SYSTEMS ENGINEERING
Research Center

Fostering Systems Engineering Education
Through Interdisciplinary Programs and Graduate Capstone Projects

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Abstract

The United States Department of Defense is experiencing significant shortages of scientists and engineers, and the shortage is even more severe in the area of Systems Engineering (SE). The challenge is to not only increase the numbers of scientists and engineers, but to improve the system level thought processes of these individuals. Graduate degree programs, as a part of a larger professional development program, are often relied on to provide this higher level perspective. However, many graduate degree programs, especially those at research focused graduate schools, tend to be narrowly focused within sub-disciplines of an academic department. While this may serve the academic community well in terms of furthering research programs and developing future researchers, it is not the only, and may not be the best, approach for educating practicing engineers returning to industry and/or government offices where their newly acquired knowledge will be applied. The graduate SE program at the Air Force Institute of Technology has been conducting defense-focused interdisciplinary and interdepartmental capstone projects over the last few years that have combined students across multiple disciplines on broadly scoped topics using SE to define, scope and integrate the individual research efforts. These projects typically result in multiple thesis documents covering several research investigations, with an additional document written by the SE students that provides the unifying framework for integration and, where applicable, transition of the demonstrated technologies. All projects have one or more sponsors, often including one from the operational organizations with the Department of Defense. These sponsors are often actively involved in the conduct of the project, thus providing relevance and subject matter expertise. Prior projects combined Systems Engineering and Aeronautical Engineering graduate students, but newer projects are expanding the pool further to include other Engineering, Engineering Management and Cost Analysis students for a variety of projects. In the past, non-SE students have been encouraged, but not required, to take introductory SE courses; recent experience has shown increased benefit from classroom exposure of non-SE students to SE curriculum elements, and this benefit can extend beyond those students directly associated with the SE capstone projects. The program has received positive feedback from most of the graduates that have participated on these projects, and the influence of the SE program has grown far beyond the number of students entering the graduate school for SE.

Introduction

The US Department of Defense (DoD) is facing major challenges associated with their Science, Technology, Engineering and Math (STEM) workforce. This problem goes beyond the needs of the core acquisition workforce that comprise only 40% of the overall STEM workforce[1], and in fact is a reflection of shortages of engineers throughout defense industries and the US workforce in general. Within the DoD, jobs associated with capability planning and requirements definition, as well as much of the studies and analysis efforts that support pre-acquisition decision making, are typically not counted as part of the acquisition workforce, but they often require individuals with STEM proficiencies. Within the STEM career fields, the DoD has singled out Systems Engineering (SE) as a critical need in order to improve the ability to conceive , develop, sustain, modify and eventually retire its' warfighting systems. Those personnel identified as occupying critical positions (typically those in the acquisition workforce) receive training and certification on SE through a series of Defense Acquisition University (DAU)[2] on-line, on-site, or resident short courses. While this promotes an understanding of SE across a wide swath of the acquisition workforce, the courses are primarily taught to the lower learning levels of Bloom's Taxonomy (Remember/Understand). Therefore, they do not bring a student to Bloom's higher levels of learning: Apply, Analyze, Evaluate or Create.[3,4] Beyond the certification programs, career engineers or scientists often pursue graduate degrees in their specific discipline, but only a relatively small percentage of them currently attain a deeper understanding or proficiency in Systems Engineering as a result of their graduate studies. While technically skilled in their individual core disciplines, the engineers or scientists completing these graduate programs are not adequately equipped to perform in an interdisciplinary environment where the needs of the system overshadows the desire to optimize or even improve the component technologies or subsystems. Bearing in mind that contractors produce designs for the DoD, the government engineer's role is often associated with facilitating trade-offs and evaluating system level impacts, not the detailed electrical, mechanical or aeronautical design. This paper presents an argument and cites examples for using selected curriculum elements from SE within the other STEM graduate programs, and reinforcing these elements with interdisciplinary capstone projects. While this may not be the traditional approach to graduate engineering research, it is proposed that this approach might better serve the graduate degree student in the United States that returns to the government workforce after completing what they view as a terminal Masters degree program.

