Promoting Systems Thinking in Engineering and Pre-Engineering Students

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Abstract

The context of engineering is one dominated by systems. In order to better prepare graduates with a systems perspective and the competencies to be effective in system design, we discuss initiatives to promote the development of systems thinking, both in undergraduate and K-12 communities. This paper describes vertically-integrated curriculum innovation, in which graduate-level coursework spawned a pilot program to embed systems in a core engineering design course for undergraduates with its resulting adoption and extension to a core design thread, and a resulting high school curriculum development and dissemination effort which has followed. These efforts have also prompted educational research to develop the academic underpinnings of the relatively under-developed scholarly foundations of systems engineering.

Introduction

It is increasingly recognized that the context of engineering is one dominated by systems and that the practice of engineering is typically directed towards design of engineering systems, ranging from the small to large scale and even complex systems of systems. Engineering curricula, with their traditional focus on the disciplinary contributions to design, encourage a mindset in which students seek technical solutions often rooted in a specific engineering discipline with little regard for the context in which their product, system, or service may be deployed, the societal or business need(s) it may fulfill or even its relations to all the other engineering, business or 'environmental' domains that can contribute to success. In order to better prepare engineers with a systems perspective and the competencies to be effective in system design, there is a need to promote the development of systems thinking in engineering undergraduates. Coupled to these efforts we also see the merits of seeding this approach even earlier in K-12 communities as part of a movement to incorporate pre-engineering into middle and high school curricula.

The genesis of the current efforts at Stevens Institute of Technology to inculcate systems into the undergraduate engineering curriculum and into K-12 pre-engineering outreach is associated with the recognition some years ago of the growing importance of systems engineering concepts to a broad spectrum of industry and government, particularly associated with the design and management of complex systems. Companies and agencies responsible for defense and aerospace systems have been a particularly strong constituency in this regard. This led in 2001 to the creation of a graduate-level program in ***Systems Design & Operational Effectiveness (SDOE)*** taught by a faculty with significant experience and reputation in the field. The SDOE graduate program (http://www.stevens.edu/sse/academics/graduate/sdoe/) has been very well received and delivered in modular form world-wide to industry and government agencies that are involved with complex systems. The program was initially a certificate program directed to practitioners and working professionals but this has subsequently expanded to include masters and doctoral degrees. The faculty and scope of the programs has grown rapidly leading to the recent formation of a School of Systems & Enterprises (http://www.stevens.edu/sse) with a significant national and international impact in the systems engineering field.

The presence of a strong graduate-level activity in the systems engineering discipline on campus lead naturally to discussion with those responsible for the undergraduate engineering core curriculum of how systems concepts could be addressed at the undergraduate level for all engineers. The surging interest at the graduate level from leading technology companies worldwide has highlighted the need for all future graduates to develop a systems perspective in response to the changing environment for engineering practice. These changes have come about from the need of businesses to compete and interact globally with more flexible multidisciplinary approaches than practiced by the traditional "stove-pipe" disciplinary organization. Also, of critical significance is that consideration of the full life cycle of products and processes is increasingly recognized as necessary in design, and this is directly addressed by the systems approach.

Systems engineers consider the needs of all stakeholders, both technical and non-technical, as well as the full life-cycle of the system, when designing a solution. A detailed overview of the systems engineering design process is shown in Fig. 1. The model shown is one known as Total Design after Pugh[1]. The figure illustrates a system life cycle starting from the left of the chart to the right. The first phase is that of understanding the need that has to be fulfilled or addressed by the design under consideration. The cycle gets completed with the last phase of testing and integration and final deployment. Each phase in the life cycle of a product, system or service, as shown in the side bars, would include essentially the same ten steps.

