skill sets a new form of education should be developed. The efforts undertaken within the Missouri University of Science and Technology seek to close this educational gap through the implementation of a two-course senior design capstone course. This new coursework was developed to provide students with the capability to put into practice the systems engineering process in order to conceptualize, design, and build a product and understanding the entire life cycle of engineering. Hence, this coursework provides a very unique educational structure that introduces students to the concept of life-cycle engineering.

The skill sets of the future engineer are encompassed within systems engineering. As stated by Bordogna, "Here is one take on how we will identify engineers in the future. They will be: holistic designers, astute makers, trusted innovators, harm avoiders, change agents, master integrators, enterprise enablers, knowledge handlers, and technology stewards."[3] These key skills are part of the systems engineering curriculum. This is because in systems engineering the purpose often begins with a customer statement from which a relevant detailed design must emerge. Hence, it is the effort of this new capstone course to provide a relevant education for our graduates that will allow them to succeed in the industrial workforce. Currently, the industrial perceptions of weakness are: technical arrogance, no understanding of the manufacturing processes, a desire for complicated and "high-tech" solutions, lack of design capability or creativity, lack of appreciation for considering alternatives, no knowledge of value engineering, everyone wanting to be an analyst, poor perception of overall project engineering process, narrow view of engineering and related disciplines, not wanting to get their hands dirty, considering manufacturing work as boring, weak communications skills, little skill or experience working in teams, being taught to work as individuals[4]. Hence, through the use of the life-cycle engineering tasks encompassed within systems engineering many if not all of these weaknesses are directly addressed. Students in systems engineering must consider the entire life-cycle, beginning from preliminary conceptual design all the way down to fabrication and beyond, into the maintainability and project retirement/closure. These new courses at Missouri S&T seek to accomplish this by extending a course into a full academic year of instruction, which will take the students from alternatives identification, to cost assessment, constraints, limitations, risk avoidance, and include the manufacturing of the component, all within an active learning environment. Active learning, in short, requires students to do meaningful learning activities and to think about what they are doing[5]. Students will address a key design problem through the use of industrial mentors, graduate managers, and faculty advisement. In addition, they will undergo a review process similar to that used in industry today all within a distance learning environment.

The subsequent sections of this paper provide a thorough summary of the methodology, an ad rem discussion regarding the first semester course, and future focus (i.e. description of the 2nd course in the sequence). In addition, details regarding the employment of graduate doctorial students as program managers, the serviceability of using experienced practitioners as mentors and guides is explained, and the outcomes in terms of deliverables are fully elaborated upon within the methodology section of the paper. The discussion section possesses remarks regarding the implementation process of this new educational undertaking, which includes difficulties encountered, resulting student projects, distance education considerations and outcomes, and work group dynamics. Finally, the paper concludes by describing the future directions of the course and elaborating on the second course.

Course Details and Description

Two courses were developed within the current existing systems engineering curriculum at the Missouri University of Science and Technology (Missouri S&T). The first course was embedded within the systems engineering program at Missouri S&T as an introductory course to the field of systems engineering. This first course was made available to senior and entry masters students. The prerequisites for entry into the two-course track consisted of students having senior level status within an engineering discipline or first semester graduate students in an engineering or hard science field of study. This supplied a variety of knowledge, which was necessary to accomplish the systems engineering as the background knowledge was diverse, ample, and complimentary for the design tasks inherent within this new capstone course. This paper will focus on revealing the intricacies of the first course and the results of the new pedagogy.