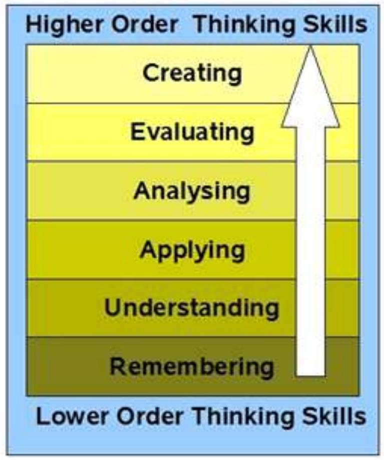

Figure 1. Bloom's Revised Taxonomy[4]

Needs of the DoD Workforce

According to the Defense Acquisition Workforce Improvement Strategy[1], the goal of the DoD was to add over 4,000 people to the Defense Acquisition Workforce (DAW) in fiscal year 2010, and almost 20,000 people over the fiscal years 2009-2015. This represents a 15% targeted increase by 2015! This is not simply a need for increased numbers; the same report provides a quote from Dr. Ashton Carter, Under Secretary of Defense for Acquisition, Technology and Logistics, on the inside front cover; "Workforce size is important, but quality is paramount."[1] Counting and credentialing an acquisition workforce by itself will not solve the problem; improved performance on acquisition programs must be the evidence of a quality workforce, and this will require greater proficiency at the higher levels of Bloom's taxonomy (applying, analyzing, evaluating and creating).[3,4]

As high as the numbers above may seem, it needs to be understood that only 40% of the DoD's STEM workforce is considered to be part of the DAW[1]; often times the DoD finds itself with similar shortages of STEM proficiencies in the requirements, analysis and operations organizations outside the DAW. In particular, the capability planning and requirements definition organizations are tasked with determining current and future needs, and then defining and validating requirements for new or modified systems or services to meet those needs. Often this requires technical skills in system architecture, modeling, decision analysis, and trade space analysis. Most of the organizations responsible for this pre-acquisition phase find themselves severely lacking in STEM proficiencies, thus adding to the overall STEM deficiencies within the DoD.

Within the STEM career fields, SE is often called out as one of the critical shortages both in terms of raw numbers as well as depth of knowledge/proficiency for those in the discipline. During the same time frame as above (2009-2015) the DoD has a stated growth target of 16% for DAW personnel certified in Systems Engineering under the Systems Planning, Research, Development and Engineering (SPRDE) category of the DAW.[1] The path for obtaining SE certification typically consists of job experience and taking a series of short courses, delivered on-line, on-location, or on-site from the Defense Acquisition University. While the short courses contribute to general knowledge and understanding, as previously stated, they do not provide the level of learning required for many who must perform in the DAW and related areas. Because the vast majority of personnel in the DoD received their formal training on SE in this manner, there is insufficient SE expertise in the workforce and too few with the level of knowledge required to serve as “trainers”. These two factors combine to yield an environment where those practicing SE do not have the level of knowledge required to perfom the task or support “on the job training” to grow future SE’s, resulting in the DoD often repeating mistakes on critical acquisition programs. The DoD needs to augment their certification process by seeding the workforce with individuals having deeper knowledge and proficiency in SE if they are to realize the quality workforce goals in the DAW Improvement Strategy.

Beyond certification associated with SPRDE and other tracks, many people within the DoD pursue advanced degrees either at the DoD’s graduate schools (the Air Force Institute of Technology (AFIT) and the Naval Postgraduate School (NPS)) or civilian universities as part of a larger professional development program. Some of these programs are formally funded by the services, typically to address specific discipline needs (positions) of the various DoD organizations. These sponsored programs can, and do, provide greater proficiency in the STEM areas (among others), but they are typically limited in number and narrowly focused in the specific discipline or sub-discipline. For example, most of the sponsored STEM related advanced degree programs for military members in the Air Force are provided by/through AFIT, and there are only 200-300 officers per year selected for those programs. Of those, less than 10% are designated for SE. As a basis of comparison, the Defense Acquisition Workforce Improvement Strategy called out a need for almost 2,000 Air Force officers in the SE related career paths of the DAW, which does not include the requirements and capability planning and analysis communities.[1] On the civilian workforce side, over 5,000 Air Force civilians are needed in the SE related career paths of the DAW, and the opportunities for fully funded degree programs are insufficient to support and sustain these numbers with the level of expertise required. Some individuals pursue part time graduate education; however these individuals are not accurately tracked and anecdotal evidence suggests their numbers are insufficient for providing the number and quality required in the SE career paths. All of this is not to suggest that the Air Force and the other services should divert more of the STEM focused programs to SE; clearly there is need for expertise associated with the technologies in the other STEM disciplines as well. What is necessary, however, is for a greater number of personnel across the STEM disciplines to attain a level of proficiency in SE greater than that attainable through the current SPRDE training program.