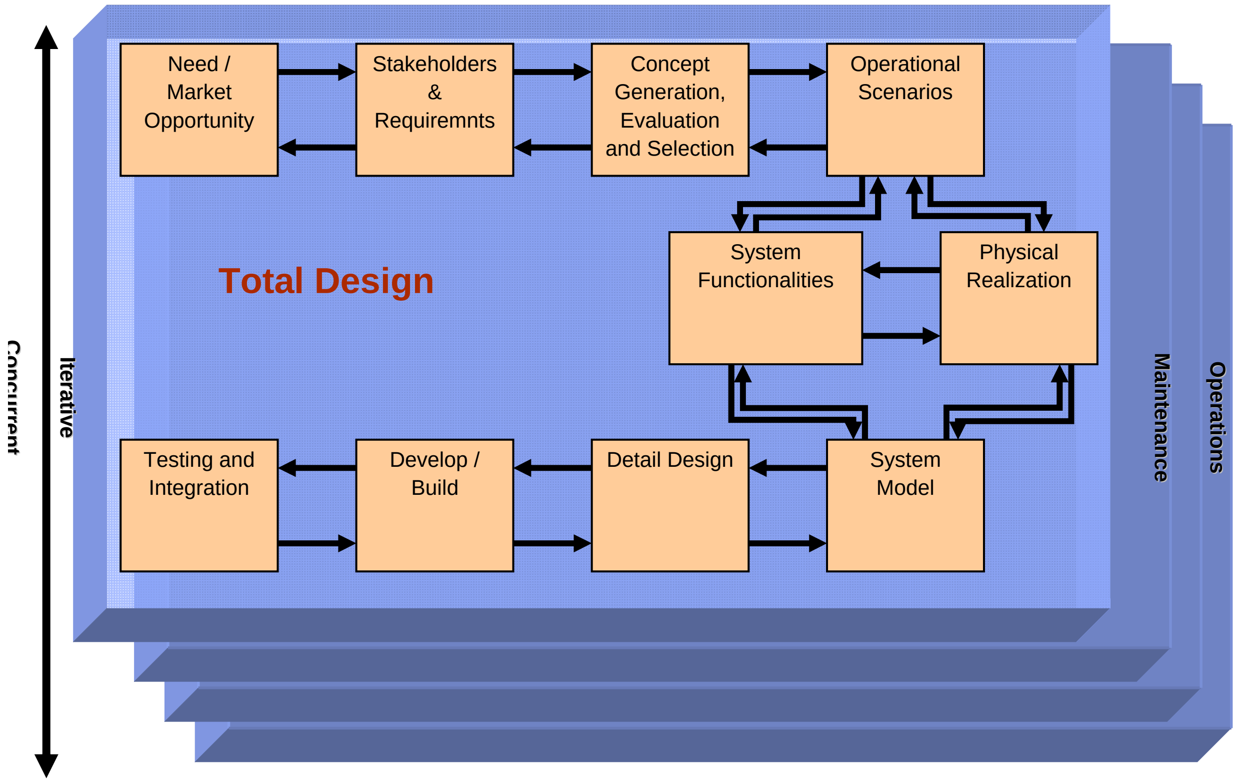

Figure 1. The Total Design approach to systems engineering (after Pugh[1])

It was recognized when considering what might be achieved at the undergraduate level, that systems thinking and systems concepts that resonate with those who have been in industry and dealing in their careers with major systems issues, might not resonate with inexperienced undergraduates. Nevertheless, it was felt that starting to introduce systems approaches early and reinforcing them with appropriate applications would be beneficial in building the systems perspective, even though the true realization of their significance might not become really apparent until students were out in the business world. That said, approximately 40% of engineering undergraduates at Stevens participate in Cooperative Education and most of the remainder have multiple industrial summer internship experiences prior to graduation – providing at least some real-world context for systems pedagogy.

In the summer of 2005, two of the authors (Jain & Gallois) lead the development of the first pilot stage of introducing a systems thread into the core engineering curriculum[2]. The vehicle for this thread was to be the core design sequence at Stevens known as the Design Spine[3]. The first five courses are core design courses taken by students from all intended disciplines; the last three are taken in the discipline - a junior course followed by a 2-semester capstone senior year project. In most cases the core design courses are linked to concurrent engineering science courses, thus providing context for the latter. The Design Spine is a key vehicle to develop a number of threads that build both technical and so-called "soft" competencies. The latter include communications, creative thinking, teaming, economics of engineering, problem solving, project management etc. It should be noted that the first four design courses have been taught by adjunct engineers, either practicing or recently retired. They bring the benefit of their design experience into the classroom. The pilot was implemented in Engineering Design I for entering Freshmen in the Fall of 2005.

Engineering Design I

The goal was to develop many of the basic concepts of the total design approach in the Freshman year to establish the foundation, recognizing as noted above, that they may not resonate with students at this stage but provide the needed basis to revisit throughout the design sequence. In Engineering Design I the second week includes a product disassembly exercise using a cordless screwdriver. This now provides the vehicle to introduce the first steps in developing total design by consideration of market needs and stakeholder requirements. Students are given an overview of the complete process in Week 2 of Engineering Design I as illustrated in Figure 1 and then asked to address the first two stages in the context of the cordless screwdriver, for example, by being asked to identify the stakeholders and their requirements, something that presents them a challenge if they are pushed to go beyond the customer/user.