The Learning Environment

The learning environment of this first course consisted of implementing multiple facets of education technology and methodologies as the courses consisted of distance learners as well as on campus students. This created a unique environment for the application of "learning by doing" as students were geographically dispersed throughout the continental United States. Hence, the course contained both a lecture component and out of class meetings. The course was taught through Cisco WebEx®, which is an online meeting and video conferencing tool. All course lectures were recorded and archived in order to assure students had the capability to review covered lecture material or reflect upon class discussions regarding the design of this immersion-training vest. The class was broken up in to six work groups whose members were a mixture of backgrounds in engineering disciplines and geographical location. Each of the teams was supplied with a doctorial student who assumed the "project manager" role. Each team was also provided with an industrial practitioner who took the "industrial mentor" role. The details regarding the roles of the doctorial students and practitioners are detailed in the subsequent methodology section of this paper. The teams were also supplied with a "faculty advisor" that was to supply both technical guidance as well as expertise in a variety of topics. Finally, all teams had one point of contact that assumed the "Dept. of Defense Representative" role that was the acting stakeholder (customer). All teams had to interact with this stakeholder.
This learning environment has seldom been implemented within academia, mimicking the organizational characteristics of current industry partners. This structure is depicted in Figure 1.

Hence, students had the availability to setup ad-hoc meetings with various people in order to discuss current design endeavors or conflicts. A communication network was created where students could use Blackboard® to communicate, exchange documents, and access course lecture materials. This environment provided the capability for students to participate in all aspects of the course, as communication and accessibility were readily available regardless of the geographical location or time of day. The uniqueness of this environment was that it allowed for all contributive members to easily connect with their groups and openly discuss issues and problems as they arose while undertaking this complex system design. Sharma and Mishra[6] provide a great deal of case studies across a variety of fields. These fields include the use of case studies in distance learning within sports medicine, computer science, medical, and a few others. In all cases the use of case studies are related to an industrial problem often with results known. However, in our pedagogy does not have well known results, rather it is the application of the systems engineering process and tools that is the main point for evaluation of the student performance.

Course 1 Description Summary

The first course consisted of giving students the task of deriving a detailed concept and design through the employment of systems engineering tools and mechanism. The project or design request consisted of designing a wireless immersive training vest for the use of preparing soldiers for combat situations they will undoubtedly encounter in their deployment to an overseas war arena. This specificity was to be derived directly by the students through interactions with a real Department of Defense representative, who took up the role of the customer, providing a real need statement. The students then were instructed in development of a