Graduate Education In and Around Systems Engineering

Most graduate programs, especially those at research-focused institutions, tend to be narrowly focused within specific disciplines and even sub-disciplines. While this is advantageous for establishing and maintaining research programs and grooming academic researchers, it ignores the fact that many of the toughest technology problems faced by both DoD and non-DoD organizations tend to be interdisciplinary in nature, often spanning both STEM and non-STEM disciplines. Unique among engineering graduate programs, Systems Engineering programs are often interdisciplinary in design and may include required courses in areas such as project management, human factors, cost analysis, et.al. In fact, the International Council of Systems Engineering (INCOSE) identifies human factors and cost analysis as part of SE, but these subjects exist within other disciplines as well. Some SE programs encourage or even require that a significant percentage of the courses in the programs lie outside the home academic department. As one might expect, graduate programs aim for the higher levels of Bloom's taxonomy. In the case of research based programs, students are evaluating and creating new methods and tools associated with SE. All Masters degree students at AFIT, as in many other research focused graduate schools, are required to perform an independent research thesis or capstone project.[5] Unique among other graduate programs at AFIT, SE Masters students may do this as part of a group (typically no more than 4 students). Group projects are encouraged for the AFIT SE program in order to expose students to broader scoped topics that demand the time and skills of multiple people working together to find solutions. Students are expected to draw upon learned skills in core areas of system architecture, requirements definition, software and systems analysis (including tradespace analysis), and project management. Additional expertise associated with quantitative analysis tools, domains of application (e.g., airborne, space, cyber or logistic systems), and/or specific technology areas are provided via the individual student specializations within the program. Of note, almost all of the specializations are provided outside of the home department, with particularly strong ties to the Department of Operational Sciences and the Department of Aeronautics and Astronautics. Historically, most of the capstone projects have been confined to SE students, thus relying on the SE students' specializations or prior experience to provide the interdisciplinary knowledge. While this has worked well, it often requires significant scoping of the topic if not all disciplines can be adequately covered by the SE students on the group.

Graduate programs in the STEM disciplines outside of SE are typically more narrowly focused in terms of the coursework and research projects associated with them. For example, an Aeronautical Engineering (AE) Masters program will typically require completion of a core curriculum (fluids, structures, and aircraft dynamics) and specializations within one or more sub-disciplines within AE, e.g., structural dynamics, or airbreathing propulsion. It is relatively rare to see a graduate AE student take a specialization in software, sensors, or operations analysis, for example. At AFIT, all Masters students outside of the SE program are required to complete their thesis as an individual project. While groups of students working on related projects is allowed, where pursued this typically involves students within a common sub-discipline as opposed to truly interdisciplinary projects. Again, programs structured like this serve the academic research community (and those that depend on it) well, but they often fall short of preparing graduates to work as part of interdisciplinary teams on large scope projects – often the norm for practicing engineers and scientists in the DoD and elsewheree. Increasingly the SE program at AFIT has heard from other program and department chairs about the desire to produce graduates capable of "systems thinking". Often times this desire comes about in response to feedback from customer focused advisory boards as to what they want from AFIT graduates. While many definitions for systems thinking exist, it is generally defined as the ability to see and understand the interrelations between a system's components (to include the human components and any surrounding environments) and how they contribute to the capability and performance of the system as a whole. The system's components may be systems in their own right, sometimes leading to large complex concepts that evolve over time as they incorporate new systems or retire legacy systems. Most engineering graduate programs do not currently provide this perspective, yet this has become arguably the most critical shortfall within the DoD's STEM workforce.

