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Introduction to systems engineering for engineering and engineering technology students

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ABSTRACT: Systems engineering is a discipline that develops, matches and trades off requirements, functions and alternate system resources to achieve a cost-effective, lifecycle-balanced product that is based upon the needs of the stakeholders. Until recently, an introduction to systems engineering course for undergraduate students was not offered at Pennsylvania State University, Erie, USA; instead, it was expected that graduating students would learn about systems engineering on the job or at graduate school. In the fall of 2000, an introductory course was created and taught by the author for undergraduate students. Because the analysis and synthesis of complex systems that arise in a wide variety of engineering, physical and social problems, systems engineering teams are typically multidisciplinary, the course was open to enrolment in both electrical and mechanical disciplines. In order to help students visualise the breadth and depth of knowledge necessary for systems engineering, a particular system (a rail locomotive) was chosen to be studied both from a in-classroom theory of systems operation and, while outside the classroom, during live locomotive test track laboratories.

INTRODUCTION

Systems engineering is a discipline that develops, matches and trades off requirements, functions and alternate system resources in order to achieve a cost-effective, lifecycle-balanced product that is based upon the stakeholders' needs. Focusing on the analysis and synthesis of complex systems that arise in a wide variety of engineering, physical and social problems, systems engineering teams typically are multi-disciplinary, comprised of individuals with the breadth and depth of knowledge necessary for a particular problem [1].

It was determined that, although systems engineering studies are often reserved for graduate level students, a multidisciplinary technical elective for undergraduate students would be offered each year in the School of Engineering and Engineering Technology at Pennsylvania State University, Erie, USA. The course would promote best practices of systems engineering, systems architecture, evolutionary acquisition, risk management, and total lifecycle project management. An additional follow-on undergraduate course would also be offered that specialised in reliability engineering for small and large-scale systems and system processes [2].

To help students visualise a systems design, integration and testing, a large complex system of study was chosen: a freight locomotive (see Figure 1). The locomotive and locomotive test track was provided at no charge from the local rail industry manufacturer, General Electric (GE) [3]. GE stated they wanted to support the systems engineering course because of the potential for the following to be achieved:

- Better connect theory taught in the classroom to real-world events;
- Enable potential new-hire graduating students to be more knowledgeable in transportation systems engineering. GE also helped define course objectives and the course structure [4].

Figure 1: A GE freight locomotive.

COURSE OBJECTIVES

In the course, students learn about systems integration, design and testing. Salt and Rothery's textbook was chosen because it was simple and to the point for an introduction to undergraduate systems design studies [5]. Additional reading material, mostly from conference and journal papers or documents, such as GE control interface documents (ICDs) or system description documents, were handed out to students as supplemental reading. Upon completion of the coursework, students should have the following:

- The ability to connect theory and real-life applications;
- An awareness of failures and real life consequences;
- An exposure to cutting-edge technology;
- A deeper knowledge of systems engineering processes and reliability engineering;
- An understanding of how mechanical systems integrate with electrical systems;

- An understanding of the importance of quality and reliability;
- The vital importance of oral and written communication;
- The vital importance of configuration control;
- The ability to interact with mechanical and electrical engineers;
- The ability to work effectively in a multidisciplinary team that includes people from other fields, including business, computer science and manufacturing.

In order to achieve these objectives, faculty from Penn State Erie and engineers at GE work in concert to present material in lectures and laboratories. Coursework takes place both on college grounds and at GE facilities. For safety and liability reasons, students can use the facilities at GE only after they have completed a vigorous safety-training programme. Incidentally, this is identical to the programme that must be completed by every new GE employee.

COURSE STRUCTURE

In addition to receiving an afternoon laboratory on dos and don'ts for manufacturing plant safety during the school semester, this three-credit course studies the following locomotive subsystems: wireless communication and navigation systems, diesel engine systems, propulsion (DC and AC motors) systems, train control systems, operator cab (human factors), air brake systems, heating and cooling, platform and truck steering, and remote monitoring and diagnostics. Each subsystem is introduced to students as a standalone design entity, later to be integrated and tested in an overall locomotive *system*.