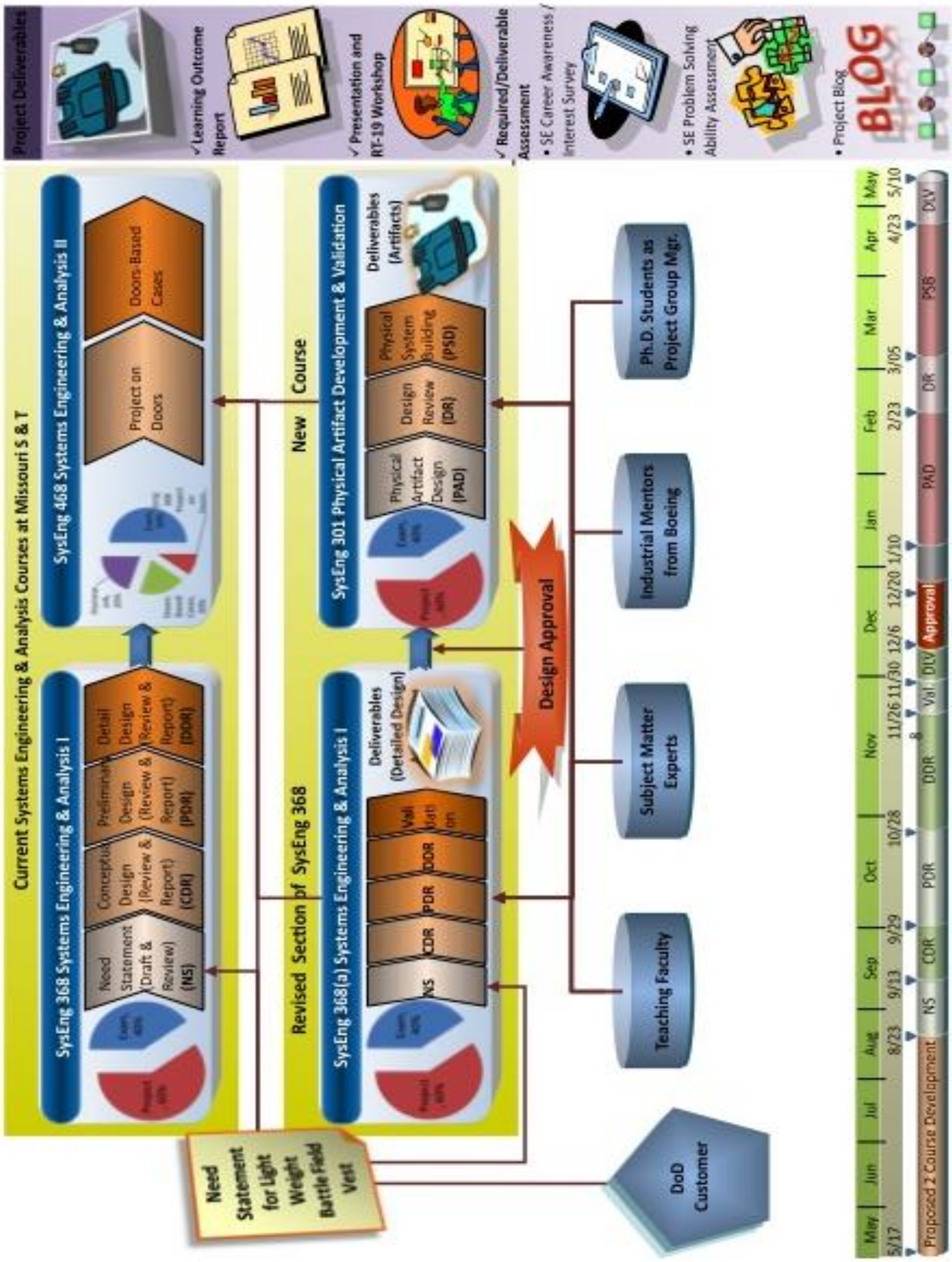

Figure 1: Overview of Capstone Course Structure

need statement relative to the customer's perceptions and expressed priority. Once an agreement between the design team and the customer was obtained, the students were instructed in the preliminary design methodologies contained within systems engineering. Their goal was to derive a detailed design for this immersive training vest. Students had clear goals throughout the semester as well as entering and exiting criteria for various design reviews. The detailed design derived in this first course will then be used in the 2nd course, which will take the design into the manufacturing, testing, and validation phases.

Methodology

The course was conducted by first deriving a need statement through interaction with the Department of Defense customer through analysis of realistic scenarios and then by having the student design teams elaborating on that information to create a feasible design that met the customer's needs. Please refer to Figure 1 for clarification of the course structures. The students were guided through a rigorous program that included project management, creation of specifications, and design reviews to develop this need statement into a final design while traversing the entire systems development life cycle. The design reviews were conducted using video conferencing software by the graduate student facilitators under the guidance of the faculty mentors, providing all students involved experience in a distributed collaborative environment commonly found in both industry and academia. The students will continue the system process in the second course where they will tackle the challenges of prototyping and validation. In the following subsections we will provide a brief discussion of the use of doctorial students, practitioners, and faculty to create this new learning environment.

Doctorial Students as Group Managers

Doctorial students in the systems engineering program were embedded within the curriculum to provide guidance, efficiency, and coordination among the distance and campus students. The doctorial students' advanced knowledge of the systems engineering process facilitated in the teaching of systems engineering fundamentals. Hence, they provided the design groups with advance knowledge regarding tasks and processes. Their direct contribution was increased as they provided the students with a direct "go-to" person from whom they could attain clarification. Furthermore, the doctorial students coordinated meeting times, they provided guidance, and controlled the meetings. This allowed student teams to keep focused during outside class meetings, and allowed them to attain instant feedback and discussion during the meetings resulting in more thorough and valuable designs.

