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Enhancing Systems Engineering Content in Aerospace Courses: Capstone Design and Senior Technical Electives

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Abstract

Systems Engineering (SE) has long been a staple in the aerospace engineering industry, but it has been slow to gain traction in academia. This is due to both the challenge of incorporating SE content in the traditional framework of engineering curricula and the lack of experience with SE by academic practitioners. This paper presents the results of a 17 month project between two large public institutions to investigate and incorporate educational tools and practical experiences in the teaching of SE in existing design courses, to be later transitioned into a broad range of courses within the curricula. The main objective of the project introduced students to the practical applications of the fundamentals of SE without displacing other course content. The target courses at Texas A&M University included three senior-level courses, of which two were required capstone design courses and one an optional technical design elective. For the capstone design courses, this content was added primarily to the early part of the semester and consisted of identifying a customer need, conducting a requirements definition study, developing a Concept of Operations, and subsequently translating it into a Request for Proposal. For the design elective, this project enhanced prior SE content in the course but then integrated the course into the collective instruction within the broad Systems Engineering Design Initiative effort at the institution.

The paper will present the modifications to course content, pedagogy used in the project, results from assessment of the project, lessons learned by the instructors, and comments from both students in the course and industry advisory board members who reviewed the course deliverables. In summary, project outcomes were achieved, and the students felt their experiences were particularly rewarding. Students enjoyed teaming on a project involving another university, and the external industry advisory board members remarked on the valuable real-world experience students received through the project. This approach to incorporating SE content within current courses with minimal disruption to other content should be applicable to most engineering programs.

Introduction

The purpose of the 17 month long project at Texas A&M University (TAMU) was to extend a two year prior effort started at the University of Texas (UT) where a Systems Engineering Design Initiative (SEDI) had been defined. This project involved TAMU using previous lessons learned in the incorporation of SEDI to extend the initiative. Through this process, TAMU faculty investigated and developed educational tools and practical experience for teaching Systems Engineering (SE) principles and practices in their particular program with the desire to later transition SE into a broad range of aerospace engineering courses offered at the institution. Selected SE principles from the SEDI effort were incorporated into senior-level capstone design courses, Aerospace Vehicle Design I and Aerospace Vehicle Design II during Fall 2013 and Spring 2014, respectively, at TAMU. Assessments and evaluations of incorporating SE principles into these courses were conducted. A senior-level technical design elective, Cockpit Systems & Displays, already contained significant SE content, but it was enhanced, upgraded, and then integrated into the two capstone design courses utilized in this project during Spring 2014. To provide a foundation to adequately compare SEDI efforts between the two institutions, the student course design challenge for the design elective was purposely selected and directly coupled to allow a joint demonstration at the end between the students. The structure of the capstone design courses offered at the two institutions, however, were too diverse to have a joint cooperative project.

The project commenced with instructors studying SEDI documentation developed during the prior work along with an assessment of current SE content in the two capstone design courses. Particular SE topics needing to be added to Aerospace Vehicle Design I and Aerospace Vehicle Design II were identified, and a new syllabus was created for each course to reflect added content. In the design elective, the existing topics related to SE were aligned with the new skills identified in Aerospace Vehicle Design I with additional changes to existing SE lectures proposed.

Systems Engineering Concepts Addressed in the Courses

In Chaput's 2013 document, he defined SE as a rigorous, disciplined, and systematic engineering approach to design, development, production, and support of products and systems. SE has a long history in the aerospace industry as it was a fundamental basis for certificated aircraft development for over five decades. While many students today had heard of it, few understand what it truly entailed. SE was a product life cycle focused activity that began with technology and system concept development and continued through operational employment, support and eventually system retirement. SE comprised a top down/bottoms up approach to product design, development, employment, and support. The overall system was decomposed into elements and subsystems. Every element and subsystem contributed to the performance of the next level up (vertically) and also contributed to the associated cost, schedule and risk. Elements and subsystems were also linked horizontally and resulted in mutual interactions, some positive and some not. It was only when all the parts and components were defined and linked (initially by requirement, then by analysis or simulation, and finally physically) that the true performance (and risk) of a system was understood and managed[1].