These first two stages are reinforced in the context of the major design project that occupies Weeks 6-14. This project is an autonomous robot, which gives students an early example of a system; one that combines various disciplinary aspects such as mechanical design, electrical circuits, sensors and programming of a microprocessor. The programming is done using C++ which is taught in a concurrent course. In the robot project students also engage in the third stage of the total design process, namely concept generation, but this is not developed in a systematic manner. It is revisited in more depth in Engineering Design II.

Engineering Design II

Following implementation of systems concepts in Design I and a revision of Engineering Design II in spring 2006, the latter now focuses on sensors and data acquisition, building on the Engineering Design I experience and continuing the development of systems thinking through the "Total Design" approach. The graphical programming language LabVIEW™ is employed to connect sensors to the students' laptop computers via a USB data acquisition module (National Instruments USB-6009 with 14 bit resolution and a counter). The custom-designed PIC board used in the Design 1 robot project is also employed to provide interfacing for experiments and in the design projects. Students learn to program in LabVIEW via assignments to connect to and calibrate a light sensor (Experiment 1 - PIC board as interface) and in Experiment 2 to perform motor speed control using a perforated disc and optical interrupt sensor. The students apply this knowledge to their group's choice of one of three projects that require use of sensors, acquisition of sensor data and its use for a simple control function(s).

Total design is revisited early when a commercial fire alarm system (multiple units – one per group – connected across the design laboratory to a master monitoring panel) is evaluated and then the individual alarm units disassembled to reveal their sensors (temperature and optical smoke sensors which relate nicely to sensors used in the course). Stakeholder requirements for the alarm system are considered and then the 4th total design stage is introduced, namely Operational Scenarios, in which context diagrams and use case scenarios are developed. This requires a collection of scenarios to be established, one or more for each group of stakeholders for the particular phase of the life cycle – only the first design phase is considered in Freshman year. Each scenario addresses one way a particular stakeholder(s) will want to use, deploy or otherwise interact with the system; it defines how the system will respond to inputs from other systems to achieve the desired effect.

Figure 2. Product Disassembly of a System (Commercial Multi-Zone Fire and Smoke Alarm)

The design projects are also used to reinforce the total design approach. Each project is presented in the form of a commercial Request for Proposal (RFP), groups choose an RFP to which they will respond. The projects include a search and recovery robot, which is based on the platform from Engineering Design I. This robot (not autonomous) is required to locate simulated victims (infra-red sources) in a debris field and place markers at a fixed distance from each. Infra-red and proximity sensors are used; many groups also use Bluetooth™ to provide wireless control of the robot via a joystick using an RS232 port on the custom circuit board used in the robot.

The second project involves a gantry crane (built from LEGO). The project is posed as a retrofit with sensors for remote control. The team is required to use limit switches and sensors to remotely control, from a laptop computer, crane rotation through a defined angular range, hoist movement and the lateral positioning of a counter weight to balance the hoist. The third project is a compact, deployable, environmental monitoring system that can link to a wireless network and includes monitoring of temperature, wind speed and direction and a simulated hazardous gas (carbon dioxide).
Each of these projects is viewed as a system and groups are required to proceed through the first four stages of the total design process, developing context diagrams and use cases on their selected concept.

Figure 3. Engineering Design II Crane Project

For the conceptual stage, the use of a systematic evaluation of their ideas is encouraged through the use of a Pugh Matrix[1] in which concepts are plotted versus customer acceptance criteria and are each rated based on an assessment of whether the concept can meet, exceed or does not meet each of the criteria. The fifth stage would be to develop system specifications to guide the physical realization of the design. However, this has been limited to a basic response in the context of the RFP due to time limitations.
It should be noted that students are assigned to the groups in both Freshman design courses to provide a diverse mix of disciplinary interest and background skills. Particularly in Design II, there is a focus on developing effective teaming skills with associated group and individual assessments.