While it is important for students to understand the inputs and outputs to each subsystem listed above, the following systems engineering process is stressed pertaining to the overall needs of the locomotive system and each subsystem [5].

A needs analysis:

- Question the customer;
- Preview the user interface;
- Conduct an input/output analysis;
- Prepare the draft user's manual;
- Prepare the statement of the problem document.

The requirements specifications:

- Engineer the tolerances;
- Specify the prototype testing;
- Specify the deliverables and resolve disputes;
- Finalise the requirements specifications.

The systems design:

- Provide enough background;
- Organise jobs that need to be done:
  - Develop the concepts;
  - Model with system block-diagrams; build and model some concepts with computer simulations;
  - Prioritise (rank) the concepts;
  - Synthesise the concepts;
  - Analyse the system;
  - Refine, revise and re-analyse the system;
  - Finalise and document the system design (system specification is now complete).

Detailed design (combined with a separate project management plan):

- Organise jobs that need to be done;
- Implement the prototype(s);
- Debug and verify;
- Documentation and configuration control;
- Design reviews;
- Acceptance testing.

Systems integration and testing:

- Complete systems integration of pieces;
- Systems test;
- Verify and validate.

Where *analysis* is a separating or breaking up of any whole into its parts, especially with an examination of these parts to find out their nature, proportion, function and interrelationship, *synthesis* entails the putting together of parts or elements so as to form a whole.

Specifics regarding the use of *Design for Six-Sigma* tools and quality engineering (Deming's 14 points) are provided to students [6]. Also, statistical process control (Pareto and *cause and effect* diagrams), advanced probability and statistics, reliability engineering (MTBF, failure rates), outcome-based approach to mistake-proofing, Failure Mode and Effects Analysis (FMEA), and other related techniques are presented to the students as outside homework and reading assignments during this course [7-11]. These are formally presented in an additional mandatory Reliability Engineering course the following semester [2].

An example of an outside reading assignment followed by a next day in-class discussion involves students being given a handout from ref. [6] regarding the following *dimensions of quality*: performance; aesthetics; reliability; features; durability; perceived quality; serviceability; and conformance to standards.

During discussions, students are asked when they buy a hamburger, which burger is better: McDonald's, Wendy's or Burger King? Why? A similar question is mentioned in class: What make of car is better, and why? Chevrolet, Ford, Toyota or Honda? A follow-on question is asked of students: if you were to purchase a car today, prioritise the dimensions of quality listed above in the order you believe is most important to least important. If you want to really get the class excited, ask students to prioritise the dimensions of quality when choosing a mate for life, such as in marriage.

After each student has prioritised their dimensions of quality, it soon becomes apparent to each student that *their* respective views regarding the importance of each dimension are not always in agreement with their peers. At this time, students begin to realise that their view of complete system *user needs* may not be in alignment with the customer (user); so it is imperative that user needs are well defined and understood before any further systems design process moves forward, (else what you design integrate and test, no matter what, may not please the customer).

Additional course information: each week, there are two one-hour lectures and one two-hour laboratory that reinforce the lecture material. The lectures take place on campus and are frequently team-taught with GE engineers as guest lecturers.

The laboratory portion of the course takes place either at GE facilities, for example, at their test track facility, or at one of the on-campus engineering labs.

For each subsystem studied, students are given homework assignments, individual and/or group laboratory projects/ reports, quizzes and an examination. Students are encouraged to use software (*MATLAB*, *PSPICE*, *LabView*, *AutoCAD*, *Excel* and *PowerPoint*) when working on projects and reports. At the end of the course, each student is required to take a final examination that has in-class and take-home components.