Within AFIT, many of the other technical programs are turning to the SE program to provide some of this systems thinking perspective. There are several programs outside of SE that now require at least an introductory SE course as part of their curriculum, and several other programs treat it as a strongly recommended technical elective. The introductory SE course at AFIT has become the highest volume course in the school, with approximately 150 graduate students/year. Most of these students are not SE majors, with the bulk of the students coming from the Electrical Engineering, Aeronautical Engineering, Space Systems, Cost Analysis and Engineering Management programs. In addition to teaching the SE process and requirements driven design, the course introduces the tools of system architecture, system analysis, and decision analysis. Supplementing traditional lectures, case study discussions are conducted using in-depth SE studies on historical DoD or NASA development programs.[6] The discussions typically reflect the broad ranging students' background and experience. Learning is further reinforced through application on a conceptualize/design/build/test hardware and software project using a challenge problem with the Lego Mindstorms robotics kits.[7] (See Figure 2.) While the students certainly have fun building robots, the emphasis is on architecting and designing before building, and providing traceability of requirements through design and test planning. Graduate level thought is emphasized through the use of architecture modeling tools, risk assessment and trade space analysis, and proper documentation and cost models to support the final design. This course, together with prior follow-on job experience or training, serves to bring students to the applying and analyzing levels of Bloom's taxonomy for the basics of SE. To go further or broader in SE requires additional coursework and/or the inclusion of SE principles on the thesis or capstone project of the student, and this requires further cooperation and collaboration on the part of the faculty research advisors in these programs.

Figure 2. AFIT Class Project: Autonomous Vehicle Capable of Navigating Through Maze

The Graduate Capstone Project as a Systems Engineering Learning Tool

The traditional approach to group projects in the AFIT SE program has been to group several SE students together on a sponsored topic broad enough to challenge the collective abilities of the group. The restriction to SE students has been necessitated by the requirement that students in all other AFIT Masters programs, except SE, complete an individual thesis project. Further, few faculty outside of a core group associated with the SE program knew enough about SE to advise these group projects. Most of these projects were notional preliminary design efforts for a concept of interest in the DoD. While this approach resulted in many successful projects, they had to be carefully scoped based on the collective expertise of the team, which often did not include depth in the traditional engineering disciplines. Relatively recent changes to the SE program offering domain specializations (e.g., airborne or space systems) has helped by bringing applicable expertise into the group projects, and the general feeling on the part of the SE faculty is that the quality of the capstone project work has improved. Supporting evidence for these improvements has come from sponsor feedback. These results cannot be positively correlated to the offering of domain specializations because during the same time frame (2002-2005) the structure and makeup of the program was changing dramatically; only one legacy core course was retained in the revised program, and new program assessment methodologies were put in place. While these capstone projects serve to elevate the SE students to higher levels of learning (and follow-on practice), they do little to broaden the base of SE practitioners and “systems thinkers” needed by the DoD.

Since 2005, there have been several opportunities to experiment with new approaches to the group capstone project. A series of projects teaming SE and AE students have been conducted in the area of small Unmanned Air Vehicles (UAVs) utilizing autonomous and/or cooperative control concepts. (Figure 3.) These projects were initiated based on mutual interest and prior friendships among specific faculty in the departments associated with these two programs. The SE students on the team were responsible for concept definition, architecture development, system integration and overall flight test planning. The AE students were responsible for control algorithm development and for conducting tests of their particular algorithm. Typically two or three AE students were grouped with two or three SE students to form the overall group. As flight testing multi-UAV concepts is a "team sport", students had to pull together as a team in order to successfully demonstrate their individual research contributions as well as the overall operational concept. In order to satisfy the requirement that non-SE students complete an individual thesis investigations, each non-SE students would produce an individual thesis document detailing their particular investigation, and the SE students would write one or more documents detailing their portion of the project. These projects achieved significantly more than those utilizing only SE students as evidenced by sponsor and student feedback, as well as the assessment criteria utilized by the faculty research advisors. All thesis and capstone projects at AFIT are graded by the faculty using similar rubrics. These particular projects could have benefitted further by including other disciplines, most notably software and/or computer engineering. Common themes among these hardware based UAV projects were the difficulties faced by SE and AE students in migrating research code (typically using MATLAB) onto the microcontrollers for flight test, or integrating new software modules with legacy modules written in dissimilar languages. Laboratory technician support could alleviate these problems, but surfaces another issue – resourcing interdisciplinary programs.