Each doctorial student then had to give a weekly report regarding the student team's progress, elaborate on team problems and difficulties, and provide resolutions to team issues. The most important aspect of their participation was to not only to reassure the team and keep them focused on tasks, but to provide the students with immediate feedback regarding their design discussions. The graduate students contributed in the teaching of systems engineering fundamentals as they could elaborate and explain concepts through one-on-one discussions with the students. This additional education proved valuable as the course lectures contained general matter and did not emphasize on any one team's specific issues. It is through the use of these doctorial graduate student facilitators that greatly attributed to the design and in the learning of systems engineering fundamental concepts.

Boeing Engineers as Industry Mentors

The embedding of engineering practitioners was also implemented within the curriculum, which provided design teams with a more comprehensive, rigorous, and experienced knowledge from which they could draw designing and engineering considerations. These mentors provided the “reality-check” to the student teams. The reality-check consisted of the mentors emphasizing the difference between theory and application. Hence, the key attribute of the mentors kept the students within a design scope that could be realizable. The mentors provided this reality-check by attending the team’s meetings and contributed by keeping students in a clear doable path throughout their design endeavors.

Department of Defense Affiliated Personnel as Mentors

One of the DOD mentors for the undergraduate students was the local ROTC commanding officer. Both he and members of his command assisted the students in finding the DOD specific knowledge that added the necessary realism to the student designs. This included briefings that were provided to military personnel prior to deployment in current war zones and sample physical artifacts (for example, interceptor body armor) for the students to examine and to learn the details of the system they were designing.

Another mentor affiliated with the Department of Defense was a Defense Industry training consultant. He met with the students twice to advise them on the feasibility of the solutions they had found and provided guidance on current state of the art. In addition, he was invaluable as a contact with both vendors and other training personnel to assist the students in gathering information on existing technologies and how they might be procured.

Deliverables

The goal of this course was to provide a detailed design of the system to be physically constructed in the second course of the series. To assess the course and work towards this final project deliverable, there were four milestones during the course: the approval of the Need Statement, the Conceptual Design Review (CDR), the Preliminary Design Review (PDR), and the Detailed Design Review (DDR).

The need statement was the first deliverable for the course. This was a written assessment of what the students thought the customer’s desires were and what were the key system characteristics were of highest value to the customer. After they were submitted, these documents were assessed by one of the PhD students acting as the DOD customer and were returned to the students with comments. Two iterations were completed to stress two important systems engineering concepts; refining the problem into a form that is appropriate for the two courses and the process of soliciting needs from a customer. Upon final approval, the need statements were used to determine the high level requirements and develop the initial system concepts.

The three reviews were one hour review sessions done using WebEx software with each of the student groups presenting separately to insure a diversity of designs. The CDR and PDR events allowed the students an opportunity to present their initial concept and preliminary design (respectively) and receive feedback from the course instructor and the PhD student DOD customer. These review sessions were scheduled outside of the regular class meeting to allow both the distance and the local students an opportunity to present their results as a team. Feedback was provided for these reviews in the form of oral comments given during the review and written comments provided after the review was completed. Each of these two reviews was also accompanied by written documentation that provided the details of the design to that point in the development process. These written reports were graded using a common rubric provided at the beginning of the course as part of the class description. Figure 2 gives a portion of the rubric used for the evaluation of the design project. In addition to the items covered in Figure 2, the projects were also evaluated on the final system architecture, the grammar and appearance of the reports, and timely submission. The grades achieved by the students in the course were similar to previous semesters and of high quality. Due to the final group project being the major assessment of the student's grades, providing the rubric at the beginning of the course and outlining the exact requirements likely contributes to this strong performance.