The homework and laboratory assignments serve to reinforce the design, test and integration systems process. For example, student teams (consisting of both electrical and mechanical engineering technology students) are given the project of system engineering a common product, such as a doorknob or coffee maker. The teams are instructed to address real-world issues, including the following aspects:

- User needs;
- Reliability;
- Ease of use;
- Cost;
- Ease of manufacturing;
- Comparison to existing products;
- Project schedule.

SUBSYSTEM EXAMPLES

Subsystem examples are described below that students study, either from field laboratory experimentation, or by learning how system needs are implemented during a manufacturing tour.

Engines Systems

As the engine is the source of all power to the locomotive, the main topics of the engines systems section include:

- Combustion engine theory;
- Gasoline engines versus diesel engines;
- Four stroke diesel engines;
- Turbo chargers;
- Fuel consumption;
- Emissions;
- Crankshaft.

During this subsystem study, students visit the manufacturing facility for diesel engines, and observe how the different engine components are manufactured, assembled, and tested (see Figure 2). In addition, students are able to see how diesel engines are reliant upon electrical engineering technology to be efficient. For example, electronic fuel injection optimises the fuel efficiency of the engine and minimises wasteful emissions. Students also visit the GE learning and training facility and learn how the engine operates and how engine parts and subsystems are assembled using cut-away mock-up engines (see Figure 3).

Communications and Navigations Systems

In this subsystem, the focus is on introducing students to wireless communications technology, both terrestrial-based and electronic navigation systems. Examples of the wireless communication and technology systems studied include:

Figure 2: Rail locomotive engine at the GE Learning Center.

Figure 3: Diesel engine crankshaft.

- Satellite communications;
- Cellular communications;
- Digital radio;
- Radio Frequency Identification (RFID);
- Spread spectrum concepts, such as Code Division Multiple Access (CDMA);
- Global Position Satellite (GPS) systems;
- Differential GPS;
- Inertial Navigation.

For example, in the GPS lab, students are able to record real GPS receiver output messages while moving on a locomotive. Parameters such as latitude, longitude and speed are recorded. This recorded information is later overlaid on a track map to create a geographic information system. Position uncertainty of the GPS receiver is also calculated using basic probability and statistics theory (see Figure 4).

Figure 4: GPS card and industrial PC cards.

By using GPS data, students are able to understand that GPS is not a perfect system as it has position errors of up to 10-15 m, 95% and that statistically *independent* output messages of GPS are only output at rates of no more than once per second. Students also learn that tracking of GPS signals does not work in tunnels or while the locomotive travels through underpasses or bridges. In other words, GPS is not always available. Also students begin to realise that tracking GPS signals and track the position of the locomotive in real time. Figure 5 shows a student engaged at the controls of a locomotive, while Figure 6 shows students at the test track.

Figure 5. Undergraduate student at the locomotive controls.

Figure 6: Undergraduate students at the test track.

RF Laboratory Measurements

Students learn how to make power-coupling measurements between antennas that are mounted on top of the locomotive roof. The importance of this field experiment is to recognise that the amount of neighbouring radio frequency device output power projected into its neighbour's radio *front-end* is contingent upon each radio's antenna beam pattern for a given frequency, respectively.

Topics of RF conductivity, susceptibility and radiated emissions are explained during this specific laboratory. Students estimate how much power will be coupled between antennas for a given frequency, using either network analysers or a combination of a signal generator and spectrum analyser (see Figure 7).

Figure 7: Signal generator and spectrum analyser laboratory.

SUMMARY

Systems engineering is a discipline that develops, matches, and trades off requirements, functions and alternate system resources so as to achieve a cost-effective, lifecycle-balanced product that is based upon the needs of the stakeholders. Instead of assuming graduating undergraduate engineering and engineering technology students will acquire systems engineering know-how on the job or in graduate school, an introduction to systems engineering design, integration and testing is offered at Penn State Erie. The material presented in these courses is readily adaptable to other industries that require engineering of complex systems. The student response to these courses has been positive. Students repeatedly express their excitement over being able to work and study in a real-world environment.

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