SE was formalized into a series of documents created for the U.S. Government, starting with the seminal Mil-Std-499 Systems Engineering Management, which provided the program manager criteria for evaluating engineering planning and output[2]. Although this document focused more on the process, procedures, and project management aspects of SE, it was used as a general guide for SE overall and for help in selecting which SE concepts to incorporate. Using the material from Chaput and Mil-Std-499, the instructors familiarized or re-familiarized themselves as necessary and then used these resources as menus to select aspects of SE most appropriate to incorporate into existing courses. Particular SE aspects related to improving and enhancing the requirements definition aspects were selected for Aerospace Vehicle Design I as this is a focus for the course. Relevant to Aerospace Vehicle Design II, SE aspects to improve and enhance Validation and Verification procedures and documentation were selected with a particular emphasis on Entrance and Exit criteria for testing. The SE aspects selected for the Cockpit Systems & Displays course focused on improving the Risk Assessment, Risk Mitigation, and Risk Management aspects, in addition to improving the project management and tracking.

Courses Descriptions and Modifications

Figure 1 displays course relationships for the three courses contained in the project. The capstone design course sequence consists of Aerospace Vehicle Design I and Aerospace Vehicle Design II, each one semester long, offered in successively. Cockpit Systems & Displays is also a one semester course and is an optional course students can complete. Students may elect to take Aerospace Vehicle Design II and Cockpit Systems & Displays concurrently. In addition to the course description, learning objectives follow for each of the three courses is included.

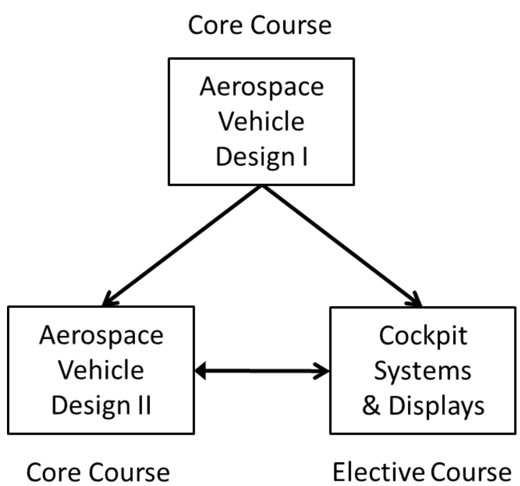

Figure 1. Relationships between courses in the project.

Aerospace Vehicle Design I

This first course in the capstone design sequence familiarizes aerospace engineering students with the methodology and decision making process involved in designing airplanes. It is the beginning course of a two-course sequence with the intent to Design-Build-Test-Fly. Faculty give students a Request for Proposal (RFP) at the beginning of the course to use in designing an airplane to meet the given mission specifications. A significant portion of the design work is completed by hand, but specialized airplane software tools are also be used for certain aspects of the design process. Students document the progress of the design through a series of professional quality, regularly scheduled Oral Reports.

Learning objectives for the course include:

1. Analyze and interpret customer requirements for a flight vehicle, size a flight vehicle to satisfy performance constraints, and determine suitable configurations for a specified mission.
2. Work successfully as a member of a team.
3. Conduct and document a detailed and comprehensive preliminary design of a flight vehicle.
4. Define system relationships and interactions between aerodynamics, structures and materials, dynamics and control, propulsion, performance, and internal systems on the design of a flight vehicle.
5. Recognize the role of civil and military regulations and the importance of considering safety, reliability, and maintenance considerations in flight vehicle design.
6. Communicate design results in briefings and presentations.

Modifications to existing Aerospace Vehicle Design I during Fall 2013

Prior to the start of this project, completion of six scheduled reports were used to address the learning objectives. To introduce the desired SE content, an entirely new report was introduced to focus on identifying customer needs, Concept of Operations (ConOps), requirements, and RFP generation, all aspects of the integrated SE curriculum. To avoid increasing the course deliverables to seven reports, the original six reports were re-structured into five reports. This was done by re-distributing and in many cases combining the deliverables more evenly across all reports. Only one deliverable content was eliminated, although this content was still included in the lectures. In addition to changes to the Oral Reports, instructors addressed the addition of SE topics in the course using a couple of methods. Telecons with representatives from industry/government organizations were added to the course to provide actual SE experience in defining requirements. In addition, overlap between previous topics were reduced to allow for two new lectures being added related to entry and exit criteria for specific gates and events, Go/No Go requirements for a preliminary design review, TRL levels, risk assessment and management, configuration management, and guidelines for technical decision making.