Item	9-10	7-8	5-6	3-4	1-2	0
Requirements development / TPMs (×2)	Requirements are clear and concise, TPMs prioritized and reflect customer statement of need, assumptions justified and documented	TPMs not prioritized, one or two minor ambiguities.	One or more assumptions are not justified. One major ambiguity.	No explanation of TPMs. One or more ambiguities in requirements. Several minor errors.	Two or three major requirements missing, two or more significant errors	Four or more requirements missing.
Functional Analysis and Decomposition	All requirements are mapped to a function. Mappings are documented and defensible.	One or two minor ambiguities in requirement mappings, only two levels of decomposition.	One or two requirements not clearly mapped to a function, documentation is unclear.	Mapping of requirements to functions is unclear, One requirement is not associated with a function.	Only one level of functional decomposition, two or more requirements not associated with a function.	Functional Analysis not connected to requirements.
Cost estimate (x1/2)	Believable, all details are documented and justified	One or two minor errors.	Documentation is thin. Hand calculations are needed to follow the discussion. One major error.	One or more parts are not justified. Values used are not referenced. Several minor errors.	Off by a factor of 4x or more	Off by a factor of 10x or more
Risk Assessment	Clear discussion of risks and basis for decision. Methods of risk mitigation are discussed.	One or two minor errors in risk mitigation plan.	One major risk not accounted for. Level of risk not clearly defined in an area.	Two or more major risks not accounted for.	Concept of risk is confused. Wrong analysis is performed.	No risk analysis performed
Technical Management Plan/WBS /Support Plan	Clear schedule of work, work responsibilities are assigned and plan is presented for support of the system.	Two or more minor errors in schedule, one minor omission in WBS and/or support plan.	Schedule is hard to follow, two or three minor elements missing from WBS.	Support plan is vague, one major element missing from WBS.	Technical management plan missing a section of work, multiple elements missing from WBS.	Technical management plan missing sections of work, no support plan.

Figure 2: Portion of Grading Rubric for Class Project

The last review was the detailed design review. This design review was conducted with the entire class to share the various solutions found by the groups and to allow for the students to ask questions of the other groups. This also served as the final exam for the students, with the final project report due to accompany the presentation. This final report was is the form of a cover letter discussing the group's recommendation, addressing key attributes of the system, cost, schedule, and risk associated with that recommendation. The remainder of this report presented the methodology followed to arrive at the recommended solution, the technologies considered, supporting material for the decisions made, and the drawings and specifications necessary to synthesize a physical system from these design concepts.

Six independent designs were created in the course, one by each of the student groups. The independence of the designs was maintained by encouraging competition between the groups. Competition can create tension between the groups, but by providing the grading rubric to the students at the beginning of the class this was alleviated. Because of the time constraints on the class, all of the group designs made us of Consumer-off-the-shelf (COTS) technologies, but there was also a good amount of new design which varied between the groups.

Discussion

One of the biggest challenges early in the course was getting the groups formed and communication established while mixing both distance and local students. The majority of the distance students were first semester MS students currently employed as engineers, while the majority of local students were seniors in mechanical engineering. While this expended nearly a full week of the class, the benefit of having a distributed classroom environment that simulates today's workplace more than made up for the delay. There was also some disparity in the approaches to the problems by these students, with the distance students focusing more on lower risk solutions and avenues than the local students. The local students tended to have creative ideas using design aspects taken from current research, but with the abbreviated class schedule the risk associated with completing the design was too high to pursue these concepts.

A key aspect of this research was the use of a distributed, virtual classroom environment for a capstone engineering experience. The classroom lectures were done using the tools provided by WebEx, but the coordination of groups took additional effort. This was accomplished using three feedback systems. Self-coordination was encouraged within the groups by allowing the group members to provide feedback on the performance of the other group members. This needed to be carefully monitored to prevent abuse, and so the peer evaluations submitted by the students were validated both by the PhD student project managers and by the course instructor during the three review sessions. Comments made by the students in the evaluation were investigated by asking the students specific information about the system during these review sessions to determine if indeed all of the students had been contributing. In addition, the PhD student project managers acted as the team manager to ensure cooperation within the groups. The third oversight of the groups was provided by the faculty mentors and the course instructor, verifying that the students were properly rewarded for their contribution to the overall group project effort.