K-12 Outreach

As mentioned in the introduction, the initiatives at Stevens to develop systems thinking at the undergraduate level have also prompted consideration of extending the approach into the pre-engineering domain. It has become a national priority to increase the numbers of students choosing STEM fields. Providing engineering experiences and curriculum components in middle and high schools is seen as a means to engage students and excite them about the opportunities for an engineering career. Given that systems thinking and perspective are now seen as playing an important role in educating engineers for the future, it follows that coupling these concepts to the engineering elements of the pre-college program has merit. Stevens, through its Center for Innovation in Engineering & Science Education (CIESE), has been very active in promoting the introduction of engineering into K-12 curricula in the State of New Jersey as part of a broader approach to increasing the STEM pipeline. As part of this pre-engineering effort CIESE, with funding from a New Jersey Foundation and partnering with the Technology Educators Association of New Jersey (TEANJ), is working to develop, pilot, and disseminate, via face-to-face and online professional development, three to four curriculum modules that introduce concepts and approaches of systems and global engineering to high school technology and engineering students. By the end of the project, it is anticipated that 700 teachers in New Jersey and across the U.S., as well as internationally, will have learned about the Systems and Global Engineering modules and that at least 100 schools will be involved in an extended, intensive Systems and Global Engineering classroom project.

These modules will provide students with an opportunity to work collaboratively with students at other locations to design a solution to a complex problem. Students will be introduced to a systems-thinking approach that fosters team work, innovation and invention, effective communication, and other 21st century workforce skills. This effort will also benefit from and leverage a recent corporate donation of Pro/Engineer software to New Jersey schools. Students will make use of this state-of-the-art CAD/CAE software tool to create sophisticated, 3D models of their designs and then use this tool to assemble a final prototype based on all design components contributed by the project team.

Systems Engineering Education Research

In spite of the growing interest in systems engineering and teaching of systems concepts, there is surprisingly little research on core concepts and common misconceptions particular to the field. A recent review of literature found no systematic studies of engineering students' conceptual understanding of fundamental engineering concepts—including those pertaining to systems engineering - despite much research on important concepts in the sciences[4]. This acute lack of research is due, in part, to the fact that the field has been dominated by practitioners with relatively little scholarly research to underpin its development. While textbooks exist for the field, there has been little study of the coherence or completeness of systems concepts presented in those texts. Therefore, some of the fundamental concepts of systems engineering need to be defined in order to build the theoretical basis of the field.

Fundamental to systems engineering is system design (SD). SD impacts the engineering of a system from early on in its life cycle. Stevens (Jain) is undertaking research that focuses on defining SD concepts. Beyond identifying the core concepts in SD, it is also necessary to explore the variety of conceptions, correct or incorrect, that students hold about SD concepts. The majority of SE programs focus on the graduate-level and emphasize practical aspects of the field. As a result, some basic concept definitions are often overlooked. Students have their own beliefs or perceived meaning of SE concepts that may not correspond to accepted views in the field.

A necessary step in the progression of SE as an academic field will be the development of a concept inventory—a multiple choice instrument designed to evaluate whether a person has an accurate and working knowledge of a specific set of concepts. Concept inventories are built in a multiple-choice format to insure that they can be scored in an objective manner[5]. However, unlike a typical test, both the question and the response choices are the subject of extensive research designed to determine both what a range of people thinks a particular question is asking and what the most common answers are.

The Stevens research has already commenced with a pilot study. Once an accepted systems concept inventory is available from the research, it will be incorporated into the assessment of the undergraduate systems thread at Stevens to help support effective pedagogy in this challenging yet very important topic as it relates to preparing future engineers.

Concluding Remarks

This paper has described how a compelling industry need has driven the development of graduate programs directed at practicing engineers and project managers in technology industries to educate them in a systems approach to design for product/process life cycle and provide the requisite knowledge of the tools and techniques. This in turn has provided the recognition of the need and the expertise to adapt the systems approaches to be incorporated into the undergraduate core engineering curriculum as part of the design sequence taken by students in all majors. Systems concepts have been introduced and reinforced in the first two design courses taken in the freshman year. The systems thread will be continued into later design courses with a goal of having it bear fruit in successful multi-disciplinary, senior capstone projects, where the success of the system is paramount and the students are able to work to achieve their disciplinary contributions within the systems context.

The importance of developing systems thinking in engineers has further evolved ongoing approaches to providing pre-college engineering experiences as a means to stimulate students to choose engineering careers. By getting systems thinking into these early experiences it is hoped to demonstrate not only the excitement of engineering, but also the holistic approach that the modern engineer must take to solving engineering problems.

Finally, these efforts have recently prompted educational research to try and identify key concepts in the systems domain that students have problems learning and how the pedagogy can be best adapted to correct the misconceptions that hinder learning.

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