Aerospace Vehicle Design II

Aircraft Vehicle Design II, the second half of the capstone design experience, acquaints students with wind tunnel and flight testing for validation of preliminary aircraft designs. Students build upon the first design course and construct, plan, and test wind tunnel and scaled flight vehicles to confirm, as far as possible, compliance with given mission specification. Documentation includes writing a professional quality wind tunnel test plan, wind tunnel test result report, flight test plan, and flight test report. Students participate in several activities created to emphasize safety in design, test, flight, and participation.

Learning objectives for this course are similar to those for Aerospace Vehicle Design I and include:

1. Analyze and validate flight vehicle performance constraints, and determine suitable configurations for a specified mission.
2. Work successfully as a member of a team.
3. Conduct and document a detailed and complete assessment and validation of a flight vehicle.
4. Define system relationships and interactions between aerodynamics, structures and materials, dynamics and control, propulsion, performance, and internal systems on the design and fabrication of a flight vehicle.
5. Detail the importance of considering safety, reliability, and maintenance considerations in flight vehicle design and testing to validate engineering designs.
6. Communicate testing results in technical reports, briefings, and presentations.

Modifications to existing Aerospace Vehicle Design II course Spring 2014

Four teams continued from the Aerospace Vehicle Design I course where SE concepts had been introduced. Therefore, students entered the second capstone design course with some SE knowledge and skills. While SE content had previously been a part of this course, it was not explicitly defined as such. Therefore, more rigor was added to the course in the areas of students being asked to manage their distribution of duties, including wind tunnel test, vehicle build, and flight test. Schedules were developed to incorporate three new reviews in the process: Wind Tunnel Readiness Review, Systems Integration Review, and Flight Test Readiness Review.

Cockpit Systems & Displays

This course integrates aerospace engineering and computer science students who respond to a given opportunity using the SE method. Through this process, students apply the methodology and decision making processes to the synthesis of a prototype real-time interface and display. Student teams learn to interpret customer needs, develop a ConOps, create defined and derived requirements, and synthesize a prototype real-time interface and display to satisfy given requirements and mission specifications. Guest speakers from industry speak to the class on essential topics as needed to provide practical applications of the material. Students document progress of the design by presenting regularly scheduled Oral Reports.

Learning objectives include:

1. Learn and apply the SE approach to specifying, defining, tracking, and creating complex engineering systems.
2. Analyze and interpret customer needs for a real-time interface and display, and develop suitable requirements.
3. Recognize means by which information is presented to aircrew and operators, enabling them to carry out their tasks safely and successfully.
4. Define basic aviation human factors and human machine interfaces.
5. Apply skills learned in real-time software development and implementation skills.
6. Recognize the role of civil and military regulations and the importance of considering safety, reliability, and maintenance considerations in real-time interface and display design, and societal and environmental considerations.
7. Work successfully as a member of a team.
8. Conduct and document a detailed and complete preliminary design of a real-time interface and display, and build and demonstrate a prototype.
9. Communicate design results in briefings and presentations.

Modifications to existing Cockpit Systems & Displays course Spring 2014

Two of the three Integrated Product teams interfaced directly with two teams at UT to achieve a collective design between the two institutions. A Project Plan module was added to this course to facilitate the design of a Work Package between teams from the two institutions. In addition, an Interface Control Document was created and added to the course. In previous semesters, only a Critical Design Review was held. Five additional reviews were added, including a System Requirements Review, System Functional Review, Preliminary Design Review, Test Readiness Review, and Flight Readiness Review. These were used mainly to keep students on track rather than seen as additional content included in the course. Figure 2 depicts students at the two institutions working on the joint design project as they tested their ground control station.