The main highlights of the course were the three design reviews, with the final review being the presentation of the final design and the concept that will be produced for the follow-on course. These were the milestones for the student groups to show their designs and receive feedback on their work. Unlike other undergraduate courses, the design project for this course not only involved a high level of detail but also included a strong interdisciplinary approach. This made some of the students uncomfortable with the deliverables of the project. This was overcome by providing subject matter experts from both the assisting faculty and from industry to assist the groups in areas that their members did not have expertise. In this way, the students were able to focus more on the systems engineering approach and less on the details of their particular engineering disciplines. In addition, as most of the undergraduate students were mechanical engineering majors, the instructor for the first course was able to use his background in mechanical engineering to provide relatable examples to the students.

One of the main difficulties with teaching this course was the pace at which the course started to move. Although we had planned for a fast paced course, it was still a faster than anticipated and additional contingencies would have been helpful when the students moved into the higher detail design work. A high level overview of the systems engineering process should also be provided earlier in the course to assist the students in planning their project and preparing for the final deliverables. In addition, the students were allowed to organize into groups as they like; it would have been preferable to have the students organized in a manner that would provide the greatest distribution of their expertise. Rather than have four electrical engineers working in a group, the groups would be formed with a mixture of mechanical, electrical, software, etc. depending on the makeup of the class roster. The introduction of additional subject matter experts later in last semester's course was helpful, but having these personnel on-board at the beginning of the class would have added greatly to the learning experience.

The first semester of the two course track used two assessments in addition to normal classroom grading. Following the mid-term evaluation of the course work a plus-minus-delta evaluation was given to the students to determine if there were any major issues identified by the students. Six of the nine on-campus students responded to this evaluation, but only one of the distance students responded. The reason is not known, but since the evaluation was returned by email it is thought that there was a perceived lack of anonymity limiting student participation. Although the response was sent to a neutral party who stripped any identifying marks, submission by email is usually associated with the sender being identified. The second evaluation was administered three weeks before the end of the semester, and was an anonymous survey to determine the effectiveness of the class based on the material presented, the usefulness of the homework, the effectiveness of the instructor, and how well the students thought the learning goals were achieved. Numerical values were assigned to the responses and the results were provided to the course instructor. For this survey, there eight of the local students and nine of the distance students responded. All of the numerical evaluations are based on a 4.0 scale.

The reaction of the students to the course overall was positive, with the local students rating the overall effectiveness of the course at 3.7 and the distance students rating the effectiveness at a 3.1. The major difference here was one outlier in the distance students who did not feel the course material was beneficial, ranking the course effectiveness as 0.0. The effectiveness of the material presented was ranked an average of 3.1, and the effectiveness of the instructor was rated a 3.8 by the on-campus students and 3.33 by the distance students. Although the most prominent negative comment was the lack of time to complete the full design, most of the students did not feel that the learning goals were undermined too severely, giving the course a rating of 3.2. The comments for both the distance and the on campus students indicated that the integration of local students and distance students caused some issues with the presentation of the lectures. The distance students preferred Powerpoint® for the presentation of the material, while the local students preferred the use of whiteboards to facilitate the discussions. All of the students commented that they much preferred working on a 'real-world' problem, but that because it was a 'real-world' problem it required an accelerated schedule, which caused mixed emotions in many.

Conclusions

The goal of this semester was to familiarize the students with the systems engineering process and have them apply this knowledge to a complex design project. The evaluation of the student's work using the rubric shown in figure 2 showed that the average performance of the students was similar to previous offerings of this course even after the additional work load introduced by requiring a more detailed engineering design. We assessed how well the students were learning the systems engineering methods by conducting mock reviews similar to the actual design regimes followed in industry. A PhD student served as the DOD customer for the reviews, and the results of the students work were presented and discussed. Because distance students were also involved, these review sessions were done using collaboration software (WebEx). Each group performed three one hour presentations that were graded based on the final project rubric. In addition, components of the final written project document were evaluated as the course progressed to monitor group performance and provide feedback. The area which seems to be the most difficult for the students to follow through as they progress through the course are the key system characteristic attributes. For the most part the students received the course positively, with only one student responding that they did not receive much value from the course. Future iterations of the course will include additional subject matter experts to lessen the amount of discipline specific engineering information the students must acquire and allow them to focus on the main systems engineering topics of the course.

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