Figure 3. Equipment supporting Multi-UAV Research at AFIT

While the interdisciplinary teaming associated with the UAV projects improved the collective performance of the students, there was no specific attempt to integrate the education plans of the students. With one exception, only one AE student across three different projects took one or more SE courses, and none of the SE students pursued deep specializations within AE sub-disciplines. Certainly the AE students learned something about SE by working with the larger group, but their learning in SE did not get much further than hardware integration and flight test conduct. The AE students did not get involved in the concept definition or architecture development effort because they were unfamiliar with the methods and tools. Conversely, however, the SE students gained considerable knowledge on aircraft stability and control and aircraft limits of performance as they were forced to work through these problems during the flight test events. Overall assessment of these types of group projects was that they improved the SE learning for the SE students (as noted using the thesis rubric and other end-of-program assessments), but did not significantly improve the SE knowledge or system thinking ability of the non-SE students associated with the project.

With the additional students from other programs now taking one or more SE courses as noted above, a new teaming approach for capstone projects is being pursued. This will again pair SE and non-SE students, but it will involve formally providing SE curriculum elements to the non-SE students. Typically this involves the non-SE students taking the introductory SE course as described earlier, but other arrangements are being made as well. Several projects underway this year have been organized in this manner, with one of them being another hardware focused UAV project, and the others being associated with space tracking or small satellite concepts. The UAV project involves incorporation of a novel hybrid-electric propulsion concept into a glider-like UAV for demonstration of long-loiter, near-silent operation. It is being sponsored by the Office of the Secretary of Defense (OSD/DDR&E) as part of a larger investigation into methods for improving SE competency across the DAW. The AFIT project will incorporate requirements reviews, design reviews, test readiness reviews and safety review boards. Team makeup includes two SE students, one of them pursuing an aircraft stability and control specialization, one AE specializing in propulsion and structures, a Computer Engineering student specializing in microcontrollers, and a cost analysis student. With the exception of the Computer Engineering student, all completed at least the introductory course in SE prior to starting work on the project. As part of the OSD sponsored effort, SE learning will be evaluated to determine if this is an effective way of improving the SE competency of AFIT graduates. Other OSD sponsored projects using a variety of teaming arrangements are being conducted at other DoD schools and eight civilian universities (some graduate, some undergraduate), and OSD will use these pilot projects to determine the feasibility and effectiveness of this approach to SE workforce development. Evaluation of these projects will include periodic student surveys, blog entries, and midterm/final reviews presented to subject matter experts and OSD sponsors. The evaluation of these OSD sponsored projects, including AFIT's, will conclude in the summer of 2011.

Summary and Conclusions

The DoD needs both numbers and quality for its STEM workforce. While this is true for all the STEM career paths, the needs are greatest in the area of Systems Engineering based on the type of work typically performed by DoD engineering officers and civilians. They need all their engineers to embrace systems thinking as a way of approaching problems and understanding how what they do fits into a larger solution set. To address SE quality issues, the DoD needs people that are effective at the higher levels of Bloom's taxonomy: applying, analyzing, evaluating and creating. In order to help achieve this, AFIT has structured a program and supporting courses that are attracting students from non-SE programs. This allows AFIT to significantly increase the production of graduates that are knowledgeable in at least the fundamentals of SE (as evidenced by course grading and the thesis/project grading rubric), and this knowledge can be developed further through follow-on assignments. For some of these non-SE students, AFIT is providing opportunities to further their SE learning by working with students from other programs, including SE, on interdisciplinary capstone projects. Experience from a broad range of these topics suggests that exposing non-SE students to the fundamentals of SE prior to the start of the capstone project pays dividend for all the students and the group project as a whole. This approach is not universally recommended for all graduate engineering students; in particular, students interested in academia or basic research as a career may not be well served by this approach. However, DoD sponsored graduate students, as well as some of those returning to the defense industries supporting the DoD, would be well served by learning about and having an opportunity to apply the basics of SE as part of their graduate program, regardless of their specific discipline or specialization.

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