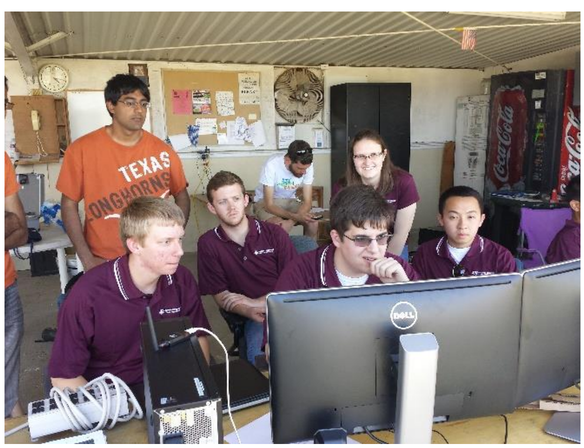

Figure 2. Joint design project ground control station.

Outcomes and Experiences

In total 28 aerospace engineering seniors participated in this project with most all of the students completing all three courses. Even though students had not been introduced to SE material earlier in their degree program, they embraced the SE lectures and content very well. They particularly liked the prospect of working closely with industry organizations during the semester.

Students accepted the new course concept of developing and tracking their own requirements very well versus previous semesters where this had been defined for them. They found the opportunity to interface directly with an industry customer or collaborator very useful and a good learning experience. Students, used to previously receiving stated requirements in a design rather than generating them, required a little guidance during the initial stages of ConOps, but the instructors felt students managed well. By the third week of the course they were well on their way and clearly understood what was needed and how they were supposed to achieve it. The students did very well with learning the new SE concepts in Block 4, and implemented them steadily. The students were least enthusiastic about the risk assessment and management topic. This is felt to stem from the fact that they had never had this in a course before, and were slightly skeptical about its value. Once they gained familiarity with the concept over a period of weeks, they embraced it.

Finally, it was once again directly emphasized to the students that Aerospace Vehicle Design I represents most but not all of the left leg of the traditional V diagram (see Figure 3), while Aerospace Vehicle Design II represents most of the right leg. This is needed because the students historically tend to view the two courses as essentially independent, rather than a single coordinated academic year long effort distributed over two semesters and with two course numbers.

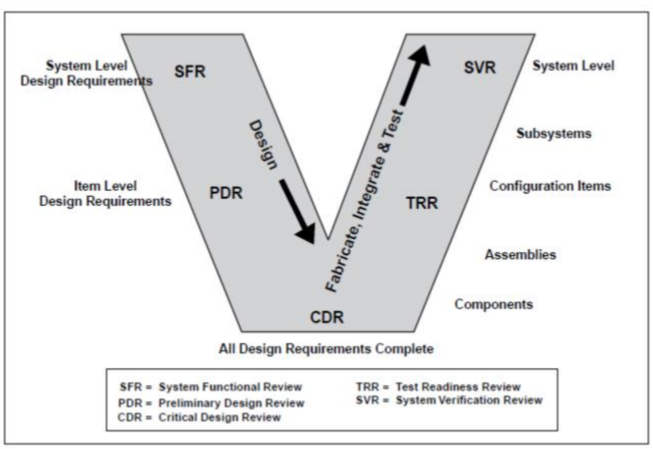

Figure 3. Systems engineering and verification[10].

Forty external members from industry/government organizations attended the CDR at the completion of Aerospace Vehicle Design I and were very complimentary of the changes to the course compared to CDRs in previous semesters. In written feedback received, they noted student generation of requirements, requirements tracking, and risk identification and management as particular highlights. While they stated a desire to improve the business plan content of the course, this falls outside of the scope of this project. Post PDR the students related they particularly enjoyed SE aspects of the course and found the approach to be very valuable. The inclusion of the SE material was accomplished so seamlessly that students felt the course had always contained the material. In review by the instructor, the SE content added to Aerospace Vehicle Design I reaches the limit of content that can reasonably be added without significantly altering the structure of the course, which is not desirable at this time.

Formal feedback was not received from the Aerospace Vehicle Design II course during the Spring 2014 semester. A goal of the current term is to assess the added value. More importantly, and related to this assessment is the definition of metrics and establishment of protocol to properly assess the performance of the contributions of individual students.

In the Cockpit Systems & Displays course students were given a formal teamwork evaluation tool developed internally, which consisted of 20 questions in which students rated not only relative performance of team members but also their own performance. Results from this assessment did not prove effective or useful as the students simply unanimously scored every engineer on their team the highest possible evaluation on each specific teamwork aspect, including themselves even though this was completed individually. Useful and insightful responses were provided for the open-ended questions, “After taking this course, how well do you feel you know and can apply the basics of Systems Engineering? Are there any specific aspects of Systems Engineering that you are not comfortable with?”
Student responses include:

- “I feel very comfortable applying SE basics”
- “The SE proved to be useful for documentation purposes of the design. As a whole I feel confident regarding SE.”
- “I learned a lot about project management, will be very good skills to have.”
- “I am fairly confident that I can apply the basics of SE to my first job after graduation. The ConOps section still scares me from time to time however not as much as before.”
- “I feel I have a good grasp of the basics of SE and their application.”
- “I think that I will easily be able to LEARN and ADAPT to the specific SE traditions/processes of a company. I feel that I don’t know the “V” diagram well enough, but I understand that the SE process can vary.”
- “I feel very comfortable with the SE process, and feel that I could implement it effectively in the future.”

- “I feel that I could apply the basics of SE pretty well. I may need a bit more practice, but I do feel that I could do a good job.”
- “This is my second SE course. I feel very confident with SE. I enjoy the process and recognize the need and usefulness.
- “I feel very prepared to use my SE knowledge.”
- “I feel very comfortable with my understanding of SE. I would like more practice with the process. My team was well versed in SE already. I’m not very familiar with the second half of the ‘V’ approach.”

Lessons Learned

1. **Doing engineering differently**. For senior capstone design, students typically enter this course with the expectation that “real engineering education” consists of a professor standing in front of a board and deriving equations for 50 minutes and “real engineering” consists of solving homework problems based on those derivations. This comes from three to four years of training in that model. Thus there is some culture shock to be expected with un-learning some things and learning new ones. This will need to be anticipated and planned for.

2. **You cannot do it all with an existing engineering course.** The SE methodology, literature, and database is so extensive that incorporating the majority, or even a significant fraction of it, into an existing course the first time is simply not practical. The best approach is to pick and choose which aspects are most suitable to incorporate, and this must be done based upon the objectives of the course. For instance, if the objective is synthesis of a new system, then generating and tracking requirements is paramount, along with project planning and reviews. Consequently, if the objective is testing of a system, then validation and verification, along with properly managed entry and exit criteria is vital. Expect to incorporate changes incrementally and over several course offerings.

3. **Start incorporating SE elements well before the start of the semester**. Attempting to incorporate SE elements “on the fly” during the semester will not work, since there is a strong causal effect due to their sequential nature. While it might look like a daunting task beforehand, once the desired level of SE and specific features to be incorporated is decided upon, the incorporation is not difficult. *The hardest part is deciding what features should be incorporated*, and this will take careful thought.

4. **Make sure students do not come away with the wrong conclusion**. The first time students take an SE based course, they are strongly inclined to make the beginner’s mistake that the purpose of SE is to generate requirements and documentation. *The purpose of SE is to undertake a process by which engineers arrive at the desired solution/system; it is not the*

process itself. This idea must be reinforced throughout. By the time the course is concluded it should become evident to them, but during the semester students will need to be reminded.

5. **Students must be taught how to communicate well with each other**. Horizontal and vertical communication between engineers conducting SE is critical. However, *students do not do this naturally*. Despite the fact that an entire class of students will largely be taking the same classes at the same time, they do not communicate well technically. To expect that students will interface technically on their own outside of class is a major mistake. Therefore, the course structure must be designed to both require and encourage student technical interactions.

Conclusions and Future Work

Overall, the project has been viewed as a success. The goal of the effort was to incorporate work started at another institution related to incorporating SE into current curricula. Not only was this accomplished but students also benefitted from working with engineering students at the other university. While logistics can be difficult coordinating efforts between several faculty members, especially those located at another institution, the benefits outweighed any issues encountered. This approach to incorporating SE content within current courses with minimal disruption is possible but proper planning and communication is key. The courses involved in the project continue to evolve based on lessons learned, and work has begun to infuse SE principles in additional departmental courses. One area lacking in the current work is a more detailed analysis of the incorporation of SE into courses. While valuable comments were received, direct feedback needs to be received from students and industry members. This is currently in development.

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